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PILOTED SPACE-FLIGHT SIMULATION AT LANGLEY RESEARCH CENTER

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ABSTRACT

The paper outlines the major manned simulation projects currently underway at Langley, including both aviation and space programs. Langley's basic approach and objectives in these programs are described.

The main body of the paper reports in detail on those piloted simulation studies having direct applicability to the Gemini and Apollo space programs. Each problem, and the simulation equipment used, is described; and the most interesting study results are presented.

The paper contains discussions of several simulation problem areas and some general thoughts about the field of manned simulation.

INTRODUCTION

Manned simulation - including simulation for research and development and simulation for training - has developed, in its present form, in only the past 15 years or so. This has been due, of course, to advances in servomechanism and control theory and, most important, to great improvements in analog and digital computers. Simulation is now "big business." In total investment of professional manpower and facilities it is larger now than the whole aviation industry was not many years ago. Simulation is growing rapidly - exponentially, it seems. Where it will go in the next 15 years is anybody's guess.

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The growth of manned simulation has been well justified. Present-day simulation probably got its start from the need for World War II pilot trainers. The economic advantages of training simulators has been demonstrated many times and we can expect this segment of the simulation field to continue its growth. The use of training simulators should expand greatly, both in industry and in public use. We now have golf-course simulators and tomorrow we may have water-ski simulators! Successful exploitation of simulation for training, education, and entertainment will depend greatly on research "fall-out."

In research, simulation is often the only tool available for solving problems - particularly where man is directly involved. In man-machine systems research, we can agree with Westbrook (ref. 1) that simulators are used because our basic knowledge is weak. Man's capabilities are not limitless and therefore it seems logical that as our basic knowledge of manned systems increases the need in research for simulation should tend to decrease. Obviously, this is not the case. Simulators are becoming more numerous and complex every day - just as Westbrook predicted. This is due, it seems, to our expanding technology, which is outpacing our increase in basic knowledge.

As a major research center heavily involved in simulation Langley has a simulation mission (within the framework of its overall mission) to contribute to basic knowledge and present objectives and also to influence future developments.

In the remainder of this paper these aspects will be discussed using as a framework the major simulation facilities and programs in operation at Langley. Particular attention is given to space-flight problems related to Gemini and Apollo.

LANGLEY RESEARCH CENTER SIMULATION MISSION

Langley Research Center's simulation mission can best be described with the aid of figure 1. This figure shows that Langley's activities are divided into two separate areas, each with its own prime objectives. These areas are Simulation Research and Research Simulation.

Simulation Research

Simulation Research is conducted with the objective of improving the state-of-the-simulation-art. As shown by the figure, problems are tackled by applying the state-of-the-art (or refinements thereof) together with new and novel techniques where necessary to the design and use of the simulator with the expectation that useful results will be obtained.

In support of state-of-the-art improvements Langley is investigating methods for improving the "effective" resolution of TV, visual-display generation systems, and holography. An example of the development of novel techniques is the Langley lunar-walking simulator shown in figure 2, and described in reference 2. Recent contract studies using this technique, wherein metabolic rates were measured, indicate greatly increased range and endurance of pressure-suited astronauts on foot as compared to 1 g tests. These results are important in determining logistic requirements, lunar experiment planning, and in design of lunar roving or flying vehicles.

Closing the loop through validation is an essential requirement and responsibility of every research organization and for progress in simulation technology. We are now beginning to get feedback from the space program for research done as long as 9 years ago. Results from Mercury and Gemini manually controlled reentry, Gemini docking, and Astronaut White's "space walk" using a simple hand-held propulsion unit have been gratifying. On the other hand, feedback from visual rendezvous experiments has been obtained which indicates that a more realistic simulation should have been conducted in order to reproduce the visual conditions encountered by the astronauts. They appear to have considerable difficulty in seeing the stars except on the dark side of the orbits. This problem is related to the optical transmission properties of the windows, as well as deposits on the windows, which would have been difficult to predict before the flight experience. Astronaut Cernan's GT-9 aborted maneuvering unit experiment is an example of a case where the simulation techniques used in preparation for the mission were inadequate. None of the methods available (including zero g airplane trajectories and 1 g vacuum chambers) were able to predict the work load required to perform the task. In the future, perhaps problems of this sort will be studied using the relatively new neutral-buoyancy, water-immersion technique for simulating zero g for long-duration test times. This method appears very promising. At this time, however, personnel experienced in the technique are scarce so that the "confidence level" of test results is still an important matter for further investigation.

Langley has supported development of the water-immersion technique with contracts and is conducting in-house studies. A further contract study of water immersion in comparison with other zero g simulation techniques is also being sponsored.

Research Simulation

Referring again to figure 1, Langley has two main objectives in research simulation. The first, high-priority objective is to provide timely support for our national programs. Most of Langley's simulation work is of this nature. Langley and other NASA research centers are called upon to do this developmental work because of the uniqueness, versatility, and timely availability of facilities and technical background developed from previous basic research efforts. Types of programs involved include feasibility studies, design studies, hardware check-out, development of operational procedures, and at times training.

Simulation studies such as these are performed because they are concerned with problems about which little information is known and any knowledge gained represents a worthwhile contribution. The number and urgency of these problems generally restricts us to rather broad investigations of only the major aspects. Refined examination of these factors or of secondary effects, requiring statistical studies, are not often undertaken because of time and manpower limitations.

With this discussion I have tried to describe how Langley views its simulation mission and also some of the problems a government research organization has in trying to fulfill this mission. Now I would like to discuss what Langley actually is doing in manned simulation. In the course of this discussion I shall also try to bring out some interesting aspects associated primarily with simulation technology.

MANNED SIMULATION FACILITIES AND PROGRAMS

Langley has at this time seven major facilities which are used entirely for the study of man-machine problems. At the moment five of these facilities are being used to support the space program (four devoted entirely to the Gemini and Apollo programs) and two are engaged in aeronautics research. This division of effort is, of course, not fixed. It has, and will, shift back and forth as needs change. In addition to these large facilities, Langley also has a number of smaller simulators that are used for research in both aero and space problems.

In the following paragraphs the more interesting of these facilities, and the problems that are being studied, will be discussed.

Supersonic Transport Simulator

The Langley Research Center has been heavily supporting the supersonic transport program for the past several years. Langley is, of course, conducting studies directed toward improving the aerodynamic, propulsive and structural efficiency of this vehicle. However, these factors do not alone determine the economic feasibility of the supersonic transport. Unlike most other airplanes to date, the operating cost will be affected strongly by how well it can cope with the constraints imposed upon it by the air traffic control system and by sonic-boom considerations.

The Langley Supersonic Transport Simulator is being used to study the interaction of air traffic control system constraints and aircraft characteristics (performance and flying qualities). Both present-day traffic control systems and possible future systems are being studied. The SST is being examined using present transport cockpit instrumentation and with improved display systems.

One problem with the transport is illustrated in figure 3 which shows the large overshoot that occurs at an airway intersection while turning at supersonic speed unless lead information is supplied. Another problem involves flying a holding pattern in a wind. Figure 4 shows the great improvement obtained when holding with the aid of a pictorial display.

Although publicly acceptable sonic-boom intensities have not yet been established, studies of a variety of let-down and climb-out profiles are being made to determine the effects on system design and operation. The supersonic transport pilot, for example, tends to have difficulty in flying these profiles because altitude, Mach number, indicated airspeed, and rate of climb are all varying and are difficult to monitor properly on separate instruments. The improvement obtained when a single flight director instrument was used is shown in figure 5. Final sonic-boom restrictions will be an outcome of the National Sonic Boom Program in which Langley has an active part.

Further details of SST studies are given in reference 3.

An interior view of the simulator is shown in figure 6. The arrangement is similar to that provided in current subsonic jet transports with a pilot, copilot, flight engineer, navigator, plus an observer. The flight instruments were modified as necessary to cover the wider operating ranges of the SST. Five Electronic Associates 231-R analog computers are used to solve the six-degree-of-freedom motion equations covering Mach numbers from 0 to 4.0 and altitudes from sea level to 100,000 feet. In addition to computing motions, the computer program also handles engine, autopilot, and other systems characteristics. The program has been used to study variable- and fixed-geometry designs and after- and duct-burning engines.

A unique feature of this simulation is the manner in which the air traffic control environment is obtained. Commercial telephone lines are used to tie the SST simulator to the FAA National Aviation Facility Experimental Center at Atlantic City, New Jersey. By this means the SST can be flown in a simulated 400-by-400-nautical-mile control area around New York City where it takes its place among as many as 100 other aircraft of various types (including other SST's) directed by 30 air traffic controllers (see ref. 4 for further description of the entire simulation).

It is interesting to note that the feasibility of tying simulation facilities together over long distances was first studied in 1956 when Langley computers were tied to the Navy human centrifuge at Johnsville, Pennsylvania, and used to study X-15 trajectory problems. While it is common practice to tie facilities together over shorter distances within an organization, one can speculate that someday this might be done over a much broader area and thus improve the utilization of these large and expensive devices. At Langley, for example, the SST simulator absorbs most of the available analog equipment and other large programs must be stopped when the SST program is running.

Variable-Stability Helicopter

Langley's Variable-Stability Helicopter is shown in figure 7. The basic, twin-rotor machine supplied by the U.S. Army has been converted by installation of analog computers and sensors and by modification to the control system so that a wide variety of vehicles (within the operational range of the basic vehicle) can be simulated using the "computer-model" technique. Briefly, this technique consists of obtaining a continuous real-time solution of the equations of motion of the aircraft being simulated and using closed-loop servo techniques to force the test vehicle to follow the desired motions. The servos operate on the difference between the desired motions (obtained from the computers operating on a model of the simulated aircraft in the computer) and the actual motion derived from the flight sensors. A complete description of this simulator is given in reference 5, and examples of the work being done are given in references 6, 7, and 8.

Flight-test simulators of this sort are a necessity for studying many critical piloting problems such as landing, hovering, and precision maneuvering. At the present state-of-the-art, ground-based facilities are just not able to provide the pilot with an adequate simulation of his visual-motion environment. This problem area in simulation technology is particularly challenging. It will require not only improvement in visual presentations but also much better understanding of the effects of motion and the problems of realistic motion-cue generation.

Langley Life-Support System Simulator

This facility is shown in figure 8 and a functional diagram of the system is given in figure 9. It should be noted that essentially everything required for life-support except food is recycled. The simulator, which is 18 feet in diameter and 18 feet high, is designed to study the problems of maintaining the well-being of a space crew of four on long-duration missions. Although the facility operates in a 1 g environment, all systems are designed to function under zero g.

The main objective of the facility is to develop the life-support technology required for long-duration missions. Involved are such areas as systems design, reliability and maintainability, toxicology, contamination measurement and control. The facility provides an opportunity also to investigate such problems as confinement, sensory-deprivation, and skill-retention. Should such studies be undertaken in the future, these problems would perhaps be investigated using the Electronic Image Generator described below.

Electronic Image Generator

This device, shown in figure 10, has the capability of generating for display on an oscilloscope a wide variety of information. Although it is now obviously too large for use onboard a spacecraft, it can be miniaturized in that all functions it performs can be programed into the vehicle computer.

It can display alpha-numerics, dials, flashing and moving spots, etc. In conjunction with a control chair, a wide variety of problems can be presented that must be solved by proper hand and foot motions. Psychophysical tests are now being developed for monitoring the crew members.

The image generator can also generate maps, a star background, symbolic rendezvous and docking targets, and landing areas. These displays can be moved about in proper response to six-degree-of-freedom motion. In this mode, and tied into the pilot's controls, it becomes an onboard simulator for maintaining piloting proficiency. The problem here is to develop suitable tasks despite the severe restriction of the small scope presentation, and this development is underway using the device in comparison with the other space-flight simulations at Langley.

Universal Flight Display Synthesizer

This system is a much more sophisticated image generator than the one just described. It has just gone into operation at Langley and is being used in flight display research as shown in figure 11. The Synthesizer is based on an electronic animation technique which allows the display designer to proceed directly from static instrument mockup to dynamic displays which are simulated at the display console by high-resolution (1200-line) closed-circuit TV. A detailed description is given in reference 9. The versatility of the system provides an effective, less costly, and time-saving means of creating dynamic displays for research.

Lunar Landing Research Facility

Ground-based simulators are not very satisfactory for studying the problems associated with the final phases of landing. This is due primarily to the fact that the visual scene cannot be simulated with sufficient realism. For this reason it is preferable to go to some sort of flight-test simulator which can provide real-life visual cues. One research facility designed to study the final phases of lunar landing is in operation at Langley. This Lunar Landing Research Facility is shown in figure 12. The facility is an overhead crane structure about 250 feet tall and 400 feet long. The crane system supports five-sixths of the vehicle's weight through servo-driven vertical cables. The remaining one-sixth of the vehicle weight pulls the vehicle downward simulating the lunar gravitational force. During actual flights the overhead crane system is slaved to keep the cable near vertical at all times. A gimbal system on the vehicle permits angular freedom for pitch, roll, and yaw. The facility is capable of testing vehicles up to 20,000 pounds. A research vehicle, weighing 10,500 pounds fully loaded, is being used and is shown also in figure 12. This vehicle is provided with a large degree of flexibility in cockpit positions, instrumentation, and control parameters. It has main engines of 6,000 pounds thrust, throttleable down to 600 pounds, and attitude jets. This facility is studying the problems of the final 200 feet of lunar landing and the problems of maneuvering about in close proximity to the lunar surface. A detailed description of the facility is given in reference 10.

Over one hundred "flights" have been made with the research vehicle, and some of the early results are given in reference 11. One of the most interesting preliminary results is that pilots prefer to fly in a manner similar to that used in helicopters. For comparable earth translational accelerations larger pitch angles (about six times) are required on the moon. However, pilots were found to use smaller pitch angles and appear willing to accept the longer time required to attain the desired velocity.

LOLA

The problems of lunar approach, orbit establishment, letdown, and final approach to the point where the previous simulator takes over are being studied at Langley using LOLA, which stands for Lunar Orbit and Let-down Approach Simulator. This simulator is shown schematically in figure 13 and consists of a pilot's capsule, a closed-circuit TV complex, and models of the lunar surface. There are four models of different scale which permit altitude coverage from 200 miles to 200 feet above the lunar surface. The models include a 20-foot-diameter sphere, two spherical segments, and one flat section. The models are arranged so that only two camera transport mechanisms and two closed-circuit TV systems are used alternately to view the four models. A view of a LOLA surface model in preparation is shown in figure 14.

LOLA illustrates vividly the complexity involved in achieving adequate visual realism over its design range.

Projection Planetarium

Another approach to the scene-generation problem is the point-light-source projection technique. This technique has been used in the Langley Projection Planetarium, shown in figure 15, to study Apollo launch-abort problems. This method was very effective in providing the required horizon-to-horizon view of Florida as seen from about 100,000 feet.

