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DEFINITION OF GROUND TEST FOR LARGE SPACE STRUCTURE (LSS) CONTROL VERIFICATION

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16. ABSTRACT

An overview for the definition of a ground test for the verification of Large Space Structure (LSS) control is given. The definition contains information on the description of the LSS ground verification experiment, the project management scheme, the design, development, fabrication and checkout of the subsystems, the systems engineering and integration, the hardware subsystems, the software, and a summary which includes future LSS ground test plans. Upon completion of these items, NASA/MSFC will have an LSS ground test facility which will provide sufficient data on dynamics and control verification of LSS so that LSS flight system operations can be reasonably ensured.

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I. INTRODUCTION

As the United States moves into the Shuttle era of space technology, there are numerous proposals from the scientific, civilian, and Defense Communities which envision the use of Large Space Structures (LSS). By definition, a LSS is very flexible, probably lightly damped, and exhibits multiple vibrational modes of very low frequency.

Many of the missions alluded to above require high performance from the LSS. This high performance takes the form of such things as extremely accurate pointing of lenses and the attainment of vibration free observation image planes.

To meet the rigorous control requirements of LSS, a new or extended body of control theory has been developed. To test these various schemes, Marshall Space Flight Center (MSFC) is establishing a LSS laboratory in which experimentation with large beams, LSS components, or even perhaps a given full-size LSS may be performed.

This paper delineates the program currently underway to develop the laboratory facility and concurrently to develop and install the first experiment in the laboratory.

II. LSS GROUND VERIFICATION EXPERIMENT

The Ground Test Verification (GTV) experiment is described by the drawing of Figure 1. The first test article will be the ASTROMAST beam as shown. The ASTROMAST is extremely lightweight (about 5 lb) and approximately 45 ft in length and is constructed almost entirely of S-GLASS. It is of the type to be flown in SAFE I.

The test article will be mounted on the faceplate of the Advanced Gimbal System (AGS) engineering model which, along with an additional torque actuator in azimuth, provides the control inputs for the system. The azimuth gimbal also provides a means of rotating the entire experiment manually to produce different test scenarios. The ASTROMAST will be gravity unloaded by a constant tension cable whose upper end is free to translate.

The AGS will sit atop the base of the test structure which will be supported by air bearings or oil film bearings and will include actuators to provide translational disturbance inputs to the test fixture. These disturbances could represent astronaut pushoff or RCS (Reaction Control System) thruster firing.

Six separately packaged inertial measurement assemblies comprise the control system sensors. Two of the packages, containing three axis translational accelerometers, are identical. One will be mounted on the mast tip, and the other on the base of the test fixture. Three other packages contain Apollo Telescope Mount (ATM) rate gyros and will be installed on the AGS faceplate. The sixth package, the Kearfott Attitude Reference System (KARS), will be placed at the mast tip along with the accelerometer package.

The signals from these instruments will be read by the COSMEC I data gathering and control system, and processed according to the control strategy under scrutiny. The control actuator signals will then be transmitted to the AGS as inputs to the dynamical system.

The COSMEC I will be interfaced to a Hewlett Packard HP9845C desktop computer which will store data as it is collected during a test run, and then provide post experiment data reduction and display offline. The controller inputs and outputs (measurements and commands) will be recorded at each sample period or at some multiple of sample periods.

III. PROJECT MANAGEMENT

The project management encompasses the technical and business management activities. These activities are required to plan, execute, control, and report technical performance of the LSS ground verification experiment. Two more important and time consuming efforts, relative to the LSS ground experiment management, are developing and coordinating the schedules among the various participating MSFC elements and utilizing the resources in a cost-effective manner. To this end, the project management has been partitioned into three categories. They are planning and control, configuration management, and procurement management.

The planning and control element provides for the planning, authorizing, and controlling of the LSS ground test effort. This activity also provides for timely visibility into the performance, cost, and schedule and is keyed to the appropriate MSFC organizations and to the Work Breakdown Structure (WBS) and the WBS dictionary. Integrated project schedules for the overall LSS are included as a function of this element. The control function integrates cost, schedule, and performance and relates progress and variance from the initial planning.

The configuration management category provides for the definition and implementation of configuration management activities for both hardware and software required in the performance of the LSS experiment. In addition, it includes as-designed and as-built configurations (for all levels), change control, change tracking, and configuration accounting.

The procurement management element includes responsibility for providing the project performance surveillance, cost control, and status reporting on all elements. It also includes arranging for the acquisition of the test article and various components of the experiment.

The integration of these elements into a smooth operation is the main objective of the project management. Once the proper integration is established in the various MSFC participating elements, constant follow-up with participating elements helps ferret out any particular problem areas. This procedure provides an excellent method for interaction and for problem solving in the project management.

IV. SYSTEMS ENGINEERING AND INTEGRATION

The scenario for the first experiment in the LSS/GTV experiment facility involves the ASTROMAST as the test article atop the AGS and employs the COSMEC I system as the digital controller. From a systems point of view, the entire apparatus; including the base, AGS, ASTROMAST, tripod, and measurement devices; is considered the plant, or process, and the COSMEC I and its associated hardware and software are the controller.

Because the experiment employs a variety of types of measurement devices, the COSMEC I system must deal with several different signal types as is expressed by the captions in Figure 1. To enhance the organization and speed of operation of the system, the measurement devices are monitored by hardware cards peripheral to the COSMEC I processor itself. Each device is sampled at a rate of 50 samples/second, thus ensuring adequate bandwidth of the digital controller. The digital controller is discussed in greater detail in the section dedicated to the COSMEC I subsystem.

Command outputs from the control algorithm implemented in the COSMEC I are converted to analog signals which drive the gimbal torquer amps. This conversion is handled by hardware cards analogous to those which monitor the measurement devices.

In addition to the candidate control algorithm, the COSMEC I carries out an inertial strapdown algorithm for the measurement devices which takes into account the effects of the acceleration due to gravity and the angular displacement due to earth rotation. This algorithm conditions the measurements so that they are true with respect to the laboratory reference frame.

A typical experiment would include disturbing the system via one of the actuators at the base and measuring the results with the system operating open loop, i.e., with the digital controller not included, then disturbing the system in a similar manner but with a candidate control algorithm in place. A comparison of the recorded results should give an indication of the success of the control algorithm. More importantly, a series of such tests could be used to determine the relative merit of different control schemes.

V. DESIGN, DEVELOPMENT, FABRICATION, AND CHECKOUT OF SUBSYSTEMS

The subsystems which comprise the LSS/GTV experiment fixture as described are currently in various stages of development at NASA MSFC. Thorough verification of each of the subsystems in controlled test environments comprises a significant part of the preliminary system testing. The subsystems will not only be tested individually, but will be tested in an integrated laboratory environment where each of the subsystems will interact with the others in a manner much as if an actual test article were being used. Such testing is designed to ensure proper operation of the complete test fixture upon assembly.

A. AGS Gimbal Drive

The Advanced Gimbal System (AGS) is a precision, two axis gimbal system designed for high accuracy pointing applications. The AGS gimbals serve the elevation plane and a third gimbal has been added to the system in the azimuth (Fig. 2). The AGS essentially rides on the azimuth gimbal so that the AGS and its performance remain unaltered by the presence of the third gimbal. The AGS receives torque commands from the COSMEC I data and control system in the form of analog inputs over the range of -10 to +10 V. This saturation represents the current limit of 27 A which is built into the AGS servo amplifier as a protective measure. Because the AGS servo amplifier outputs a current which causes an applied torque proportional to the current, the control algorithms used in the COSMEC I must be designed to produce torque command signals.

The AGS gimbal torquers, with the power supply and servo amplifiers used in the ground test verification experiment, can generate 37.5 ft-lb of torque over an angular range of approximately ±30 deg. The azimuth torquer is capable of generating 13.8 ft-lb over an angular range of about ±5 deg. It can, however, be set manually to allow the ±5 deg of rotation at any position about the 360 deg of azimuth freedom. This allows the test article to be rotated to any position desired without remounting.

The power supply for the gimbal system (pitch, yaw, and roll) is a 100 Adc supply with output voltage variable from 0 to 35 V. (The AGS requires 30 V.) The line to the power supply is 208 V, three phase, and in the worst case the input power to the supply should not exceed 2550 W.

B. COSMEC I Data and Control System

1. System Aspects

The COSMEC I is an AIM 65 based micro system which is used to handle data from the control system sensors, output commands to the control system actuators, transmit data for storage to the HP 9845C desktop computer, and implement the control and inertial strapdown algorithms. The COSMEC I is a powerful eight bit micro system which uses special hardware and software to allow the handling of a variety of devices (sensors, actuators, etc.) in real time. This, along with the use of high speed hardware arithmetic processors to reduce computation time, makes the COSMEC I an excellent machine for use as a digital controller.