The Apollo launch-abort situation is illustrated in figure 16. The problem is for the pilot, under severe time restrictions, to arrest tumbling and to position the capsule for reentry - using only visual cues acquired through one rather small window. Results of the study are given in reference 12. It was found that except for some double failure situations, the pilots could perform this manual abort within the time limits.

Proper motions of the Florida scene were obtained from a surplus Nike-Ajax radar drive upon which the point-light-source projection was mounted. The radar drive had been modified by the addition of a third axis. This surplus equipment is being used at Langley for a number of studies because of its ready adaptability to analog simulation work.

Figure 17 shows a Nike drive adapted for rendezvous simulation. The Gemini half-cockpit can also be seen. In this study the star background was driven by the Nike in three degrees of freedom and the rendezvous target (represented by a flashing light) was driven in two degrees of freedom by a small auxiliary drive system referenced to the star field. A closeup of the star projector is shown in figure 18. This projector operates on a concept developed by Spitz. It consists of a point-light source reflecting off a centrally located highly reflective sphere which directs the light outward through the many holes representing the stars. The size of the holes is varied to vary star magnitude. The star images are brought to a focus on the inside of the planetarium by lenses glued to the surface of the projector. Simple geometric relationships such as the size of the projector and the diameter of the projection sphere govern the focal length required for these lenses. Although this type of projector does not have the precision required for the study of navigation problems it is very adequate for pilot control problems such as rendezvous where the star field is primarily used as an attitude reference.

Another application of the Nike radar drive is shown in figure 19 where it has been converted into a two-axis, visual-motion simulator. Instrument and scope displays can be put into the cockpit, or the entire assembly can be put into the Projection Planetarium on the sting support. This equipment is being used in a basic study of visual-motion cues to obtain design information for future simulators.

Rendezvous Docking Simulator

The Rendezvous Docking Simulator has been in operation at Langley for the past 3 years and is shown in figure 20. This simulator employs full-scale mock-ups of spacecraft cockpits mounted in gimbals. The facility is unique in that the entire gimbal assembly is supported by a cable system attached to an overhead crane. The cable arrangement effectively rigidizes the system and avoids pendulous motion so that correct linear motions can be commanded. A novel lightweight hydraulic-pneumatic counter-balance system is used to support the gimbal assembly. This permits the use of a relatively small vertical-drive motor which has only to overcome the inertia of the hanging system. The facility enables simulation of the docking operation from a distance of 200 feet to actual contact with the target. A full-scale mock-up of the Gemini vehicle is shown suspended in the gimbals. An Agena target was suspended near one end of the track. On this was mounted the actual Agena docking mechanism and also various types of visual aids. We have been able to devise visual aids which have made it possible to accomplish nighttime docking with as much success as daytime docking. Many of the astronauts have flown this simulator in support of the Gemini studies and they, without exception, appreciated the realism of the visual scene. The simulator has also been used in the development of piloting techniques to handle certain jet malfunctions in order that aborts could be avoided. In these situations large attitude changes are sometimes necessary and the false motion cues that were generated due to earth gravity were somewhat objectionable; however, the pilots were readily able to overlook these false motion cues in favor of the visual realism. This facility is now being used to develop docking techniques for the Apollo program. The LEM pilot's compartment, with overhead window and the docking ring (idealized since the pilot cannot see it during the maneuvers), is shown docked with the full-scale Apollo Command Module target in figure 21. Still another configuration - Apollo docking with the LEM target - is shown in figure 22. Reports of some of these studies are listed in references 13 to 15.

The Rendezvous Docking Simulator and also the Lunar Landing Research Facility are both rather large moving-base simulators. It should be noted, however, that neither was built primarily because of its motion characteristics. The main reason they were built was to provide a realistic visual scene. A secondary reason was that they would provide correct angular motion cues (important in control of vehicle short-period motions) even though the linear acceleration cues would be incorrect.

The RDS has translational and rotational velocity plus linear acceleration characteristics adequate for studying VTOL and helicopter take-off, hover, and landing problems. In such studies both angular and linear motion cues will be realistic.

At the present time, however, since emphasis on space docking is decreasing, the facility is being modified to serve as a closed-circuit TV carriage. It will view an HO-scale model of a Kennedy Airport runway in the study of Category II (break-out at 100 feet) landing problems. This simulation technique is considered adequate in this case because of the large model-scale and because visibility under Category II conditions is often rather poor. Peripheral vision will also be supplied in these studies (which is not generally the case) - an important requirement, particularly where rapid decisions (upon break-out) must be made.

Visual-Optical Simulator

This facility was formerly called the Visual Docking Simulator. It presents to the pilot an out-the-window view of his target in correct six-degree-of-freedom motion. The scene is obtained by a television camera pick-up viewing a small-scale gimbaled model of the target.

For docking studies, the docking target picture was projected onto the surface of a 20-foot-diameter sphere and the pilot could, effectively, maneuver into contact. This facility was used in a comparison study with the Rendezvous Docking Simulator - one of the few comparison experiments in which conditions were carefully controlled and a reasonable sample of pilots used. All pilots preferred the more realistic RDS visual scene. The pilots generally liked the RDS angular motion cues although some objected to the false gravity cues that these motions introduced. Training time was shorter on the RDS, but final performance on both simulators was essentially equal. A detailed discussion of these tests is given in reference 16.

For station-keeping studies, since close approach is not required, the target was presented to the pilot through a virtual-image system which projects his view to infinity, providing a more realistic effect. In addition to the target, the system also projects a star and horizon background. A cockpit view of the simulation is shown in figure 23. A report of some station-keeping studies is given in reference 17.

Space Tethering

Langley has been studying space tethering for several years. Recently we have been conducting studies in support of a proposed Gemini experiment wherein tethering is used as a station-keeping technique. In this technique a light, elastic cable is tied between the two vehicles, brought taut, and then the system is set into slow rotation. After this has been accomplished, the system should require no more attention from the crew.

The piloting problem was to see if the pilot could perform the maneuver using visual and/or motion cues alone while at the same time damping out any cable oscillations. For this study the Rendezvous Docking Simulator was used. A light string was tied between the two vehicles to provide the visual cues. The cable characteristics and the Gemini motions caused by the pilot's maneuvers and by the cable were computer-programed. It was found that the technique was feasible.

It is interesting to note that a second simulation of this problem was run on the Visual-Optical Simulator. In this study the pilot was again given a view of the cable and also a view of the Agena target motions against the earth-star background. In this simulation the pilot was given no motion cues. Although the motions could be damped using only visual cues, several test subjects felt that the motion cues supplied by the Rendezvous Docking Simulator simplified the problem. A report of these studies is now in preparation.

Zero-Gravity Simulation

As mentioned previously, Langley is conducting in-house and contract studies of extra-vehicular activities wherein zero gravity is simulated by the water-immersion technique. Some results of these studies are given in references 18 and 19, and a photograph taken during ingress-egress studies is given in figure 24.

Water immersion is a very useful technique where motions are slow. When more rapid motion is required, as in studying one-man propulsion systems, other approaches are required. For these studies Langley has been using the RDS in a manner similar to the LLRF technique. The test subjects are suspended in a sling support from a single RDS cable. As they translate about, the RDS tracks them, keeping the cable vertical. The test subjects operate in an effectively zero g environment in the horizontal plane. Tracking was originally done visually using closed-circuit TV, but recently a fast-response servo system using cable angle sensors has provided better operation. This simulation is shown in figure 25.

Some results of tests where subjects moved about merely by jumping and also where propulsion in the form of simple "jet-shoes" was provided are given in reference 20. Both methods, within limits, appear feasible.

Full six-degree-of-freedom equipment for studies of more sophisticated one-man propulsion systems is now being procured. Called OMPRA (One-Man Propulsion Research Apparatus), the device will provide a gimbal system for rotational freedom, a quick response vertical servo for this translational freedom that is not now feasible with the RDS, and a versatile maneuvering unit. This apparatus, shown in figure 26, should be operational early next year. A paper reviewing use of various zero g simulator techniques is given in reference 21.

CONCLUDING REMARKS

In this paper I have attempted to present Langley's approach to simulation as a research organization. Also I have tried to give a broad view of the facilities available at Langley and how they are being used to provide, in many cases, early information on new problems.

Finally, I have discussed some problem areas in simulation technology which may be worth further study. The more important technical problems appear to be in visual fidelity, accurate reproduction of visual contrasts and lighting conditions, and understanding of motion cues and motion cue generation.

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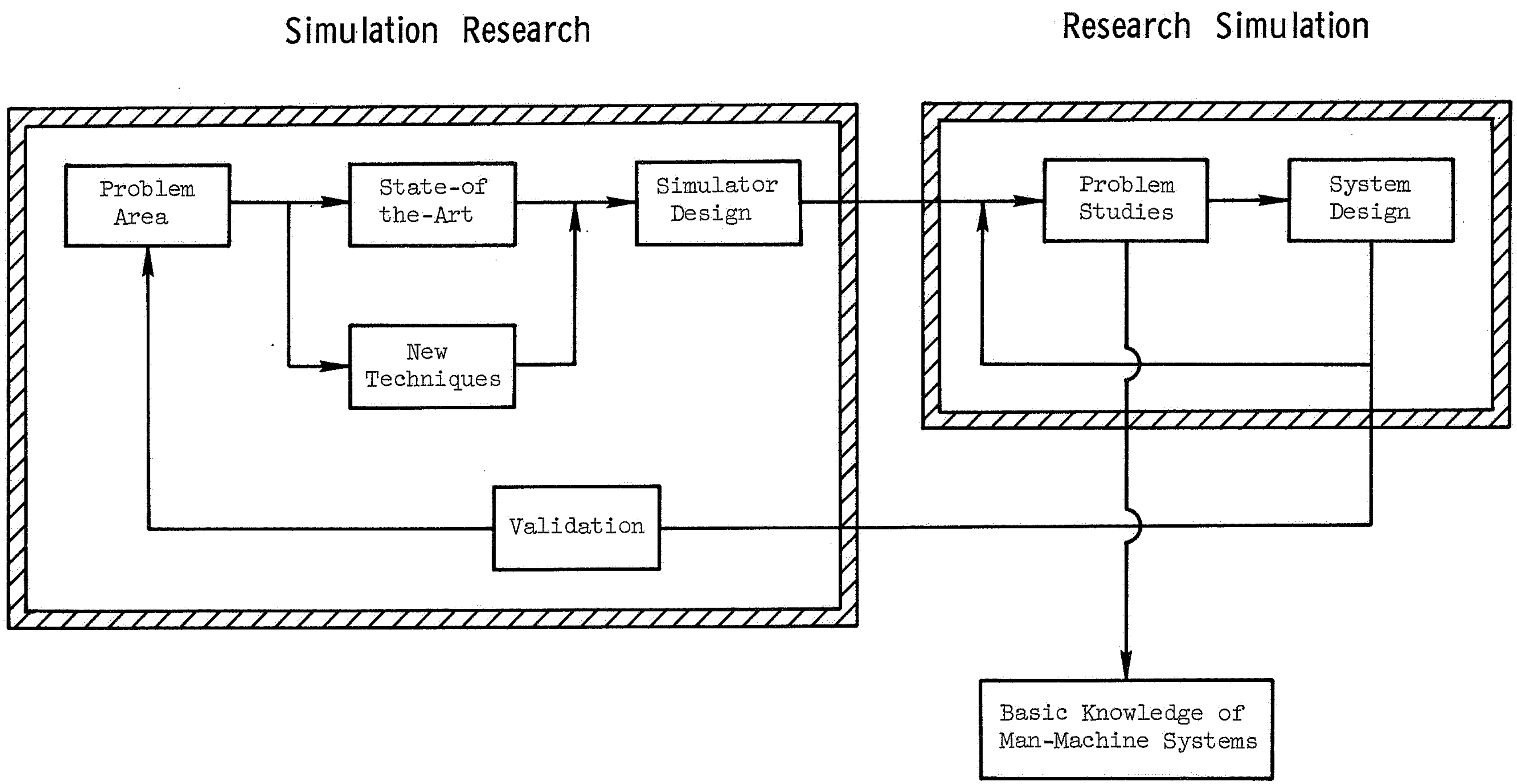

Figure 1.- Langley Research Center simulation mission.

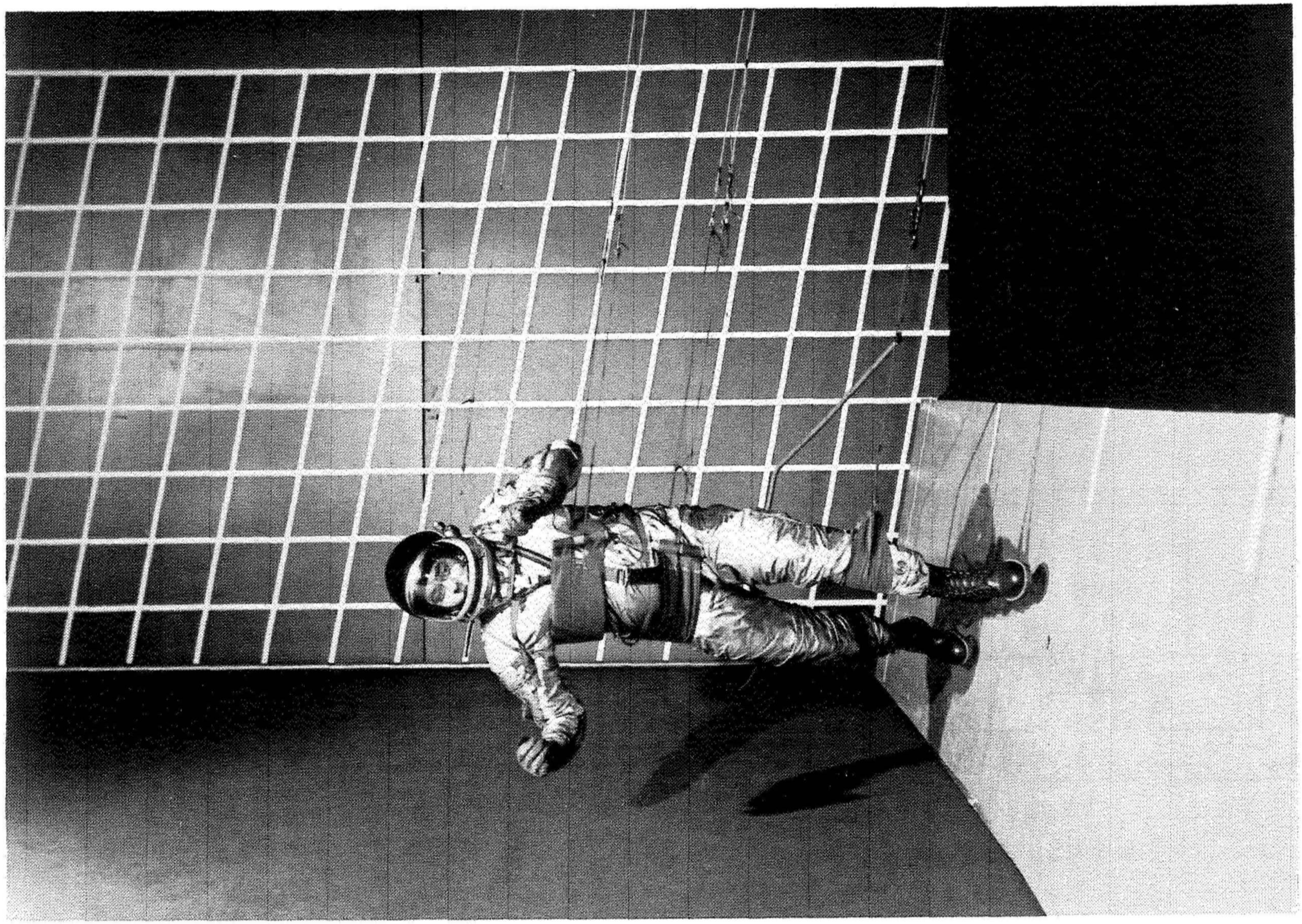

Figure 2.- Lunar walking simulator.

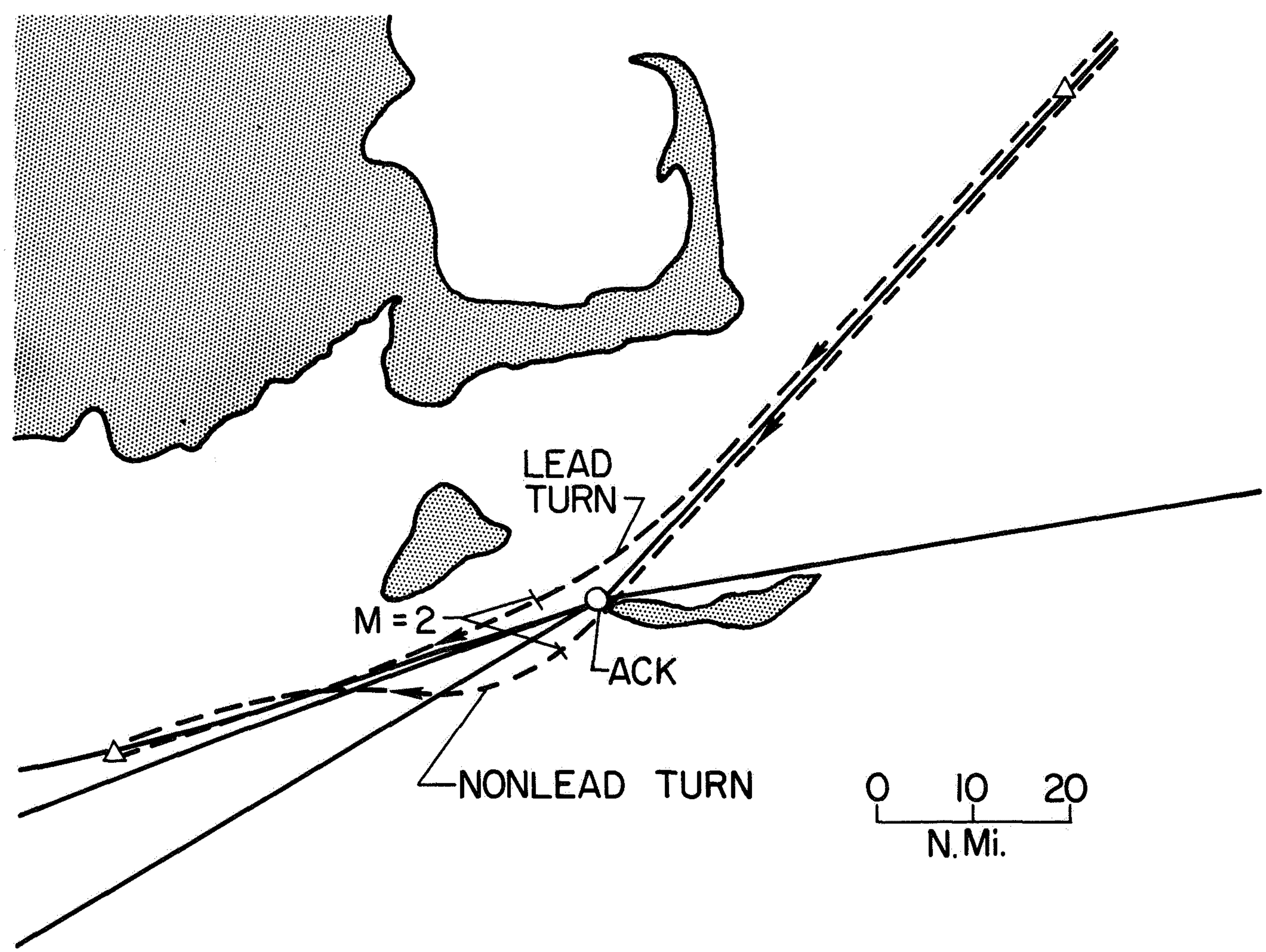

Figure 3.- Supersonic transport turns.

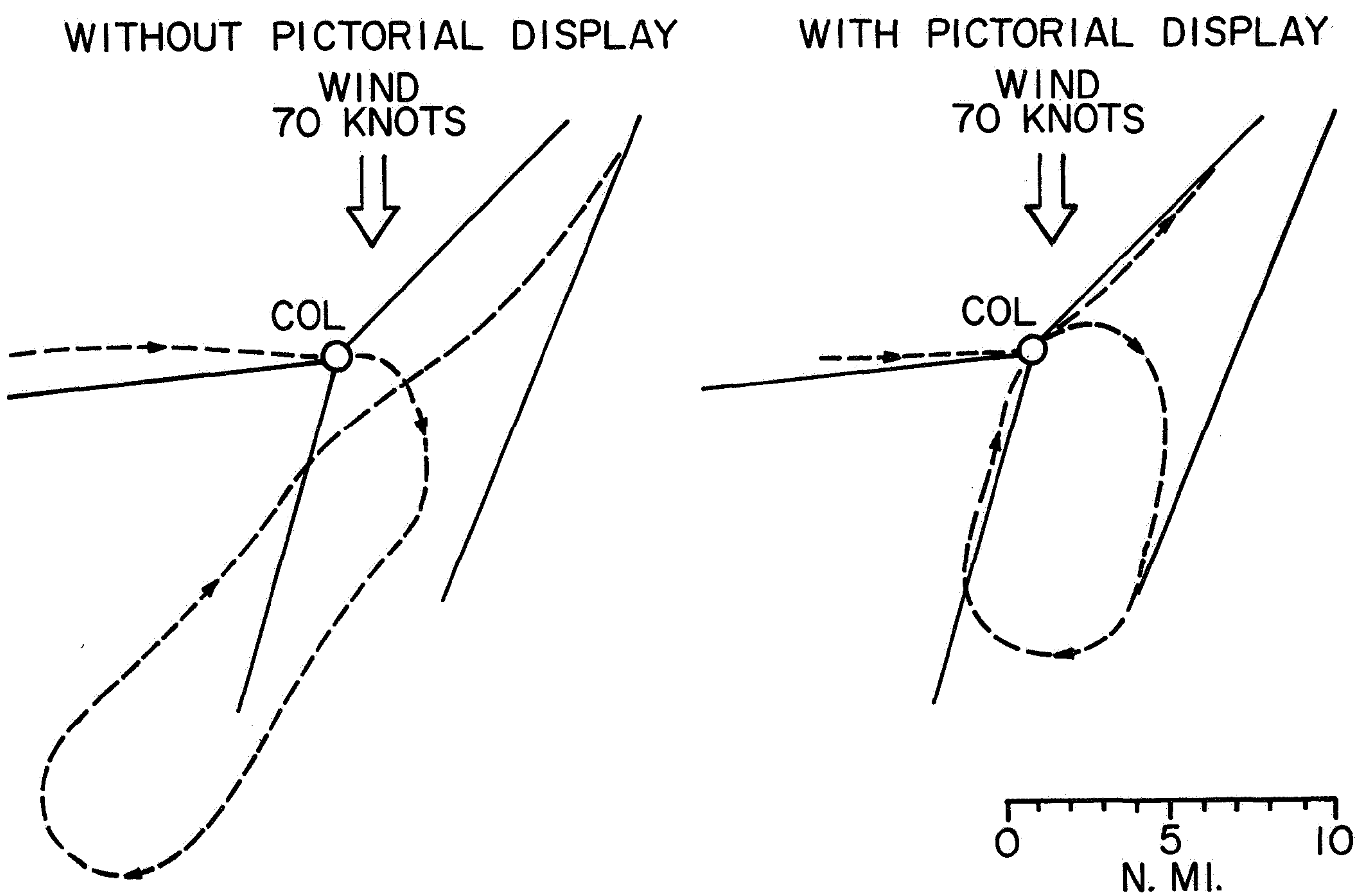

Figure 4.- Supersonic transport holding patterns.

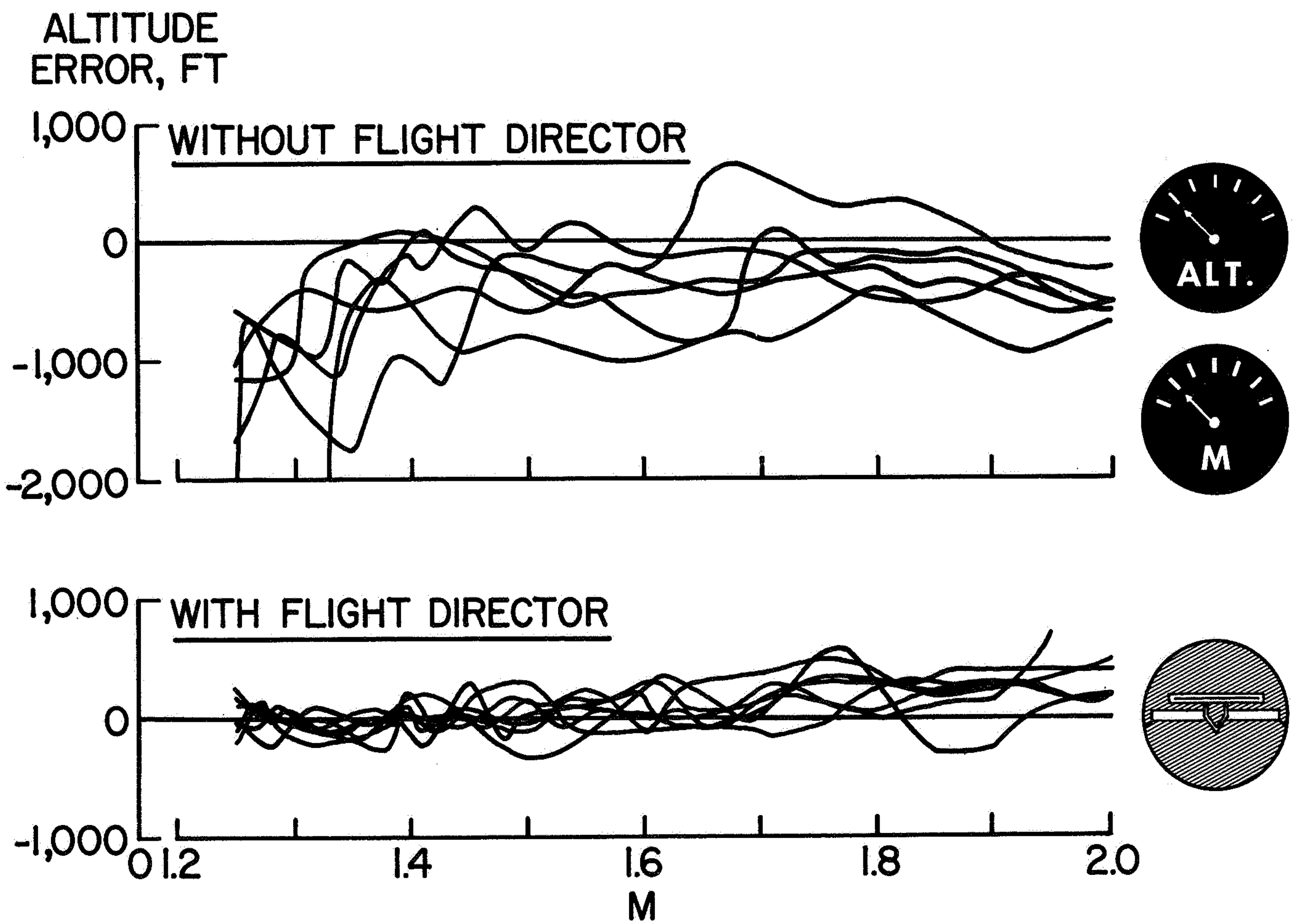

Figure 5.- Supersonic transport altitude error in following sonic-boom profile.

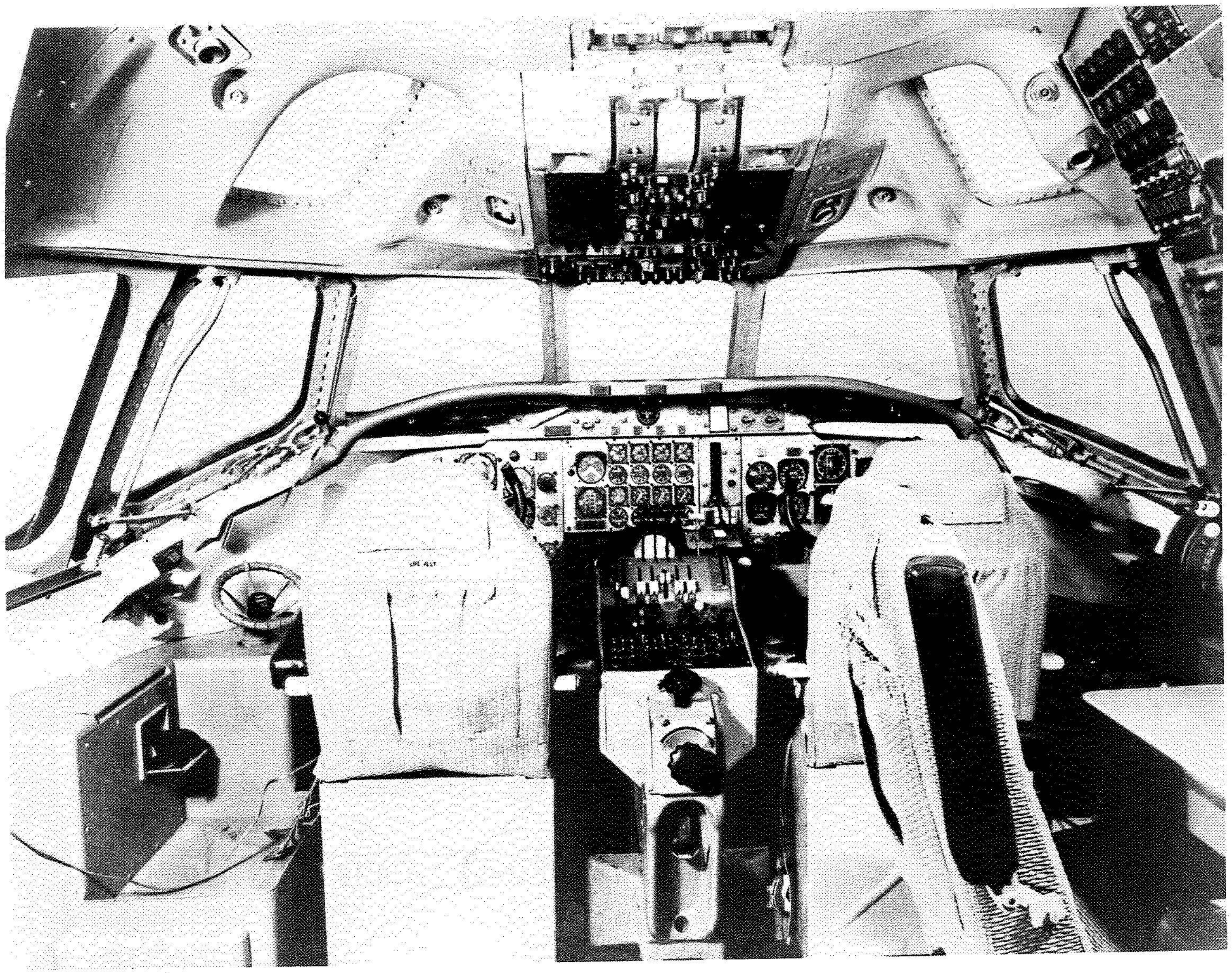

Figure 6.- Supersonic transport simulator cockpit.