2. Hardware

The AIM 65, which is the heart of the COSMEC I, employs the Motorola MC6502 microprocessor operated at a two megahertz clock rate (Fig. 3). The system includes 32 kbytes of random access memory (RAM), an alphanumeric keyboard, a single line display, a cassette tape machine for mass storage, and a small printer. The entire system is housed in a very portable package much resembling a suitcase.

The COSMEC I "reads" a variety of types of sensor output signals via interface cards which are an integral part of the COSMEC I system (Fig. 4). These cards allow the COSMEC I processor to interface in a similar manner (with regard to computation) with the ATM (Apollo Telescope Mount) rate gyros, the KARS (Kearfott Attitude Reference System), the accelerometer packages, and the AGS (Advanced

Gimbal System), each of which has a different type output or input signal. The COSMEC I also features a real time clock which will prove useful in the recording of experimental data.

In order to carry out the large number of calculations required for implementation of the inertial strapdown algorithm and the control algorithm, the COSMEC I employs four hardware arithmetic processors connected on the system bus. Each of these processors can execute a 32 bit floating point multiply in 42 microseconds and they are operated so that they process in parallel, thus minimizing computation time. The dynamic range of the processors is $\pm 9.2 \times 10^{18}$ so there is little possibility of exceeding the computational range of the machine. Also, this eliminates the need for scaling of measurements in order to avoid machine overflow. Using the arithmetic processor units and assembly language programming, the inertial strapdown algorithm can be executed in approximately 10 milliseconds and the first proposed control algorithm in about 6 milliseconds. This puts the total computation time at well under the allowed 20 milliseconds required to meet the 50 Hz sample rate.

3. Software

The software used in the COSMEC I system may be separated into four basic groups: (1) utility software for handling the various hardware cards which interface to instruments, (2) software to implement the control algorithm, (3) software to implement the inertial strapdown algorithm, and (4) initialization and startup software to ready the instruments and equipment for a test.

The hardware cards which interface the COSMEC I's processor to the measurement instruments and actuators are individual by their very nature, and some special software is required to handle each card. However, each card makes information available to the processor as digital words, which is the unifying feature of the system.

The digital controller software for the first ground test experiment will implement a linear discrete multivariable controller having multiple inputs and outputs. The controller will be in state variable form and will be programmed so that the system matrices are initial input data to the program and can be stored on tape and easily changed. The first controller software will be designed to implement a controller of up to ninth order having nine inputs and three outputs.

Because the inertial measurement instruments measure with respect to inertial reference space, there is a natural bias in the measurements due to the acceleration of gravity and earth's rotation. That is, in the earth based experiment the accelerometers measure about 1 g acceleration downward and the rate gyros measure about 15 deg/hr rotation while at rest with respect to the laboratory reference frame. The inertial strapdown algorithm provides a means of removing this bias from the measurement instruments.

In order to give the measurement instruments initial conditions and begin measurement for a test, initialization software is provided for the instrument strapdown algorithm. To begin a test, the structure will be stabilized with respect to the laboratory reference frame and the initialization routine will be executed. The strapdown algorithm will then be started and the apparatus will be ready to carry out a test.

C. Inertial Measurement Assemblies

Three different types of inertial measurement assemblies are planned for use on the Ground Test Verification structure in the first experiment. The Kearfott Attitude Reference System (KARS), the Apollo Telescope Mount (ATM) rate gyros, and two accelerometer packages developed by NASA. Each of the instrument packages generates signals in a particular form different from the other instruments as was mentioned in the section dealing with the COSMEC I interface cards. These different signal types are pursued as each instrument package is discussed in detail in the following paragraphs.

1. Kearfott Attitude Reference System

The Kearfott Attitude Reference System (KARS) is an attitude measurement system designed for use in the U.S. Army remotely piloted vehicle (Figs. 5 and 6). It provides measurement resolution of 13.9×10^{-3} deg/sec in the pitch and yaw axes (axes transverse to the ASTROMAST) and 25.0×10^{-3} deg/sec in the roll axis (axis along the length of the ASTROMAST). The dynamic range of the rate gyro outputs of the KARS is 40 deg/sec in pitch and yaw and 70 deg/sec in roll. Because of its light weight (8.9 lb), the KARS will be used as the mast tip rotation sensor in the first ground test experiment. Although the KARS includes accelerometers and outputs measurements of linear acceleration, the measurements are not used in the ground test experiment because of inappropriate scaling of the instruments.

The output signals of the KARS are in the form of asynchronous digital pulses. One signal, the change in angular position in yaw for instance, requires two channels; one for pulses representing positive rotation and the other for pulses representing negative rotation. The COSMEC I system accumulates the pulses over a 20 millisecond period to produce measurements of the angular rate and position of the ASTROMAST tip.

The KARS outputs three digital health check signals. One signal represents a check of the motor voltage and the pickoff excitation voltage and the other two are over and under temperature signals. In the ground test experiment, these signals will be monitored at the system console.

2. ATM Rate Gyros

The Apollo Telescope Mount (ATM) rate gyro packages are designed to measure small angular rates very precisely. Each package measures angular rate in one axis (Fig. 7) with resolution finer than 0.5×10^{-3} deg/sec and offers a dynamic range of ±1.0 deg/sec. The ATM rate gyro packages will be mounted on the faceplate of the engineering AGS so that they will measure the rotation of the base of the test article. Because they will be rigidly mounted to the gimbal system, these sensor packages will most nearly measure the actuator inputs to the system.

The output signals of the ATM rate gyro packages are ±45 V analogs and are handled by the analog to digital converter card of the COSMEC I system where they are converted to 12 bit binary words.

The ATM rate gyro packages require a warmup period of about 20 min and then stabilize about 20 min after the warmup period ends, thus requiring on the order of 40 min to become ready for a test. Each package requires 1.5 A during warmup and then 1.25 A after stabilization/ both at 28 Vdc.

3. Accelerometers

Two identical accelerometer packages (Fig. 8) will be used on the ground test experiment fixture in the first test. One package will be placed on the mast tip along with the KARS and the other on the test fixture base as shown in Figure 1. The necessary electronics for each accelerometer package is included on board the instrument package itself as shown in Figure 9.

The accelerometers provide resolution finer than 0.0001 g and a dynamic range of ±3 g with a bandwidth of 25 to 30 Hz. They require about 20 min for warmup, during which time each package requires 1.2 A at 28 Vdc. After warmup the power requirement reduces to about 0.9 A per package.

The signals from the accelerometers are different from either those of the KARS or the ATM rate gyros. As in the case of the KARS, two channels are required for each of the degrees of freedom of the accelerometer package, i.e., six channels per accelerometer package. One channel of each pair carries a 2.4 kHz square wave synchronization signal and the other channel carries the acceleration information. Zero acceleration is represented by a signal identical to that of the synchronization channel, positive acceleration by an increase in frequency, and negative acceleration by a decrease in frequency as compared to the synchronization channel. As in the cases of the other instruments, these signals are monitored by a hardware card in the COSMEC I system.

D. Beam Containment Structure

The beam containment structure includes the tip support mechanism, the base, the disturbance actuators and signal sources, and power supply for the entire test fixture. This is essentially that equipment required of a laboratory to carry out dynamic testing of structures such as the ground test experiment. As depicted in Figure 1 the beam containment area can accommodate structures approaching 120 ft in height. Access is provided at various levels along the structure via catwalks. Also the control room for experimental operations is at a position about 50 ft above the base of the structure, thus making the experiment quite accessible with regard to viewing the experimental operations and so forth.

1. Tip Support Mechanism

The tip support mechanism is a tripod mounted on air bearings as shown in Figure 1 with a constant tension cable extending downward to connect to the tip instrument package. The cable connection point is incorporated into the tip instrument package mount assembly. The tip support mechanism is designed to support the weight of the tip instrument package and possibly some of the weight of the ASTROMAST beam without affecting the structural properties of the system by adding stiffness to the beam tip motion. The tripod is allowed about 18 in. of total translational freedom in each of its two translational axes. This will prove to be quite adequate for the GTV experiment because the tip deflections are expected to be less than 6 in. and the distance between the mast tip and the tripod support floor is about 60 ft as compared to the olatively short tripod of 3 ft.

2. Base

The base for the GTV experiment will be supported by air bearings in a similar manner to the tip support tripod. It is designed to be restrained as little as possible in the two translational degrees of freedom but not allow any rotational freedom. Translation of the base provides the means of applying disturbances to the system. The disturbance actuators will be hydraulic and/or electromechanical in nature depending upon the frequency band of the applied disturbance signal. The disturbance system is designed to allow independent input signals to the two translational axes whether they be broadband random, sinusoidal, or a combination of both.