Figure 7.- Variable-stability helicopter.

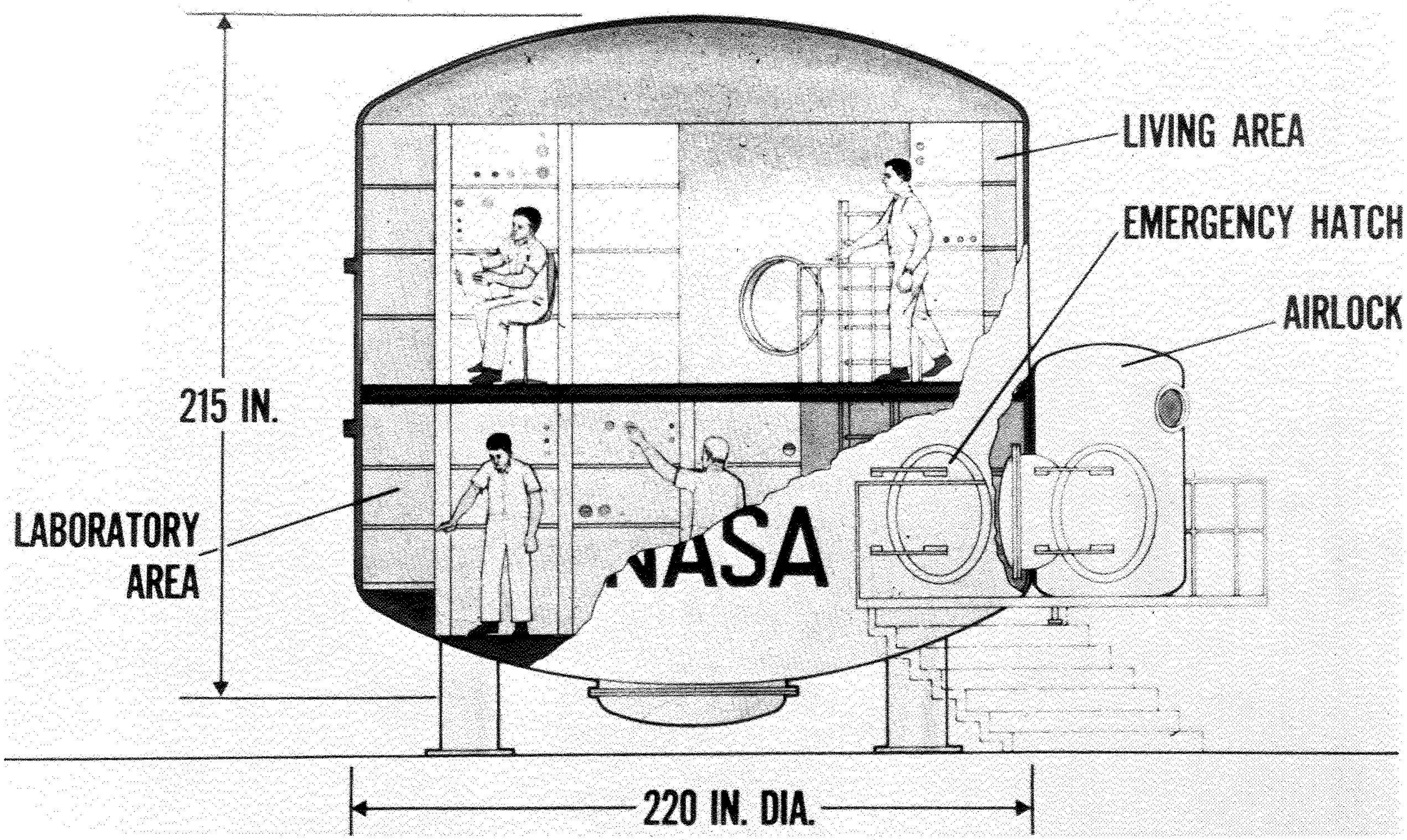

Figure 8.- Integrated life-support system.

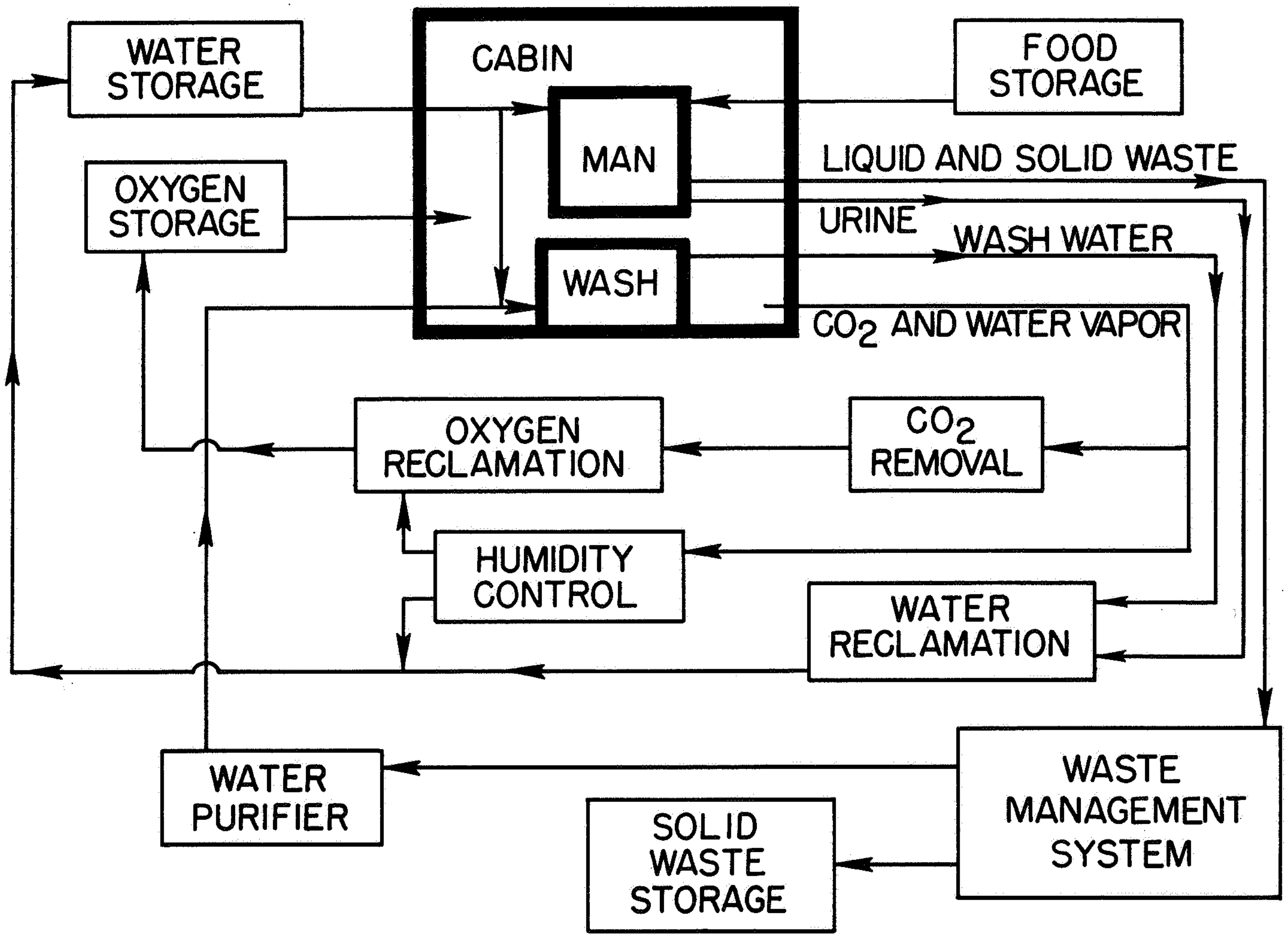

Figure 9.- Life-support system functional diagram.

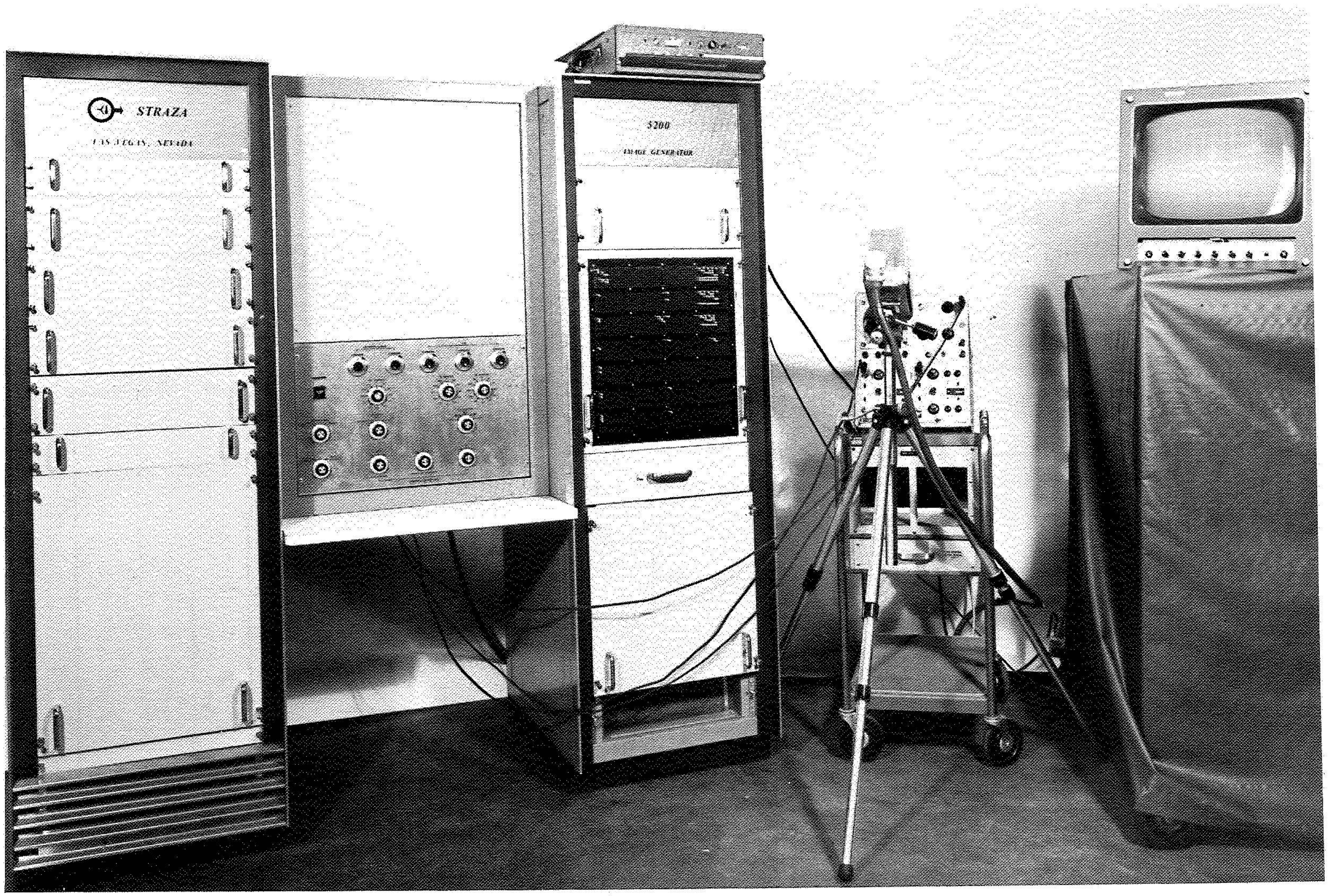

Figure 10.- Electronic image generator.

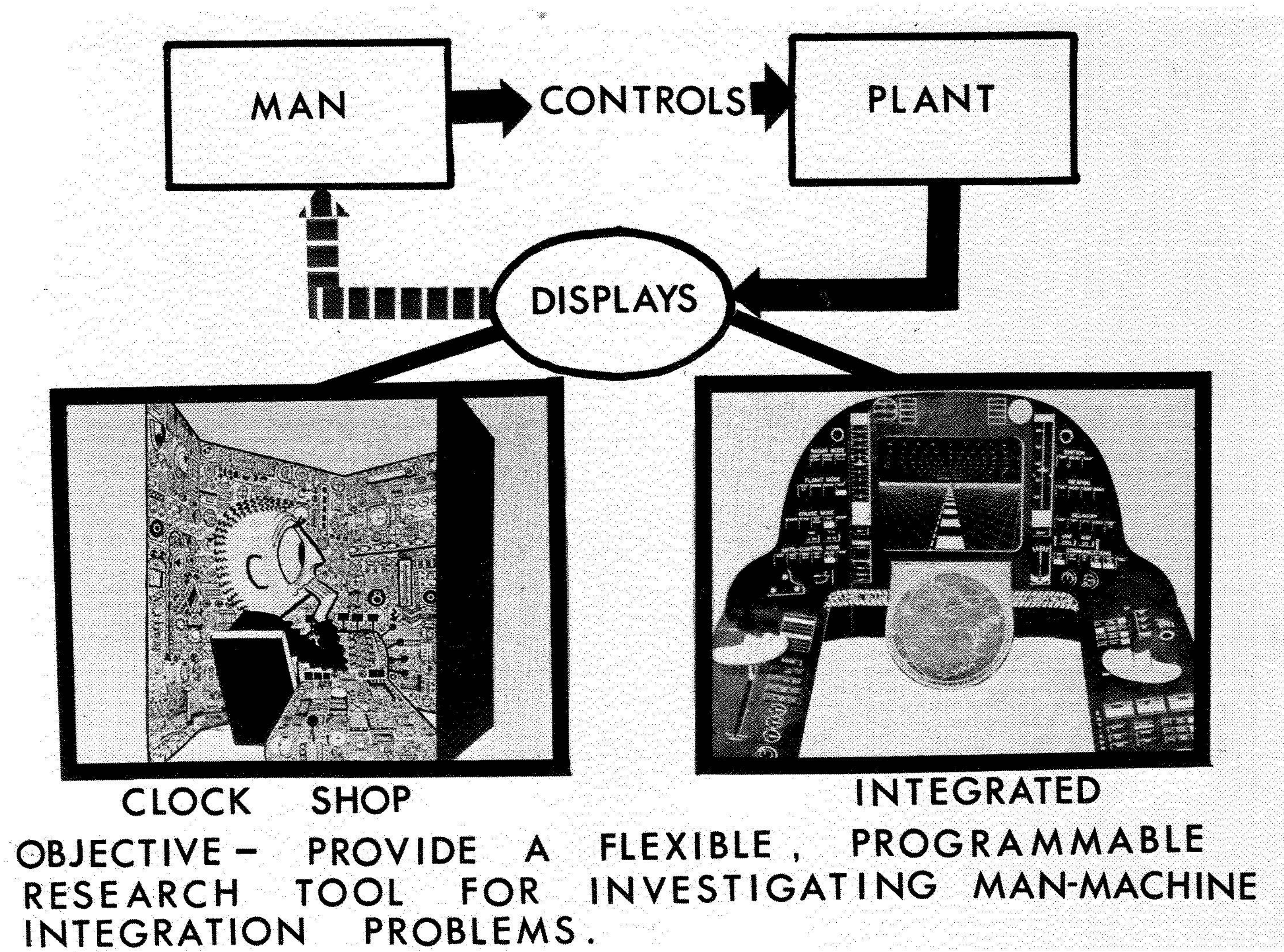

Figure 11.- Flight-display research.

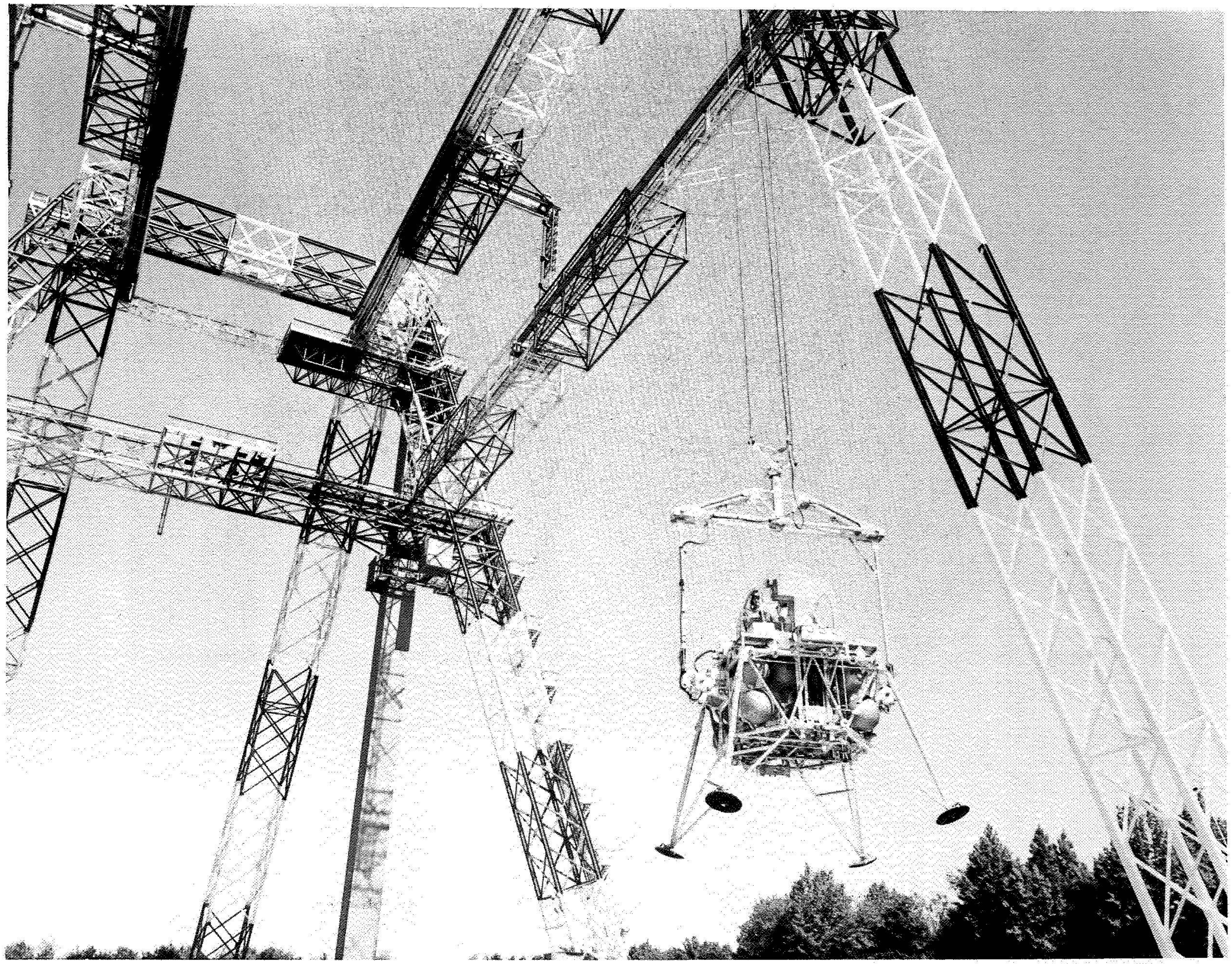

Figure 12.- Lunar landing research facility.

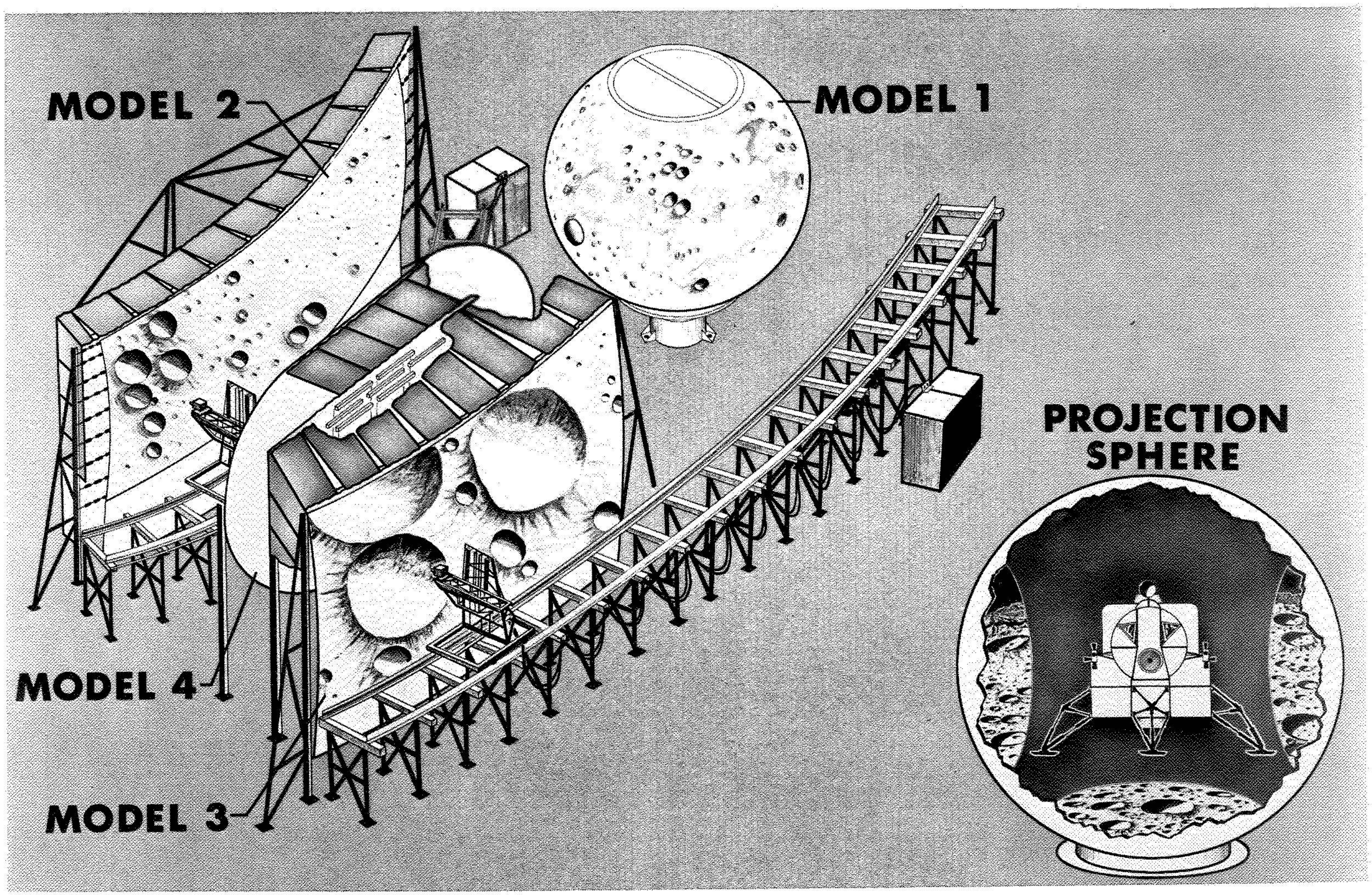

Figure 13.- Lunar orbit and letdown approach (LOLA) simulator.

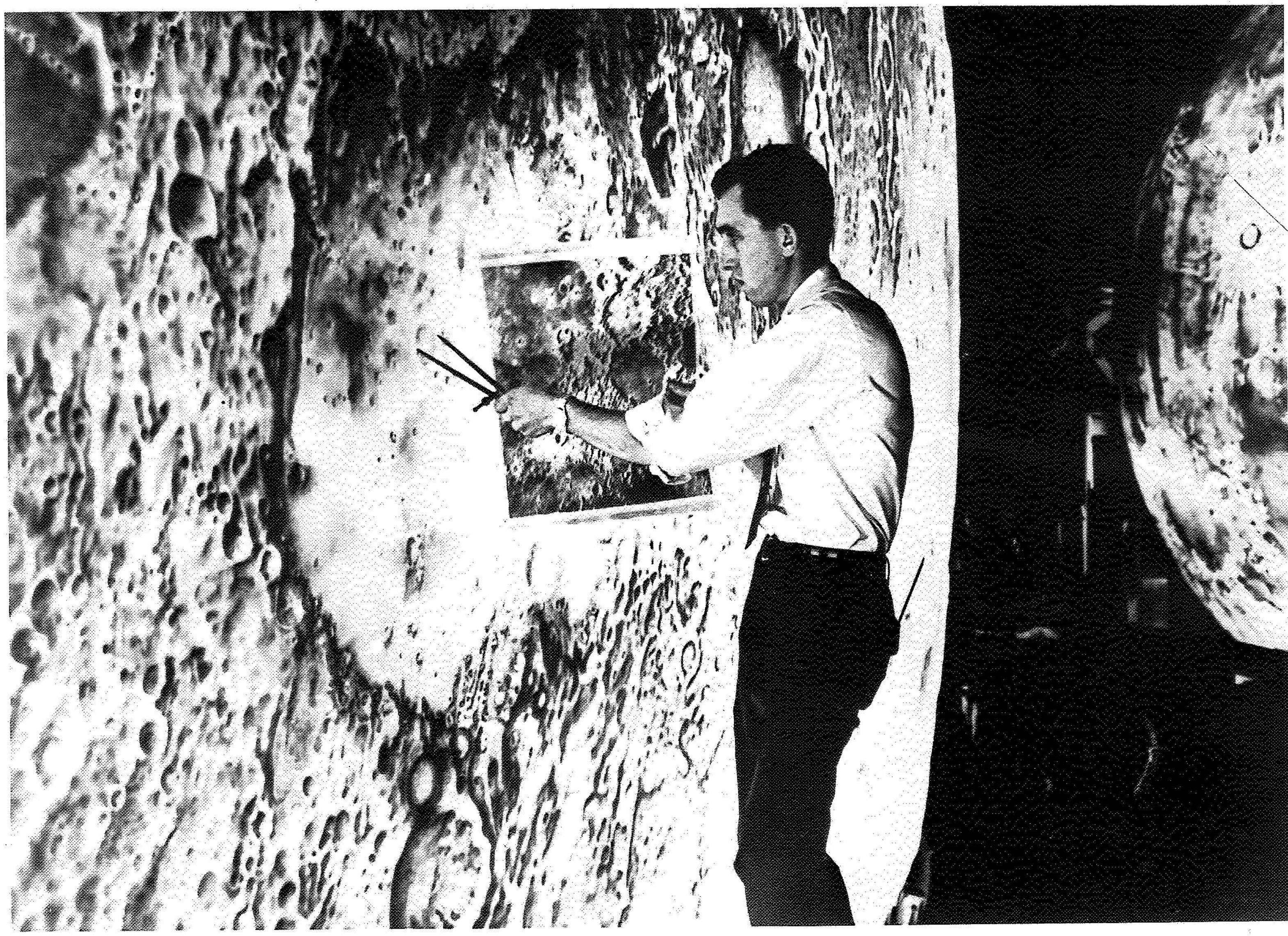

Figure 14.- LOLA model preparation.