E. Facility Computer Interface and Utility Software

During testing, the COSMEC I data and control system will send data for storage to the HP 9845C desktop computer via a 16 bit parallel interface. Once a test run is completed, the HP 9845C will be available for display of data and possibly some data reduction. Also available is a Hewlett Packard 1000 series minicomputer to which the data stored on the HP 9845C can be transferred. The HP 1000 series mini system includes the necessary software for several sophisticated data reduction techniques. Using the combined power of the two machines, much will be possible in the way of data reduction and display for post analysis efforts.

V. SYSTEM MODEL AND EXPECTED PERFORMANCE

For purposes of system studies and controller design, an analytical model of the Ground Test Experiment is necessary. This section describes the development of such a model and the following section compares it to the results of modal tests of the ASTROMAST beam carried out at NASA MSFC.

A. Introduction

Modeling of the Ground Test Verification (GTV) experiment was carried out in two distinct stages. The first stage involved modeling the ASTROMAST itself as it would be tested in the first open loop modal test, i.e., the beam alone in a cantilevered position. This produced modal frequencies, mode shapes, and mass integrals which were used in the second stage of the modeling process to develop, through modal synthesis, a model of the entire GTV experiment including the AGS and the beam containment structure.

B. ASTROMAST Beam Model

The ASTROMAST is a symmetric beam 512 in. in length and triangular of cross section. Three longerons form the corners of the beam and extend along its full length unbroken. The cross members which give the beam its shape divide the beam into 91 sections having equal length and mass and similar elastic properties. This sectioning was used advantageously in the modeling process.

As a first step, a single section of the beam (Fig. 10) was modeled from its geometry and the elastic properties of S-GLASS. This provided the necessary information for a 91 element lumped mass model which was used to determine the modal frequencies, mode shapes, and mass integrals of the beam in a cantilevered position. Because of the symmetry of the beam, bending in the two transverse planes must be uncoupled and identical, i.e., bending modes in one transverse plane must be exactly repeated in the orthogonal transverse plane, and torsion must also be uncoupled from these bending modes. This allowed a simplified analysis of the ASTROMAST beam via a model comprised of 91 infinitesimally thin discs of mass connected by massless beam segments. A two dimensional model was used to find the modal frequencies, mode shapes, and mass integrals of the ASTROMAST beam in bending. In this model each of the 91 lumps was allowed to translate in a direction transverse to the beam and to rotate about its own center of mass (Fig. 11). Also, shear and bending deformation were taken into account. Because the beam is very stiff longitudinally, deformation in this direction was considered negligible and, therefore, not modeled. The modal data resulting from the analysis of this model are shown in Table 1 along with the results of the torsional analysis.

Again, because of the symmetry of the beam, the torsional analysis could be carried out separately from the bending analysis. The beam in torsion is a one dimensional problem because the lumped masses are allowed only to rotate about the longitudinal axis. If the beam is assumed to be uniform, a closed form solution to the torsional bending problem can be found. This was done as a check of the numerical method; and indeed, the results of the two techniques compare favorably as shown in Table 2.

C. Complete System Model

Using the model of the ASTROMAST beam alone and a rigid body model of the AGS (Advanced Gimbal System), a complete system model was produced using modal synthesis. The following are the major assumptions included in this model:

1) The tip support structure has negligible effects upon the structural behavior.

2) The AGS is rigid,

3) There is no stiffness associated with the translational motion of the base.

The first assumption is easily justified by the fact that the tether "string" which supports the tip will be approximately 60 ft long and very light as compared to the tip mass of about 32 lb. Also, the tip deflections are expected to be at most a few inches in magnitude. The second assumption is justified when the stiffness of the AGS is compared to the relative flexibility of the ASTROMAST beam. As for the third assumption, the base of the experiment would be unrestrained if it were not driven by the disturbance actuators. Of course the actuators will not only provide a disturbance input as desired but may also passively restrain the base in some way. This will be incorporated into the model as more data become available concerning the disturbance actuators. The mathematical model of the GTV experiment structure incorporates five rigid body degrees of freedom. Two of these result from the translations of the base; the other three from the rotations of the gimbal system. In addition, the ASTROMAST is represented by its first seven flexible body modes to produce the system model summarized in Tables 3 and 4.

VII. MODAL TEST OF ASTROMAST BEAM

Modal tests have been conducted on the ASTROMAST beam at MSFC. So that gravity would have as little effect as possible on the test results, the ASTROMAST was cantilevered in a hanging position for the modal test. In order to do this, a mounting bracket was fashioned as shown in Figure 12 so that the ASTROMAST could be mounted and then deployed downward under the influence of gravity (Figs. 13 through 16).

When fully deployed, the ASTROMAST exhibits a longitudinal twist of about 280 deg as shown in the photograph of Figure 17. This twist contributes to coupling between the torsional and bending modes; and, although it was not included in the model described in Section VI, the model seems to describe the beam quite well as is discussed later in this section.

Testing using three different levels of input was found to produce the same experimental results with regard to the modal model. This shows that the ASTROMAST behaves in a linear manner over a typical range of input excitations, thus making it an excellent choice of test articles for the LSS/GTV experiment.

Typical modal damping for the ASTROMAST beam was found to be about 0.2 to 0.3 percent. This is in the range predicted for the ACOSS model No. 2 typical LSS which was constructed (on paper) of graphite epoxy. The ASTROMAST is similar in that the S-GLASS members from which it is constructed are also a composite of fiber and resin and would be expected to have similar damping characteristics.

The lower modal frequencies of the cantilevered ASTROMAST beam as measured in the laboratory and as computed from the model described in Section VI are summarized in Table 5. The preliminary nature of the test data accounts for the modes predicted by the model which have not yet been identified and measured in the lab. However, it is clear that the model is in reasonable compliance with the actual structure. The modes determined experimentally thus far agree very well with the model as is revealed by the average percent error of about 10 percent. Error in the model may be due to the unknown characteristics of the S-Glass as a composite. Since the actual percentage of S-GLASS present in the beam members was unknown, they were assumed to be made entirely of S-GLASS. This error in the modulus of elasticity could account for some of the modeling error present.

VIII. SYSTEM ASSEMBLY, VERIFICATION, AND USE

The LSS/GTV experiment fixture will be assembled in the high bay area of building number 4619 at MSFC. As mentioned earlier, each of the subsystems is being thoroughly tested independently in order to minimize the difficulties to be encountered upon assembly of the complete system.

After assembly of the entire test apparatus, proper communication between the subsystems will be verified and proper operation of the subsystems in the test scenario will be established. The health status of each of the instrument packages will be of major concern at this time. Once each of the subsystems has proven to be operating properly in the test environment, the system will be ready to be tested in the operational configuration, i.e., to carry out a test of the first candidate control algorithm.

Once the experiment fixture is shown to operate properly and consistently, it will be available for testing on a regular basis and will be operated by Test Lab personnel.

IX. SUMMARY AND FUTURE LSS/GTV DEVELOPMENT

MSFC is developing a LSS ground test facility to help verify LSS passive and active control theories. The facility is not parochial to the control area alone but has a wide purview of activities in which experimentation can be accomplished. These areas include but should not be limited to the following;

1) Subsystem and component testing.

2) Remote sensing and control.

3) Parameter estimation and model verification.

4) Evolutionary modeling and control.

All of these areas are currently in the planning stages of the facility development and should be an integral part of the facility within the immediate future.

TABLE 1. MODAL FREQUENCIES OF CANTILEVERED ASTROMAST BEAM MODEL IN BENDING AND TORSION

Mode	Frequency (Hz)
First Bending Mode	0.618
Second Bending Mode	3.917
Third Bending Mode	11.179
First Torsional Mode	6.877
Second Torsional Mode	20.628
Third Torsional Mode	34.373

TABLE 2. TORSIONAL MODE FREQUENCIES RESULTING FROM ANALYTICAL UNIFORM BEAM CLOSED FORM SOLUTION AND 91 ELEMENT LUMPED MASS NUMERICAL SOLUTION

Mode	Closed Form Frequency (Hz)	Torsional Beam Frequency (Hz)
First Torsional Mode	6.92	6.88
Second Torsional Mode	20.74	20.63
Third Torsional Mode	34.58	34.37

TABLE 3. LSS/GTV EXPERIMENT STRUCTURE MATHEMATICAL MODEL RIGID BODY MODES

	Mode Number 1			Mode Number 2			Mode Number 3		
	X	Y	Z	X	Y	Z	X	Y	Z
Base Translation	0.7208357	0.0000000	0.0000000	0.0000000	0.7208357	0.0000000	0.0101980	-0.0012932	0.0000000
Roll Gimbal Rotation	0.0000000			0.0000000			0.1187835		
Azimuth Gimbal Rotation	0.0000000			0.0000000			0.0000000		
Elevation Gimbal Rotation	0.0000000			0.0000000			0.0000000		
Beam Base Translation	0.7208357	0.0000000	0.0000000	0.0000000	0.7208357	0.0000000	0.0101980	-0.0012932	0.0000000
Beam Base Rotation	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.1187835
Tip Instrument Package Translation	0.7208357	0.0000000	0.0000000	0.0000000	0.7208357	0.0000000	-0.2214391	0.0280927	0.0000000
Tip Instrument Pacakge Notation	0.0000000	0.0000000	0.0000090	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.1187835

	Mode Number 4			Mode Number 5		
	X	Y	Z	X	Y	Z
Base Trasnlation	-0.2426753	0.0000825	0.0000000	-0.0000439	0.2133059	0.0000000
Roll Gimbal Rotation	0.0075818			0.0009661		
Azimuth Gimbal Rotation	0.0063638			0.0000033		
Elevation Gimbal Rotation	0.0000000			0.0064128		
Beam Base Translation	-0.0791644	-0.0000825	0.0000000	0.0000413	0.1025569	0.0000000
Beam Base Rotation	0.0000000	0.0063038	0.0075818	0.0064128	0.0000033	0.0009661
Tip Instrument Package Translation	3.2468774	0.0017931	-0.0015743	-0.0001019	-3.2637730	0.0125100
Tip Instrument Package Rotation	0.0000000	0.0063638	0.0075818	0.0064128	C.0000033	0.009661

TABLE 4. LSS/GTV EXPERIMENT STRUCTURE MATHEMATICAL MODEL FLEXIBLE BODY MODES

Frequency (Hz)	0.95			1.10			1.80		
	X	Y	Z	X	Y	Z	X	Y	Z
Base Translation	0.6340323	0.0000061	0.0000000	0.0003125	0.4801170	0.0000000	0.0302741	0.0000061	0.0000000
Roll Gimbal Rotation	0.0017399			0.0001548			0.0184101		
Azimuth Gimbal Rotation	-0.0497098			0.0000250			0.0024533		
Elevation Gimbal Rotation	0.0000120			0.0603346			0.0000814		
Beam Base Translation	-0.6432107	-0.0001104	0.0000000	0.0003297	-0.5500624	0.0000000	0.0327604	0.0004000	0.0000000
Beam Base Rotation	0.0030120	-0.0497098	0.0017399	0.0002246	0.0000250	-0.0001548	0.0000814	0.0024533	0.0184101
Tip Instrument Package Translation	0.5985857	-0.0000565	-0.0085947	-0.0003538	0.5674084	0.0884027	0.0370206	0.0081332	0.0000380
Tip Instrument Package Rotation	-0.0000228	0.0345617	-0.0103021	-0.0453606	-0.0000090	0.0000523	0.0000700	0.0043433	0.7151111

Frequency	3.25			3.71			0.21		
	X	Y	Z	X	Y	Z	X	Y	Z
Base Translation	-0.4059115	-0.0021554	0.0000000	0.0019001	-0.4084157	0.0000000	0.1169710	0.0530800	0.0000000
Roll Gimbal Rotation	-0.0001958			0.0001902			0.0000152		
Azimuth Gimbal Rotation	0.0339763			-0.0001598			0.0105723		
Elevation Gimbal Rotation	-0.0002347			-0.0616555			-0.0074173		
Beam Base Translation	0.4070748	0.0027616	0.0000000	-0.0022049	0.5963746	0.0000000	0.1546738	0.0750166	0.0000000
Beam Base Rotation	-0.0002847	0.0339763	-0.0001958	-0.0016555	-0.0001598	0.0001902	0.0074173	0.0105723	0.0000152
Tip Instrument Package Trasnlation	0.3724887	0.0012984	-0.0236142	-0.0018192	0.3201788	-0.1791701	0.1921388	0.0510700	0.1028174
Tip Instrument Package Rotation	-0.0003839	0.0924256	0.0305842	-0.0919095	-0.0005578	-0.0008476	0.0371458	0.1227077	-0.0027129

	0.23		
	X	Y	Z
Base Translation	0.0377894	-0.1626017	0.0000000
Roll Gimbal Rotation	0.0000524		
Azimuth Gimbal Rotation	-0.0034170		
Elevation Gimbal Rotation	0.0377894	-0.1626017	0.0000000
Beam Base Translation	-0.0500081	0.2299638	0.0000000
Beam Base Rotation	-0.0227311	-0.0034170	0.0000524
Tip Instrument Package Translation	0.0637058	-0.1613539	0.2150347
Tip Instrument Package Rotation	0.1153053	0.0400853	-0.0013618

TABLE 5. SUMMARY OF MODAL FREQUENCIES FROM MODEL AND TEST RESULTS FOR THE CANTILEVERED ASTROMAST BEAM

	Experimental (Hz)	Analytical (Hz)	Percent Difference
Bending*	0.56	0.62	11
	3.4	3.9	16
	—	11	—
Torsion	—	6.9	—
	21	21	0.0
	29	34	19

* Two modes at each frequency.

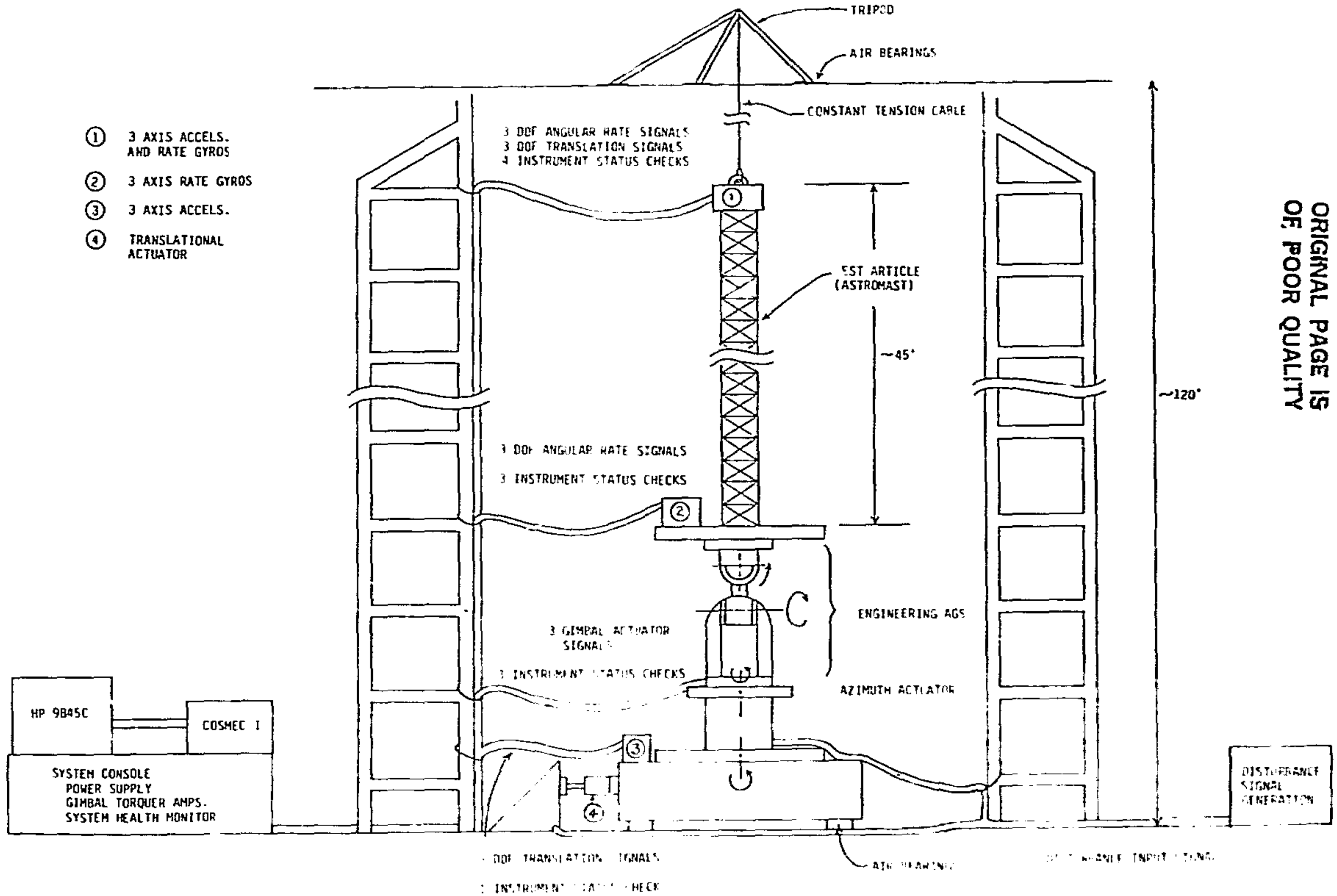

Figure 1. NASA MSFC large space structure ground test verification experiment.