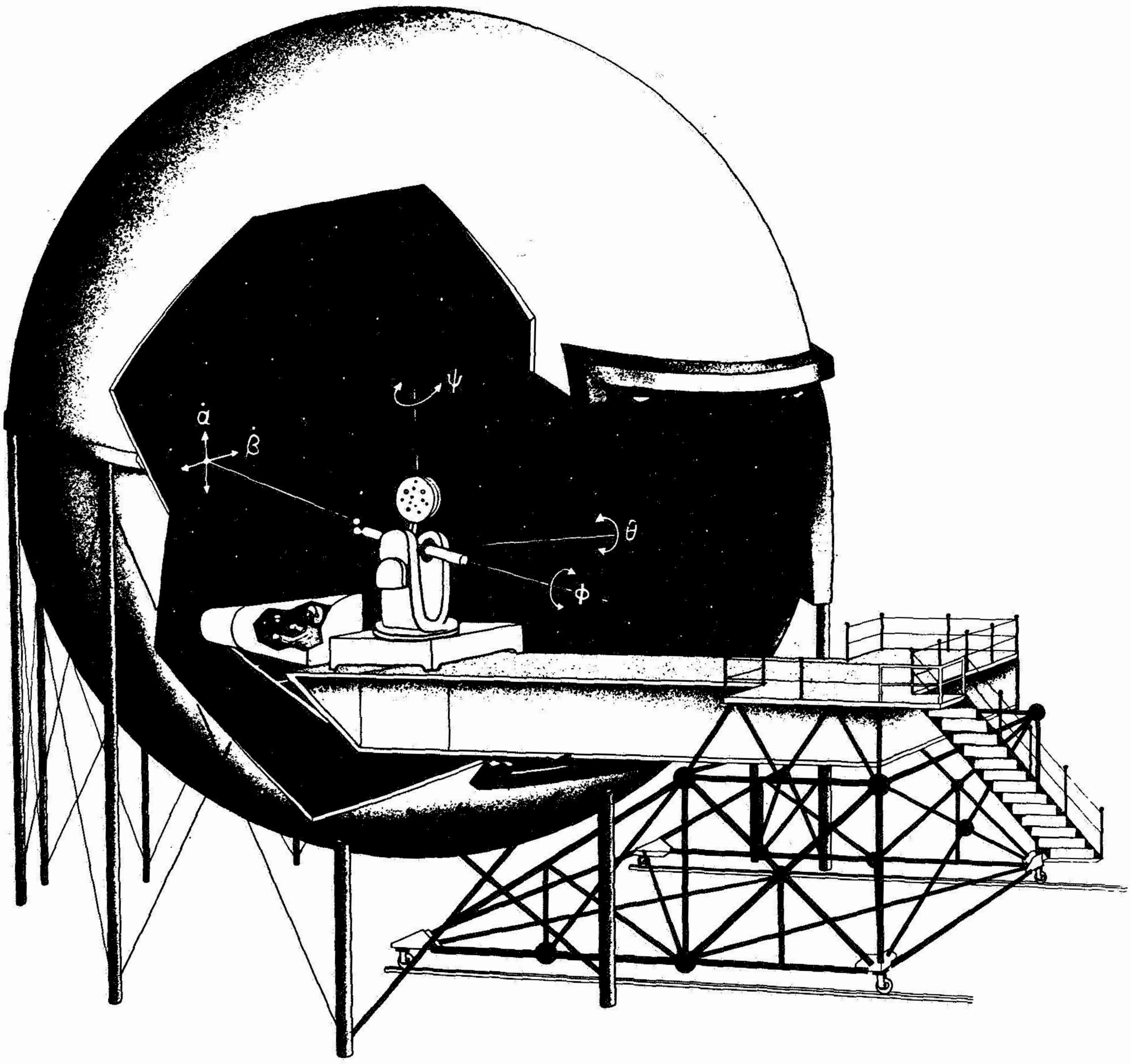

Figure 15.- Projection planetarium.

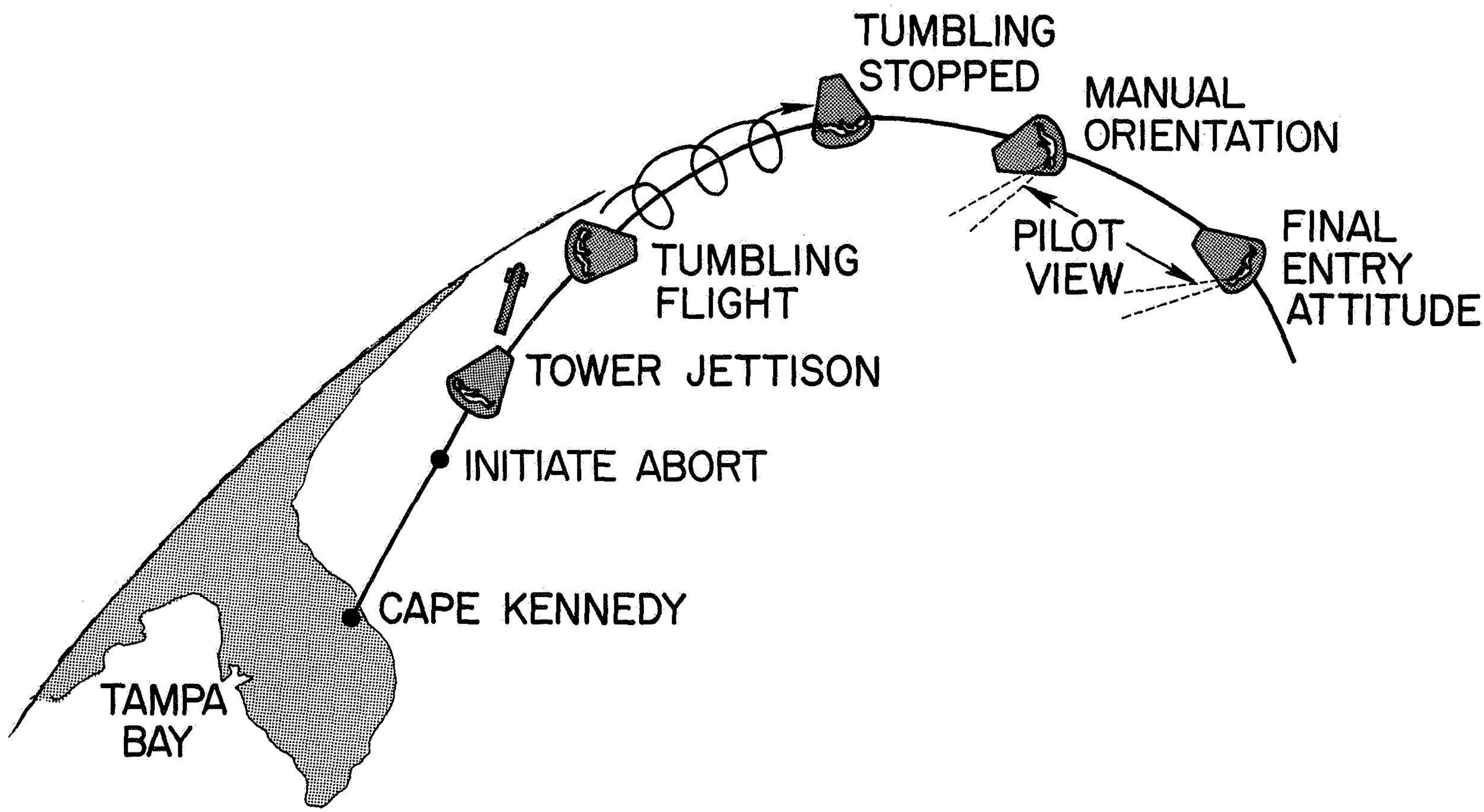

Figure 16.- Apollo launch-abort trajectory.

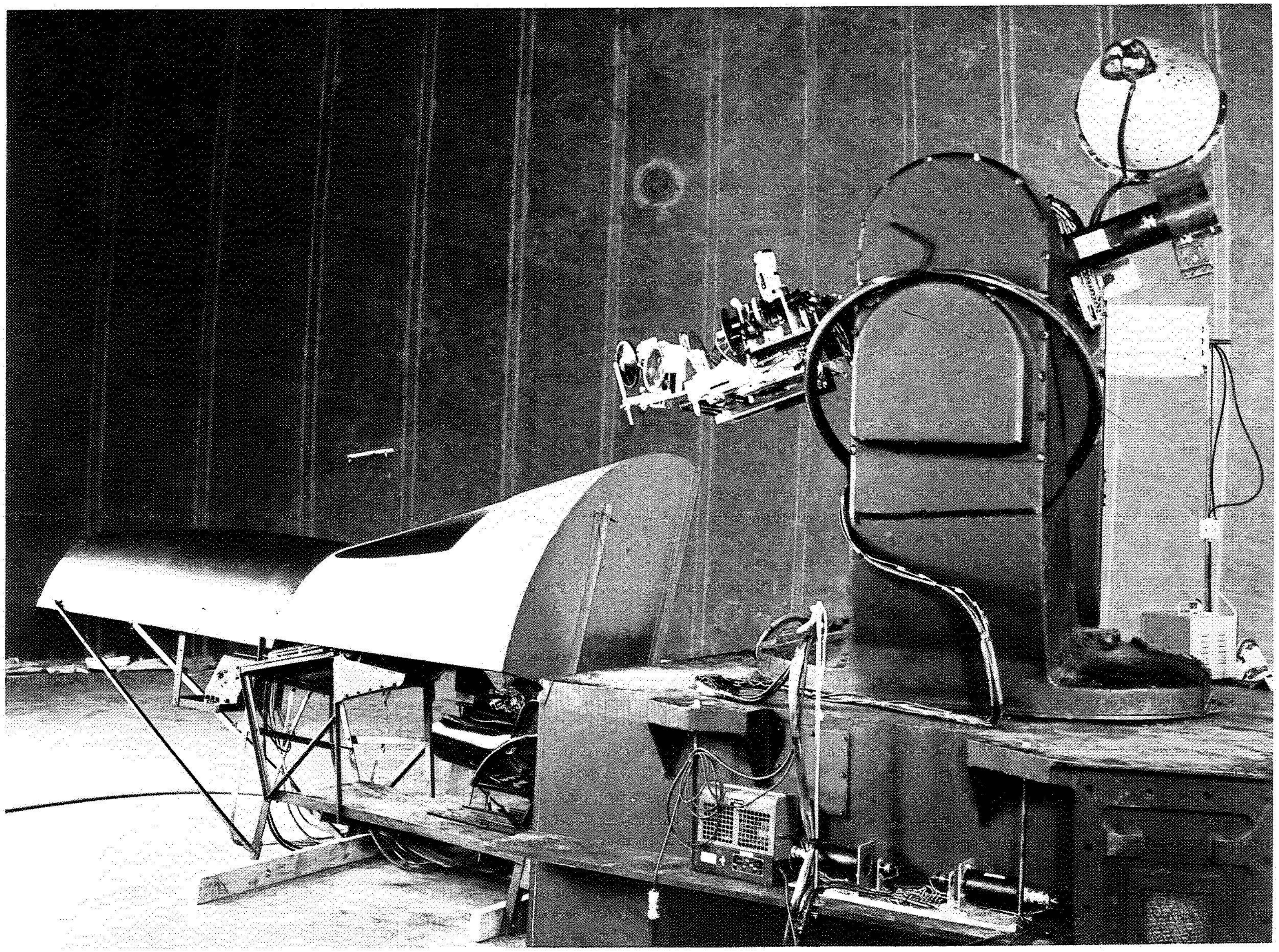

Figure 17.- Visual rendezvous projection equipment.

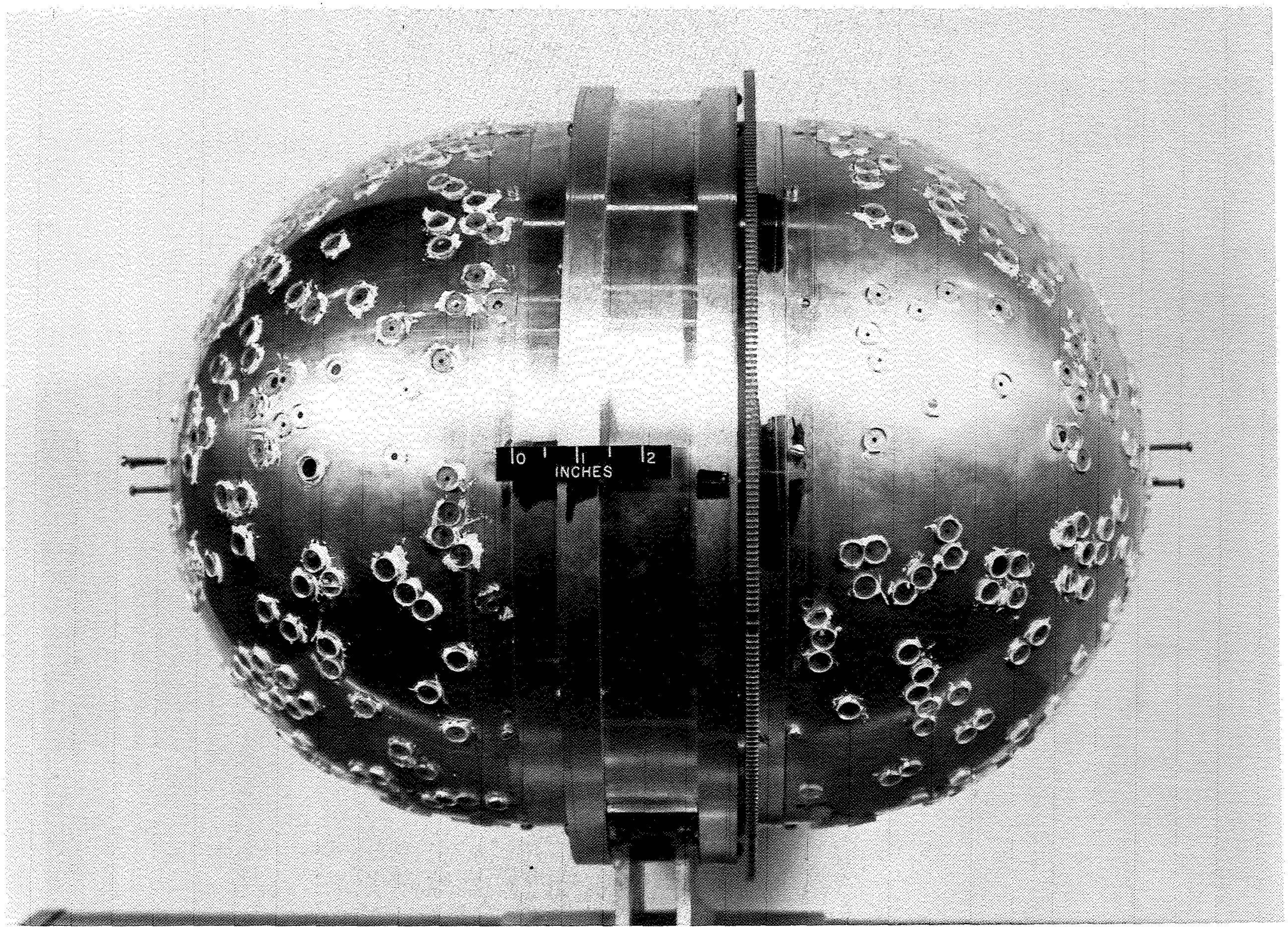

Figure 18.- Star-field projector.