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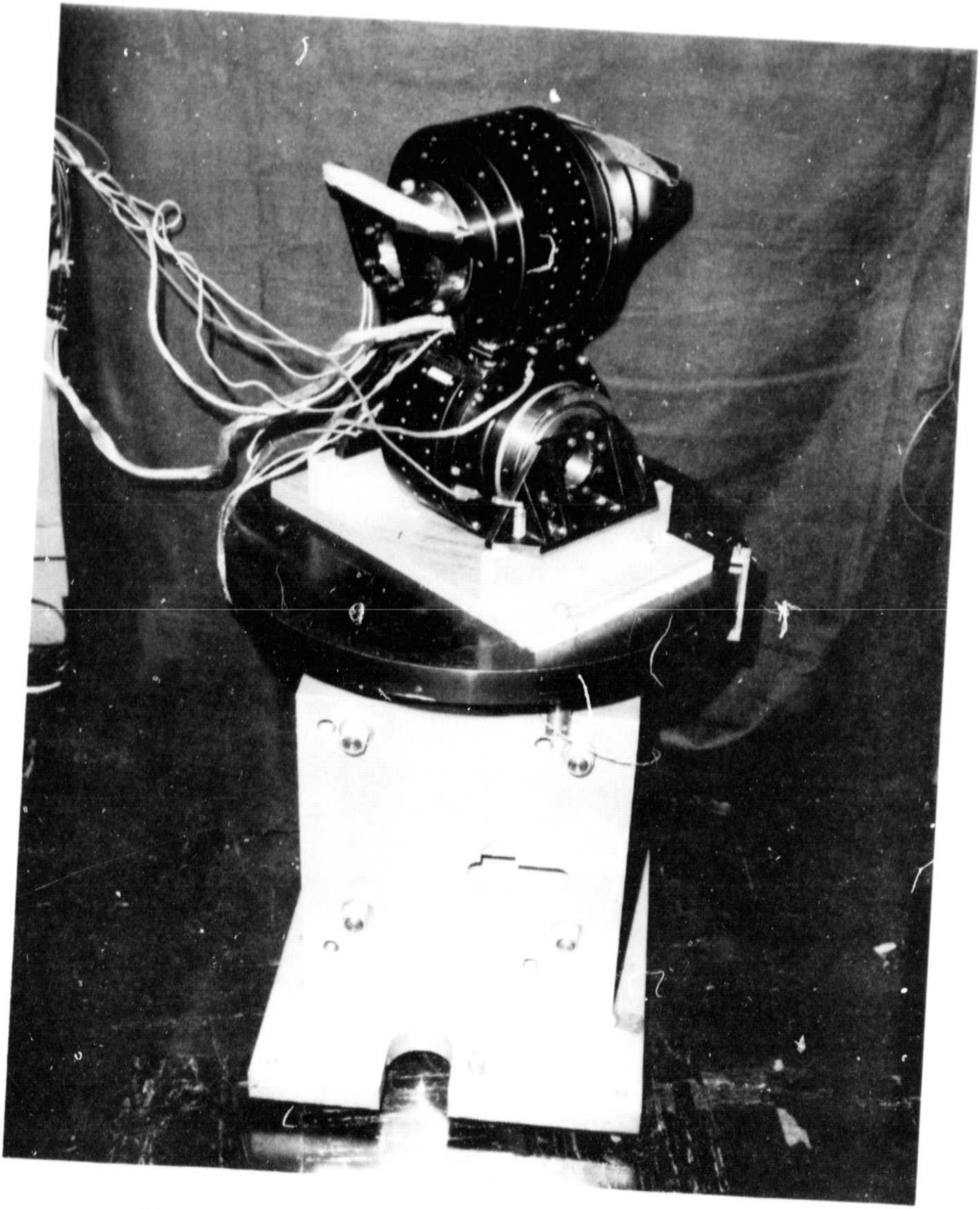

Figure 2. AGS engineering model and azimuth gimbal.

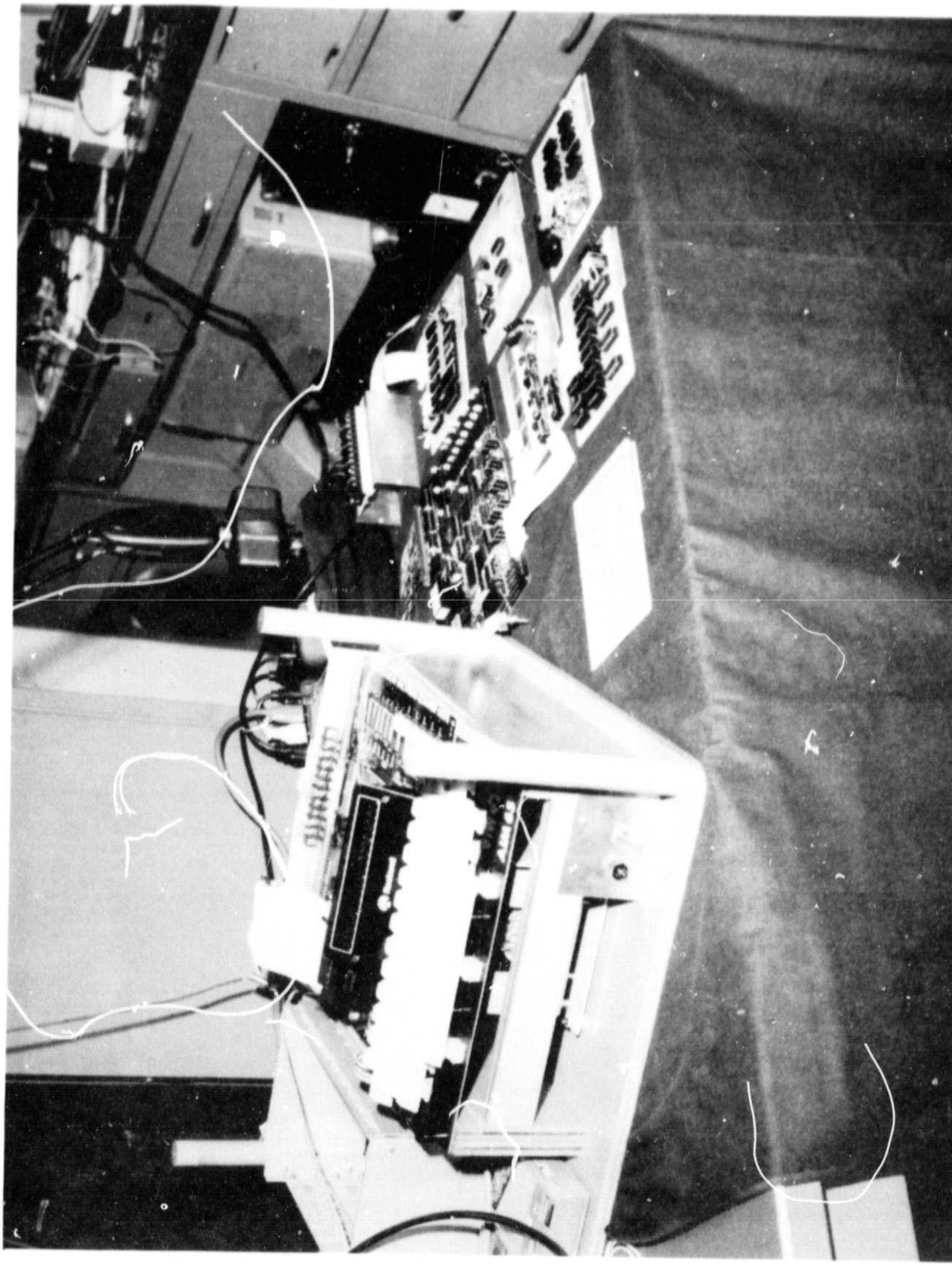

Figure 3. COSMEC-I laboratory system featuring the AIM 65 micro-computer.

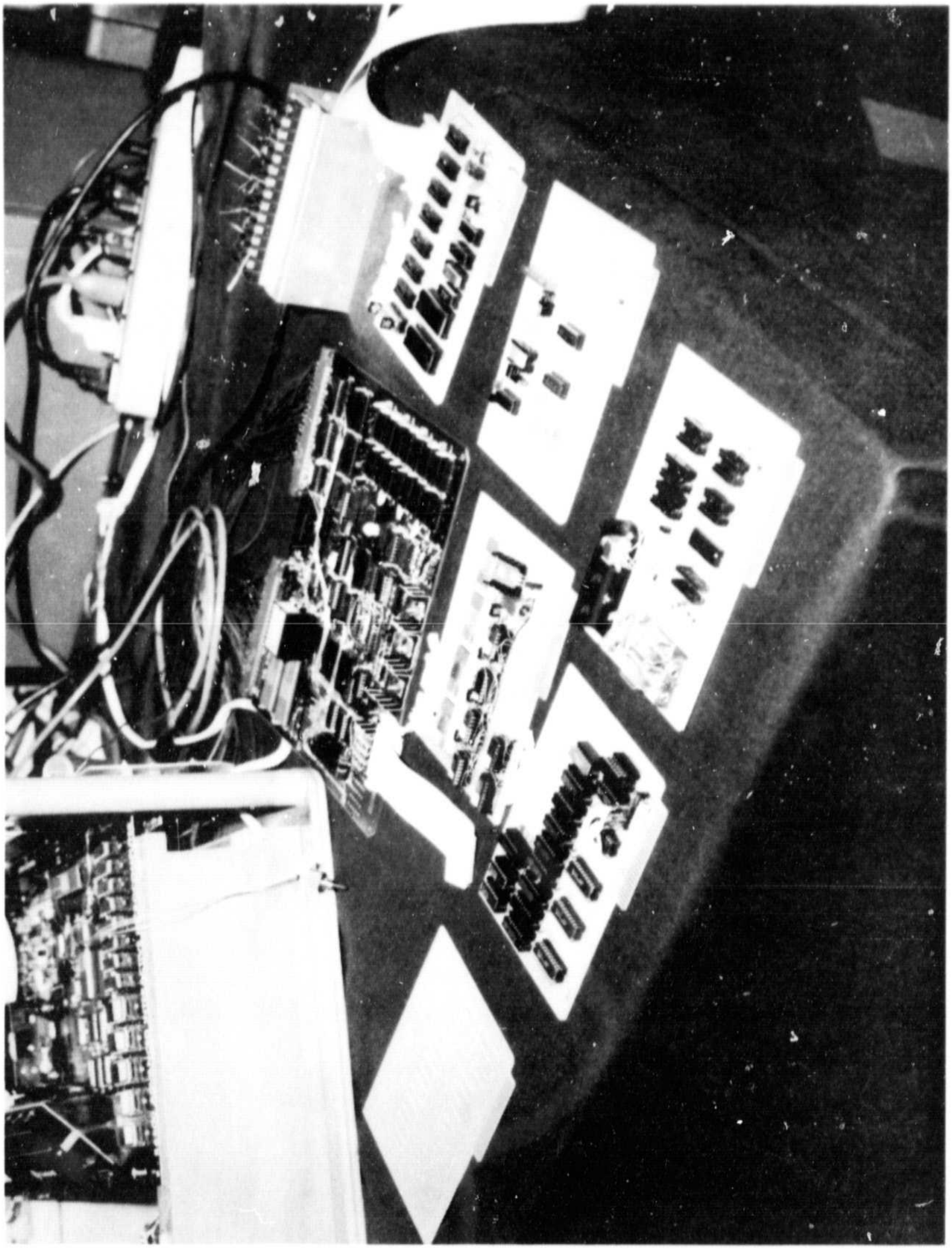

Figure 4. Hardware interface cards for COSMEC I data and control system.

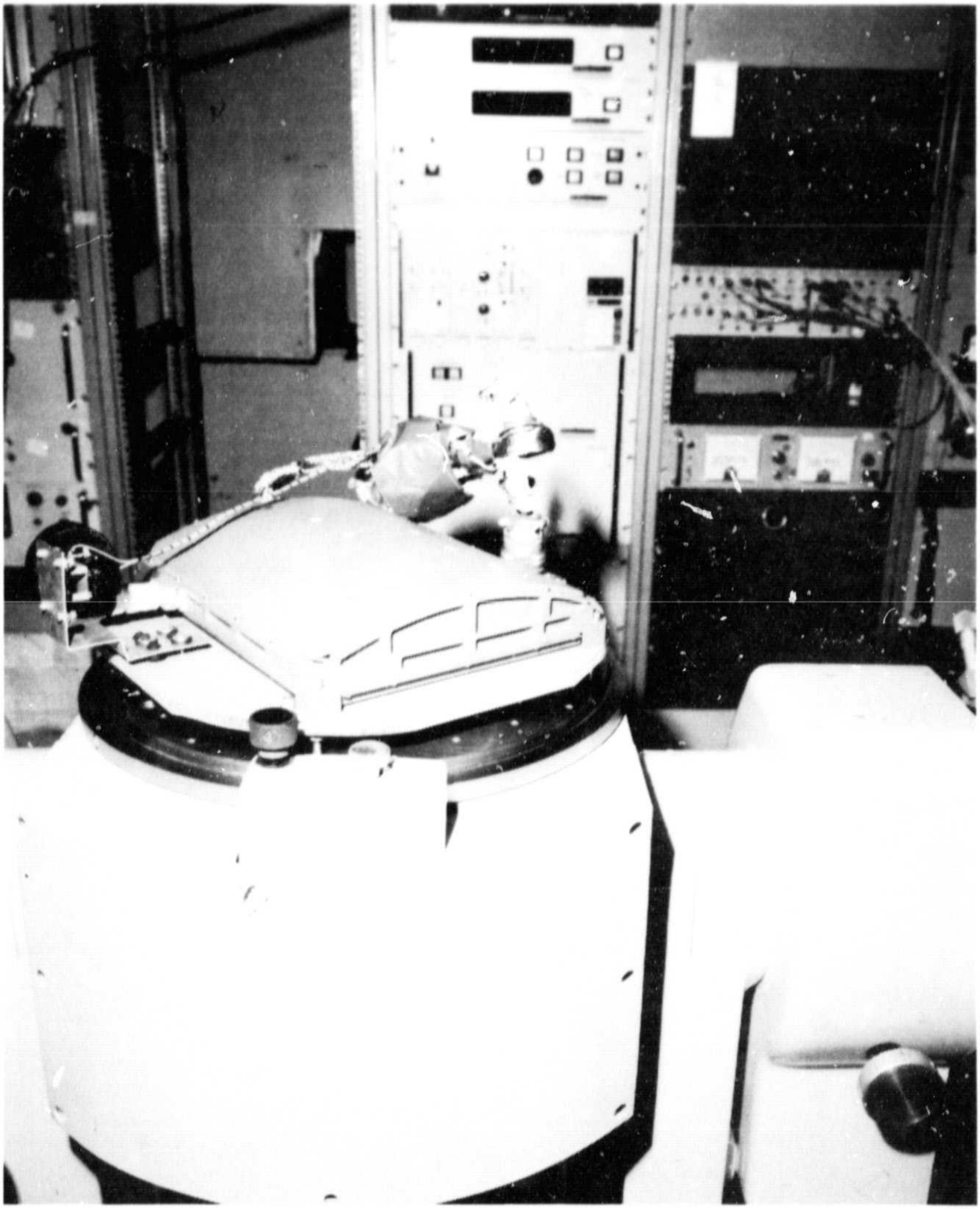

Figure 5. Kearfott attitude reference system on test table.