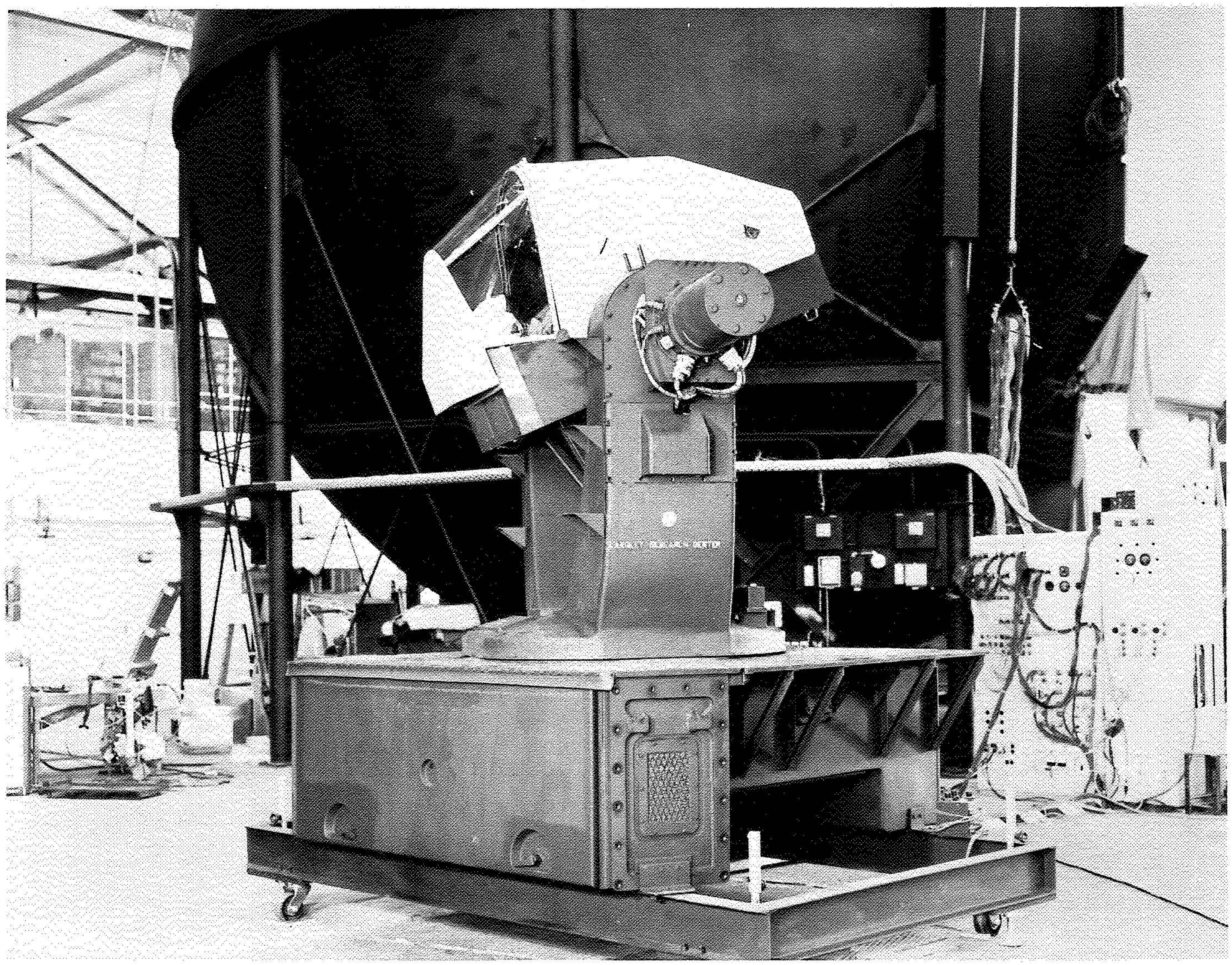

Figure 19.- Two-axis visual-motion simulator.

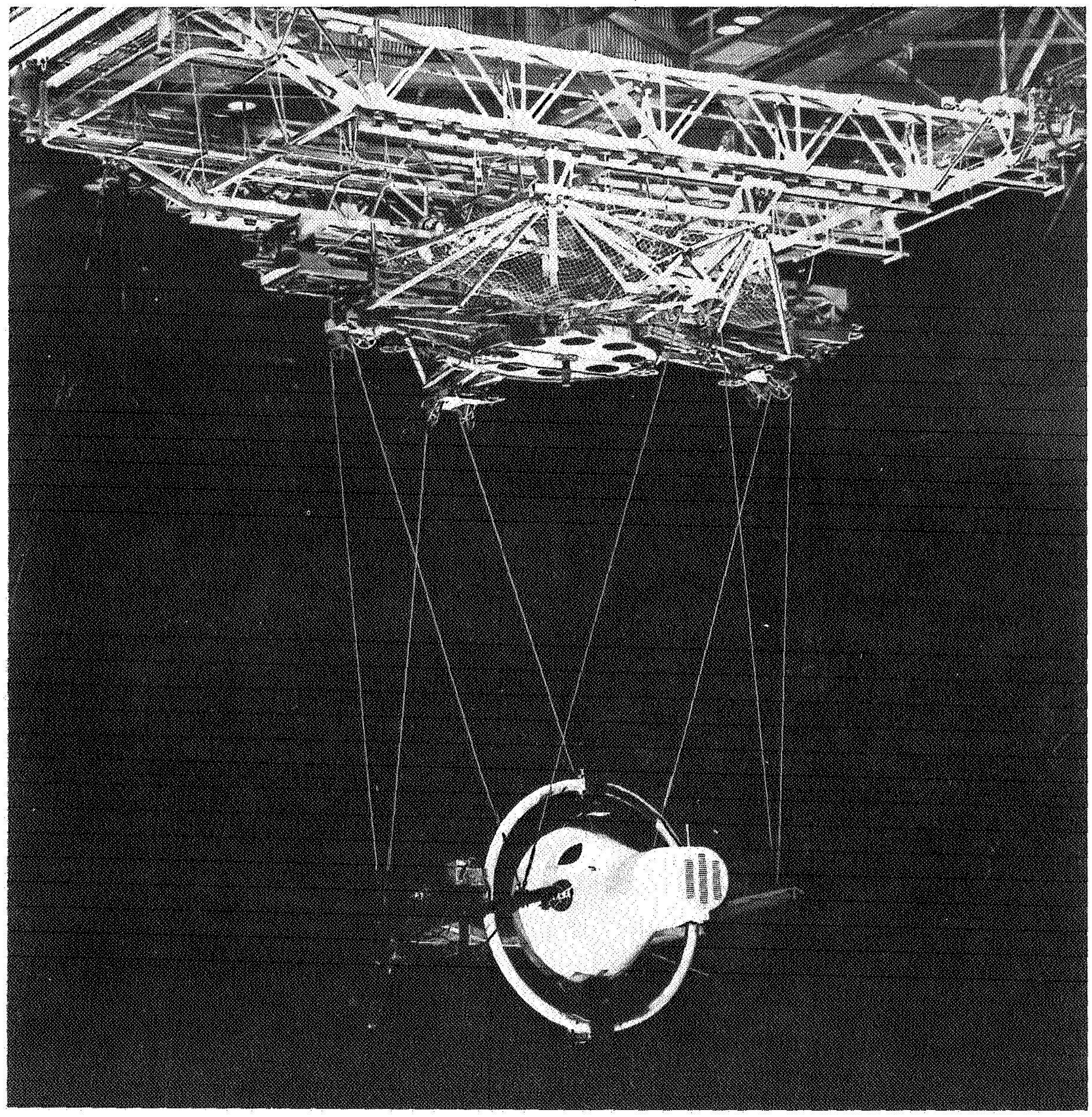

Figure 20.- Rendezvous docking simulator.

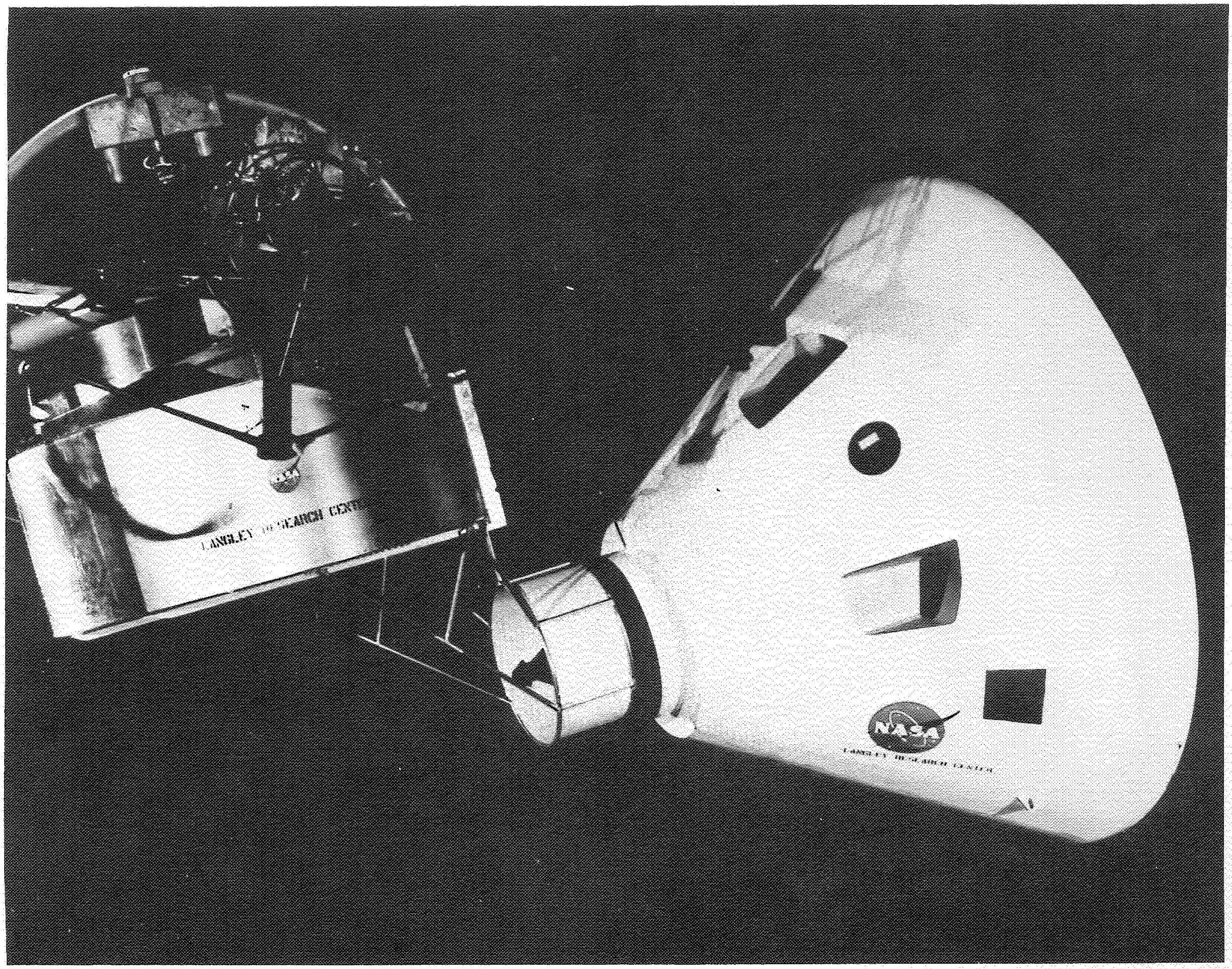

Figure 21.- LEM docking simulation.

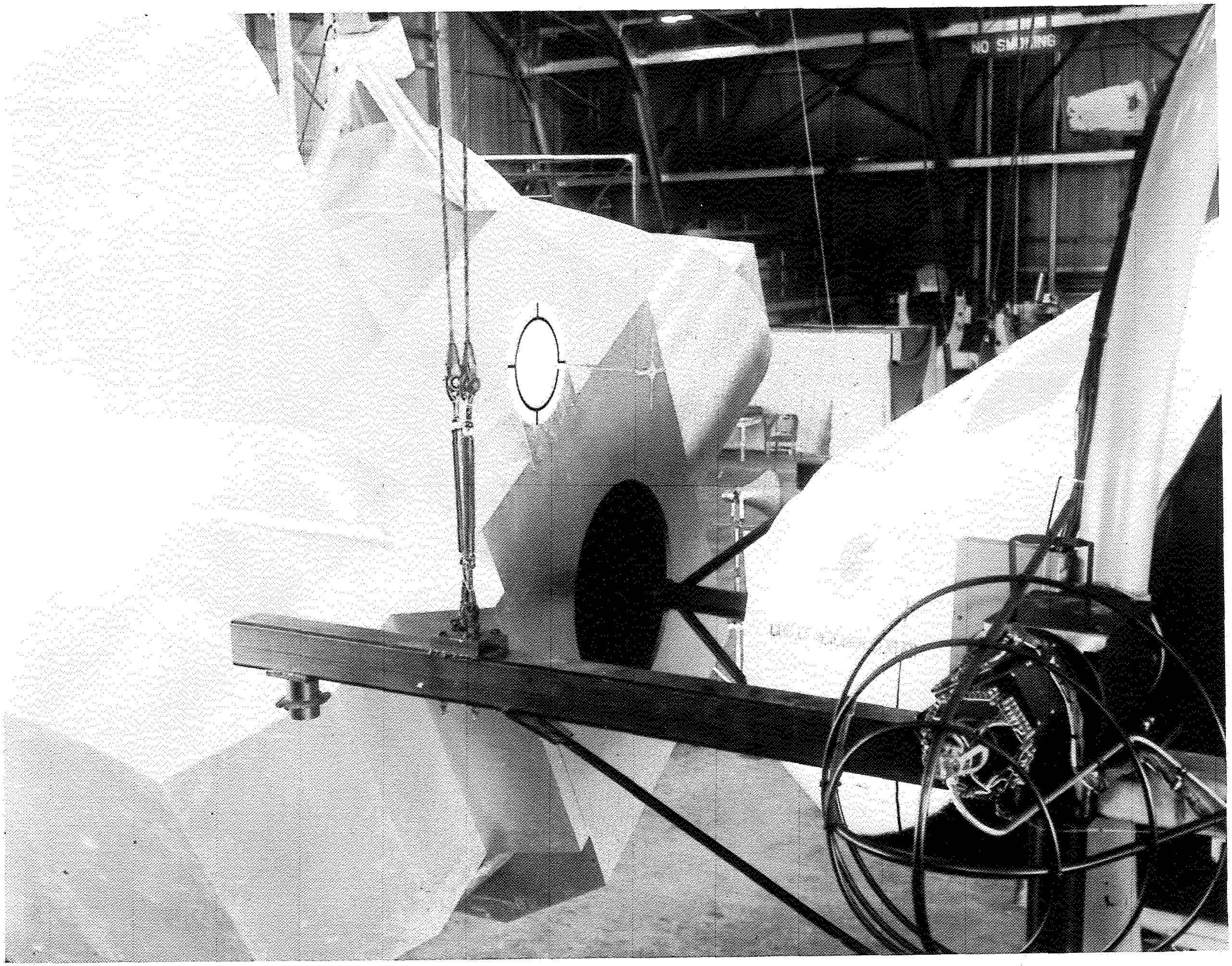

Figure 22.- Apollo docking simulation.