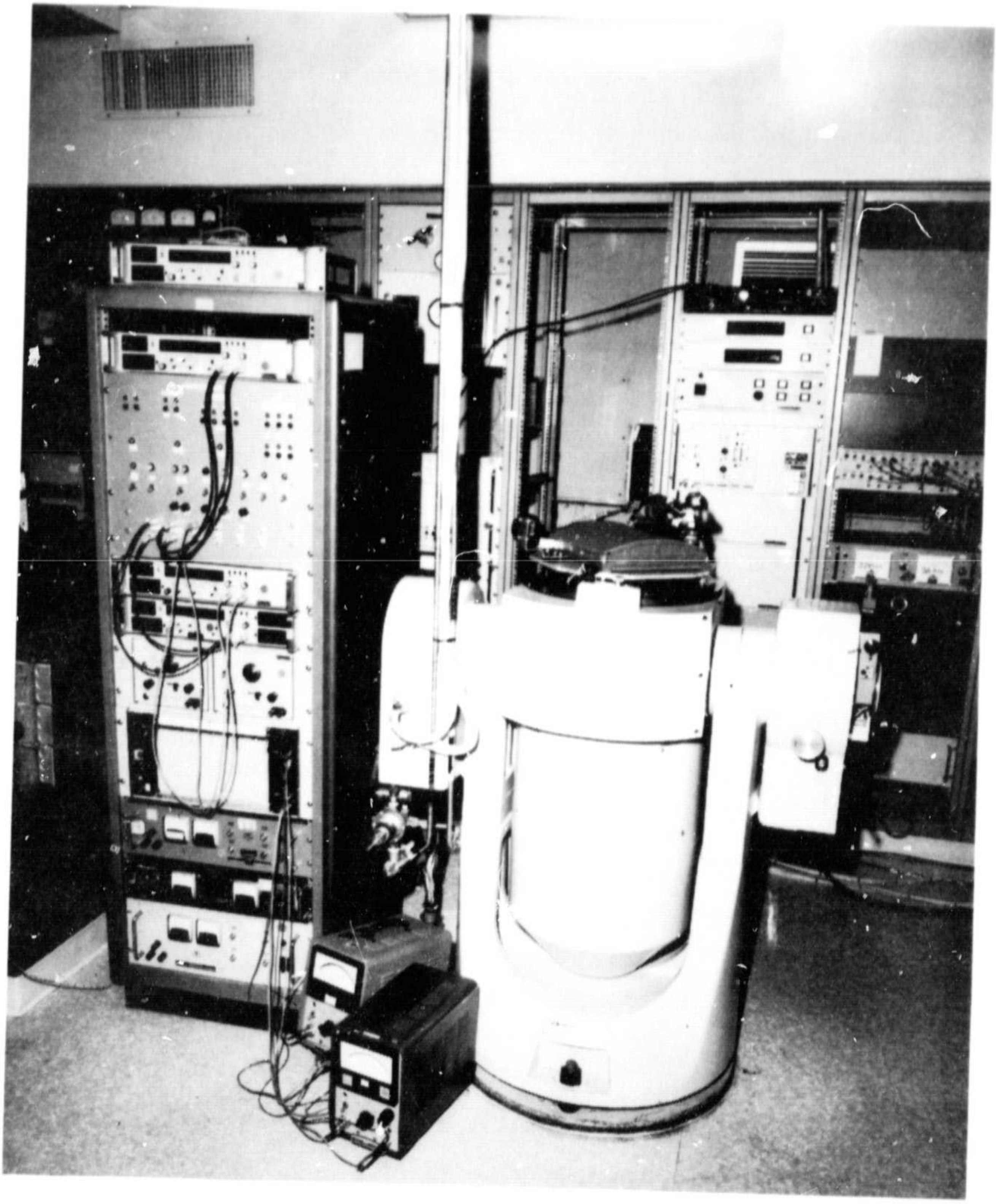

Figure 6. Kearfott attitude reference system and electronic test equipment.

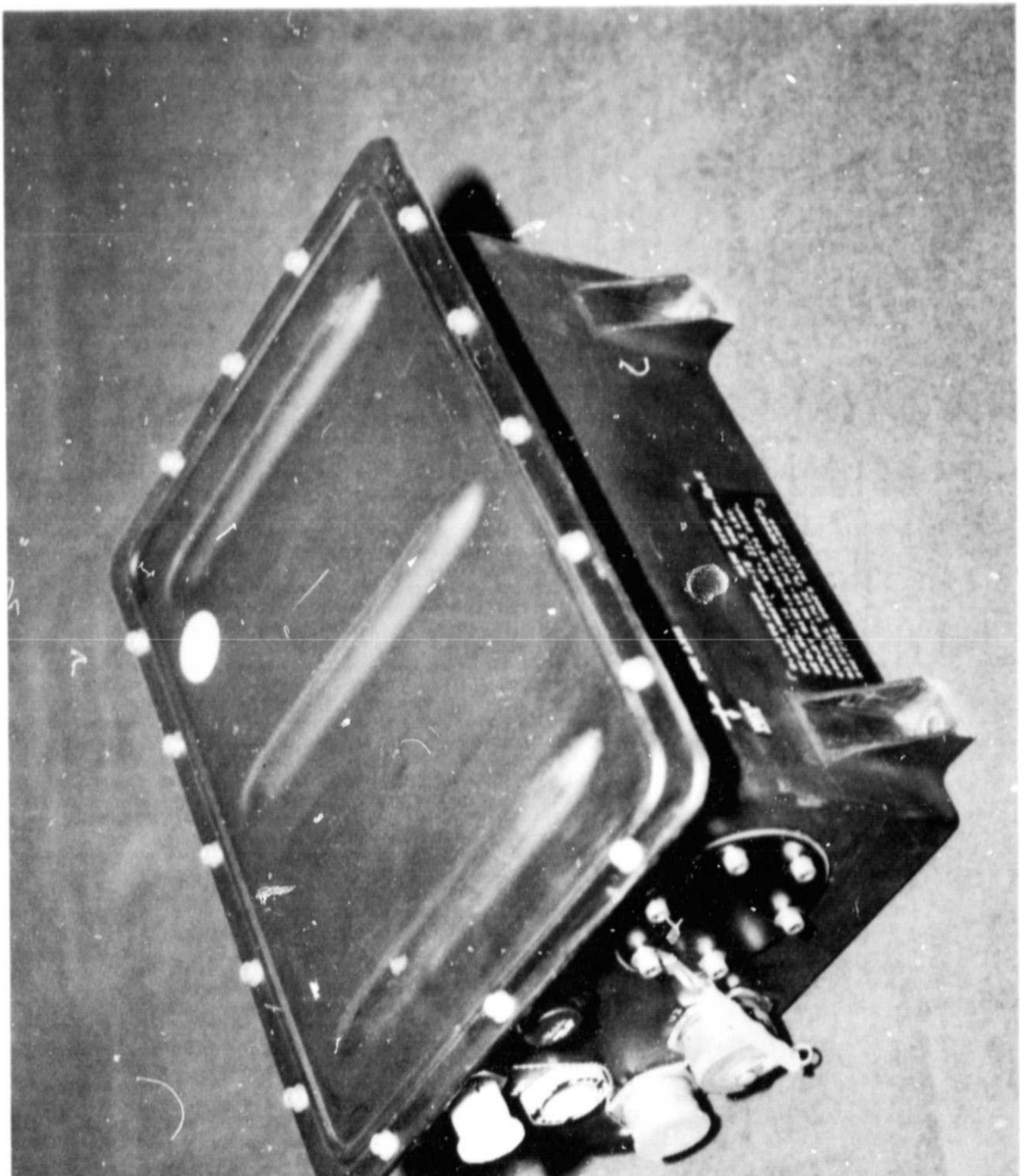

Figure 7. ATM rate gyro package.

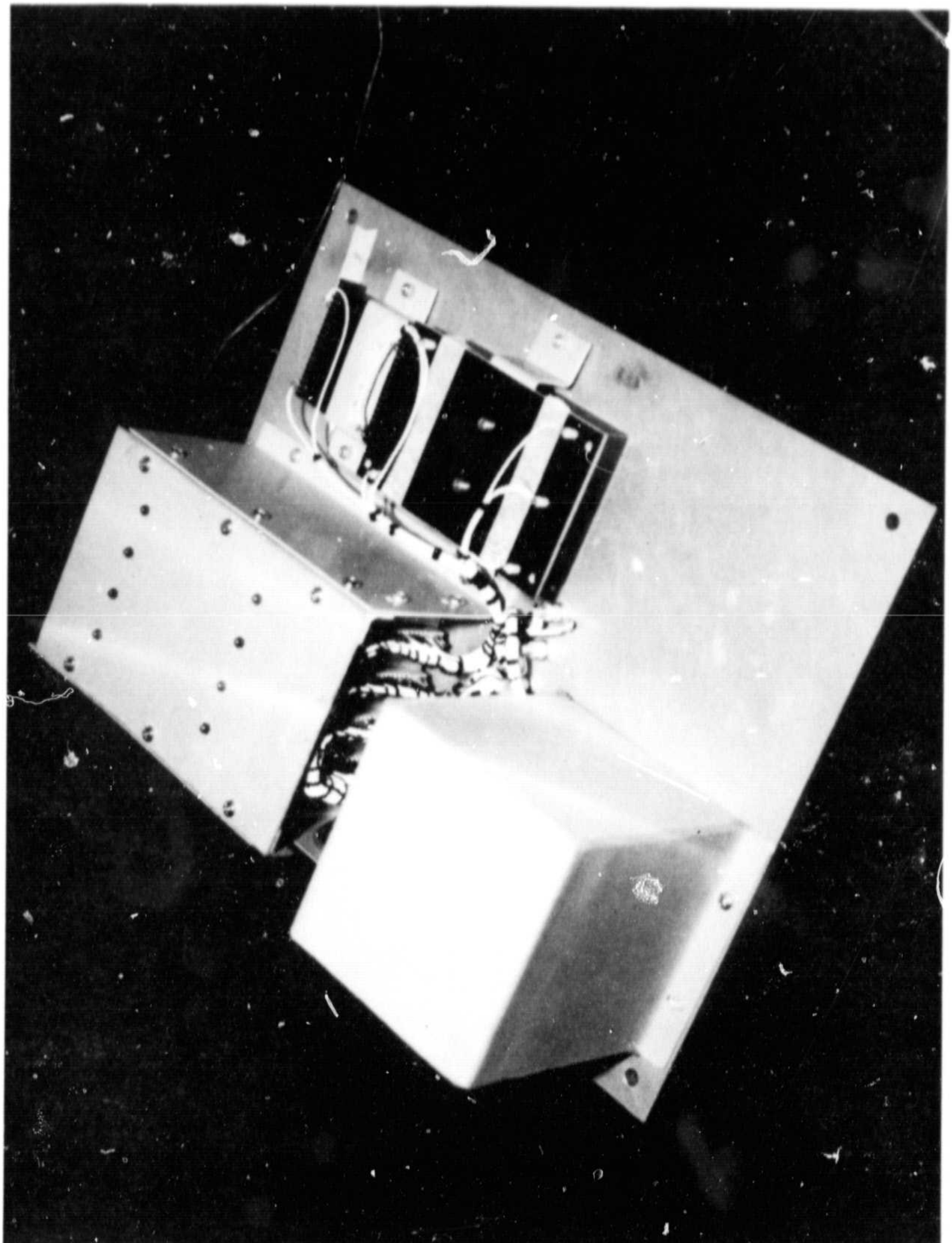

Figure 8. Three axis accelerometer package.