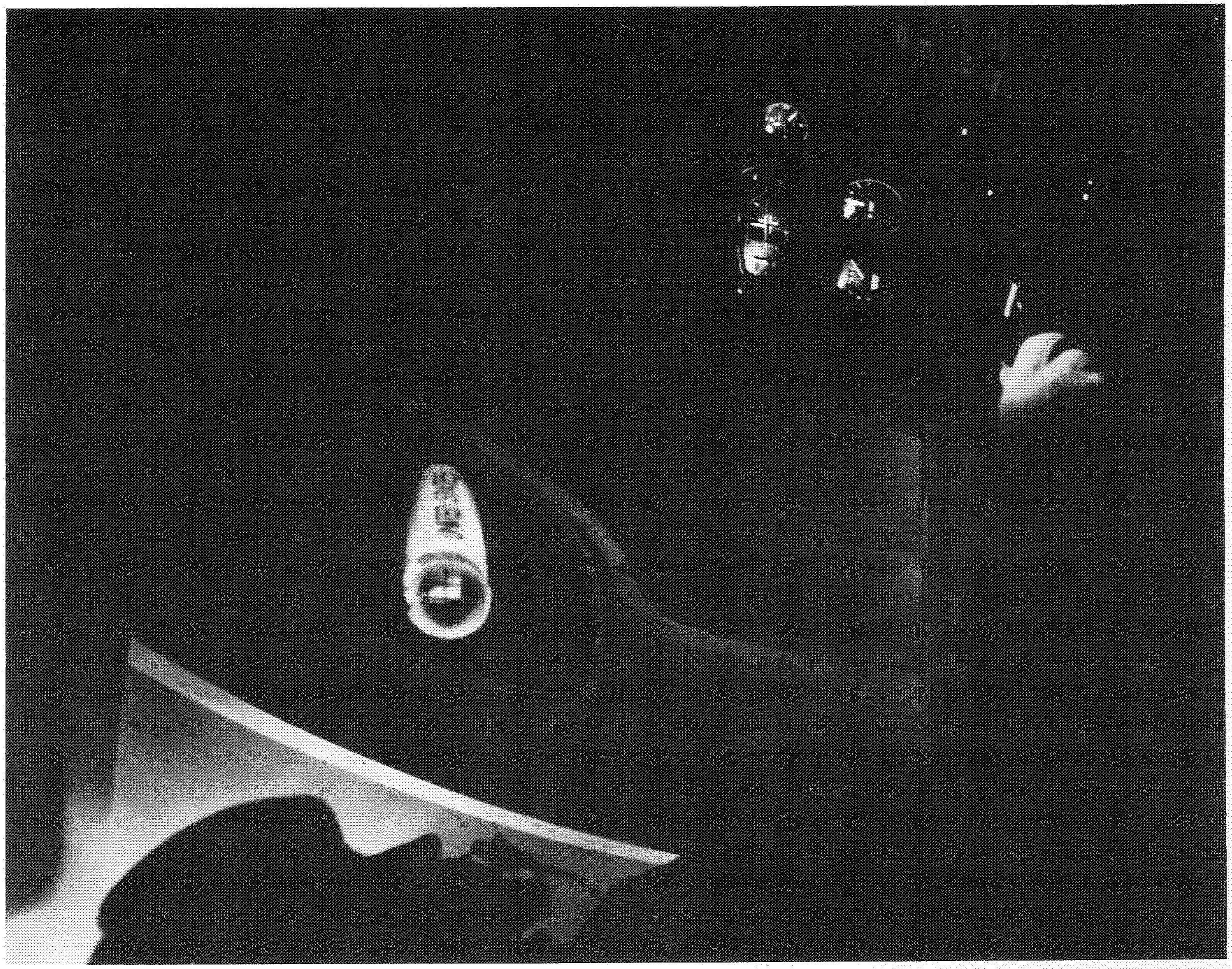

Figure 23.- Station-keeping simulation.

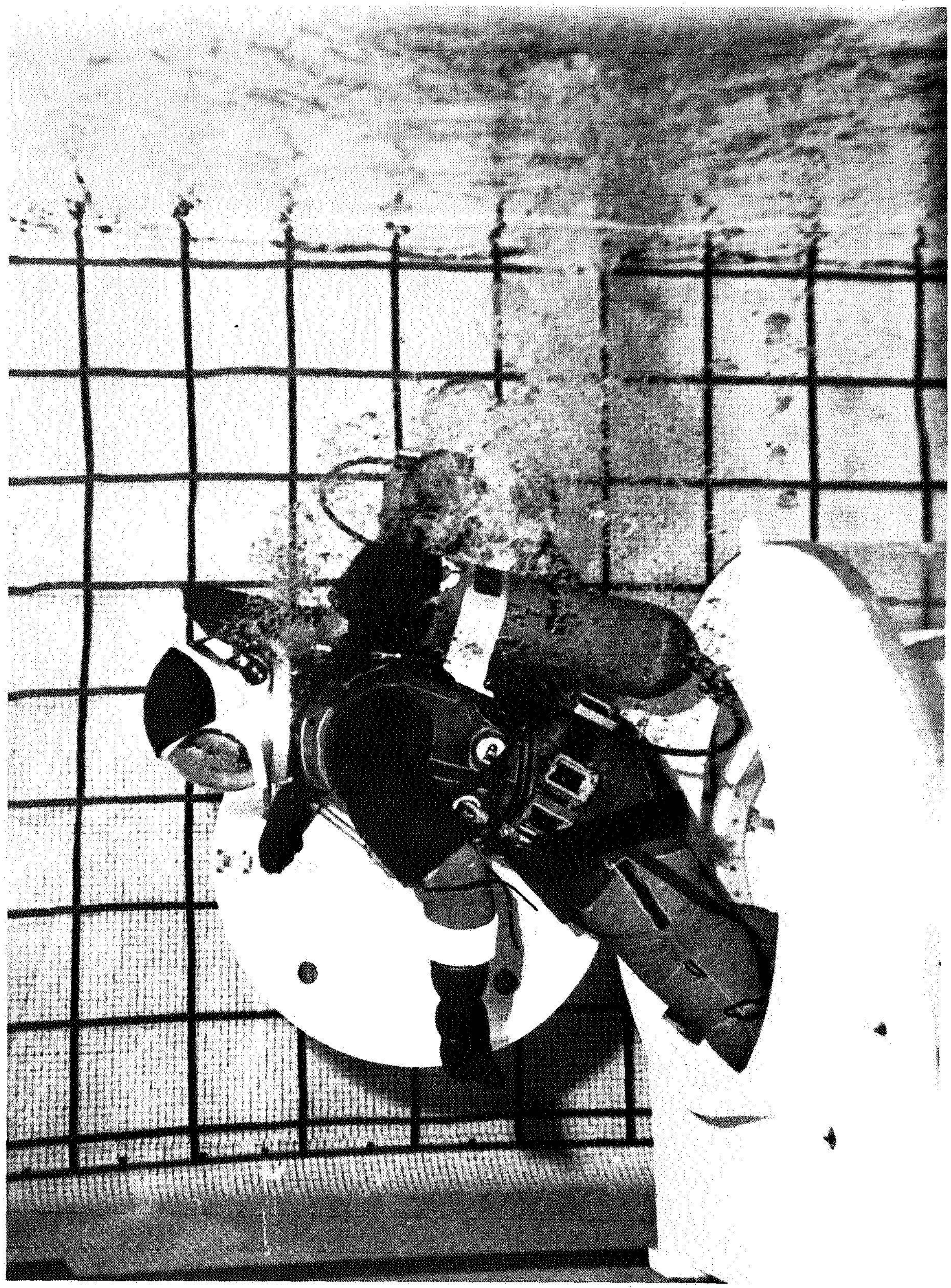

Figure 24.- Water-immersion zero-"g" simulation.

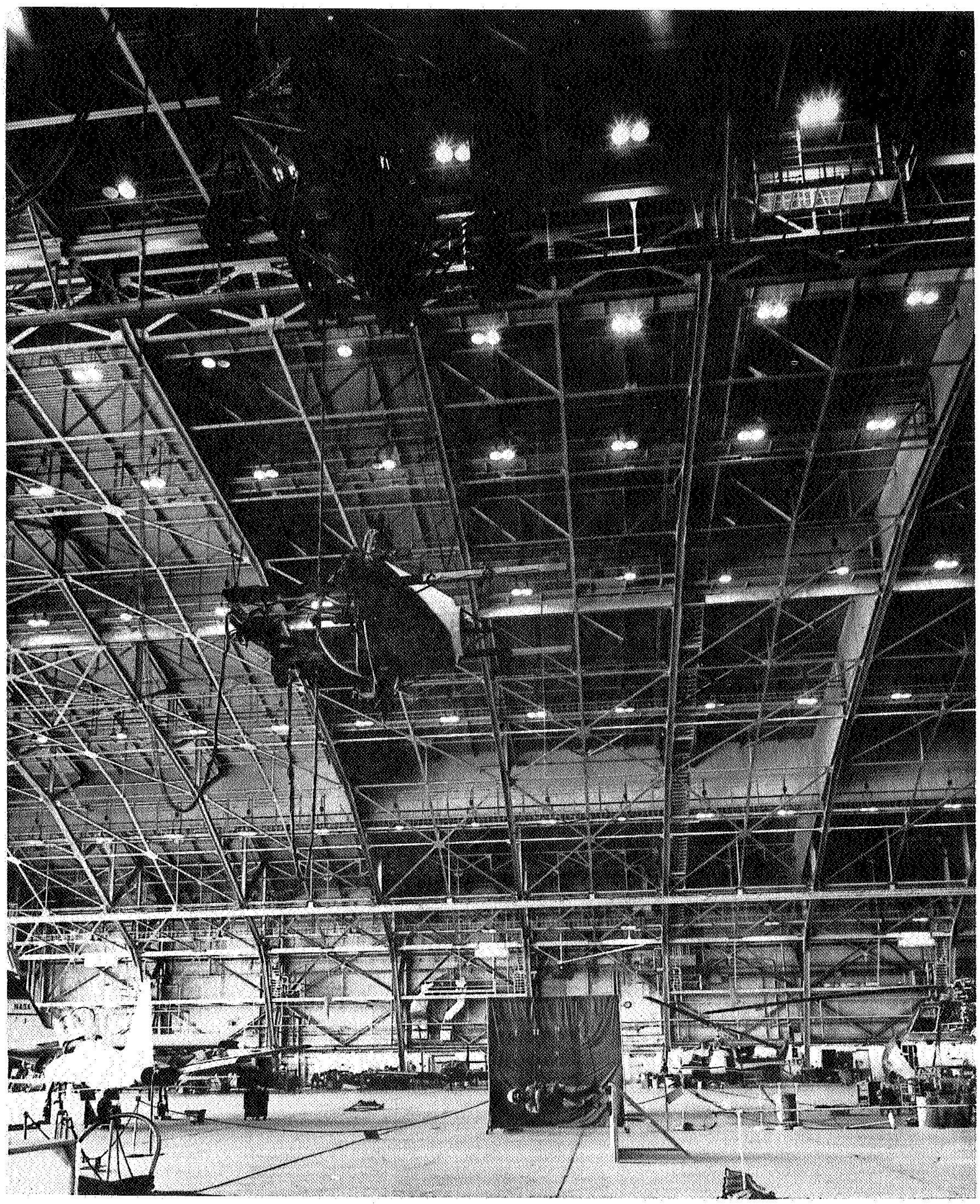

Figure 25.- "Jet-shoe" suspension on rendezvous docking simulator.

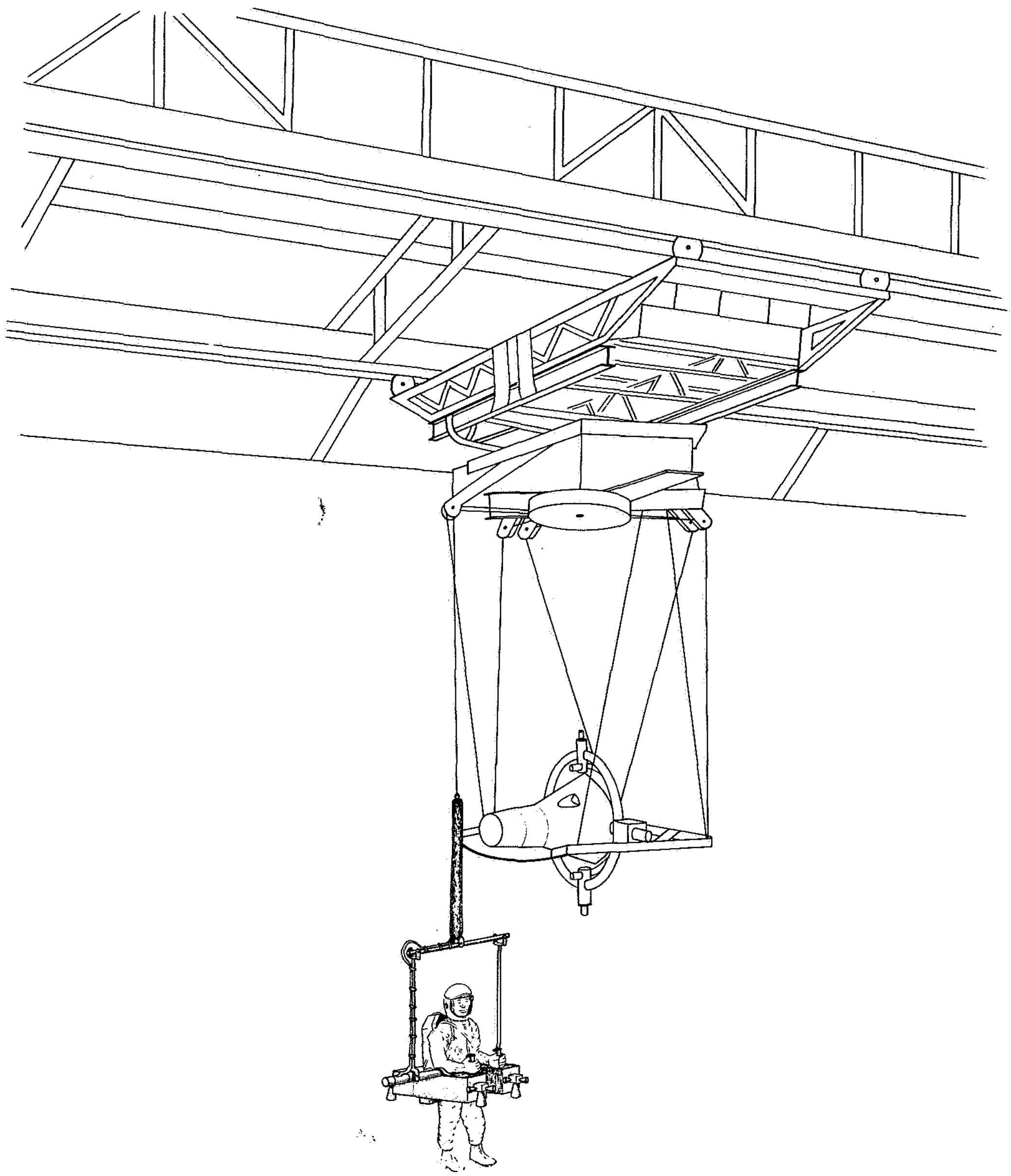

Figure 26.- One-man propulsion research apparatus.

NASA-Langley, 1966