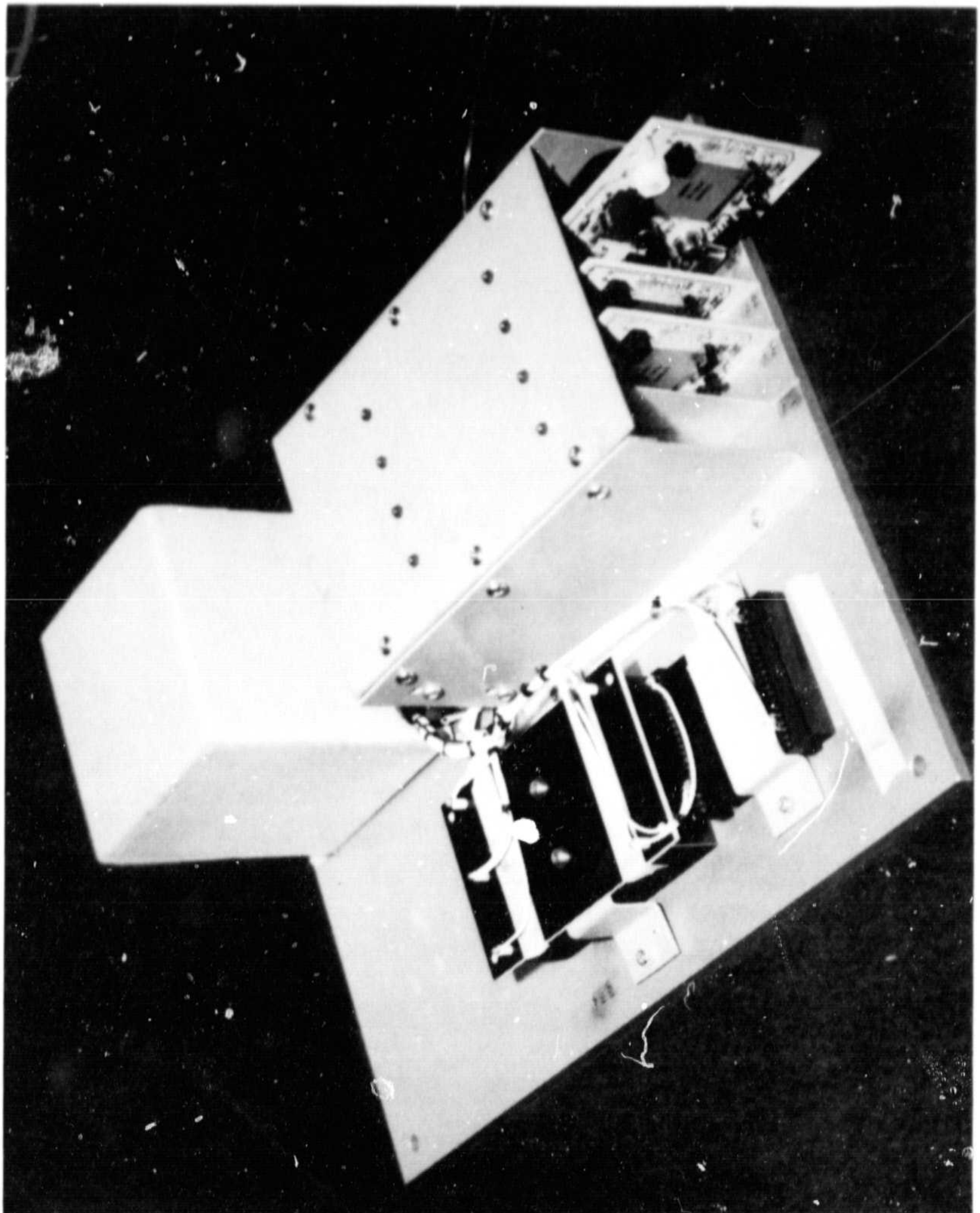

Figure 9. Three axis accelerometer package showing on-board electronics.

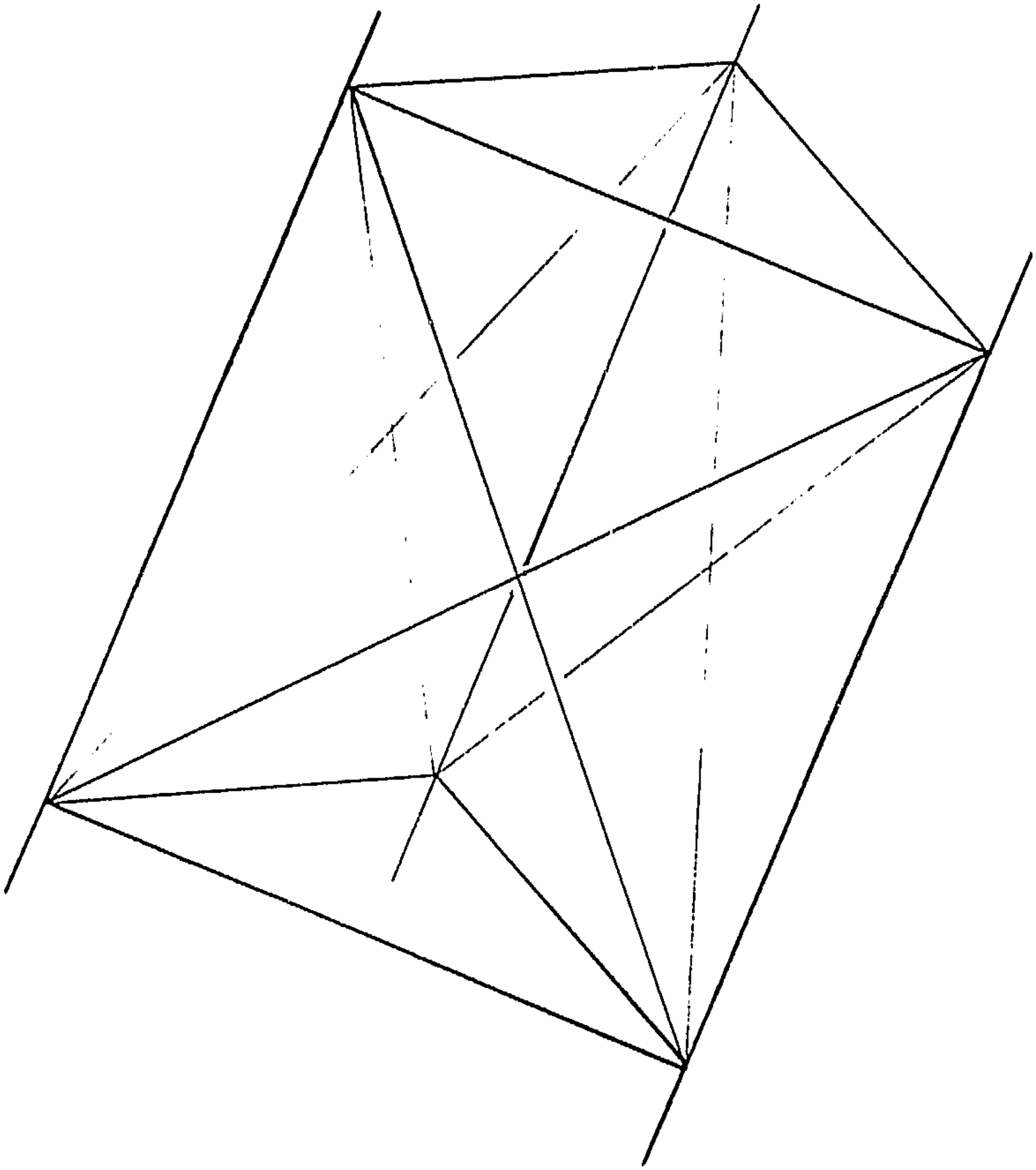

Figure 10. Schematic diagram of a single section of the ASTROMAST beam.

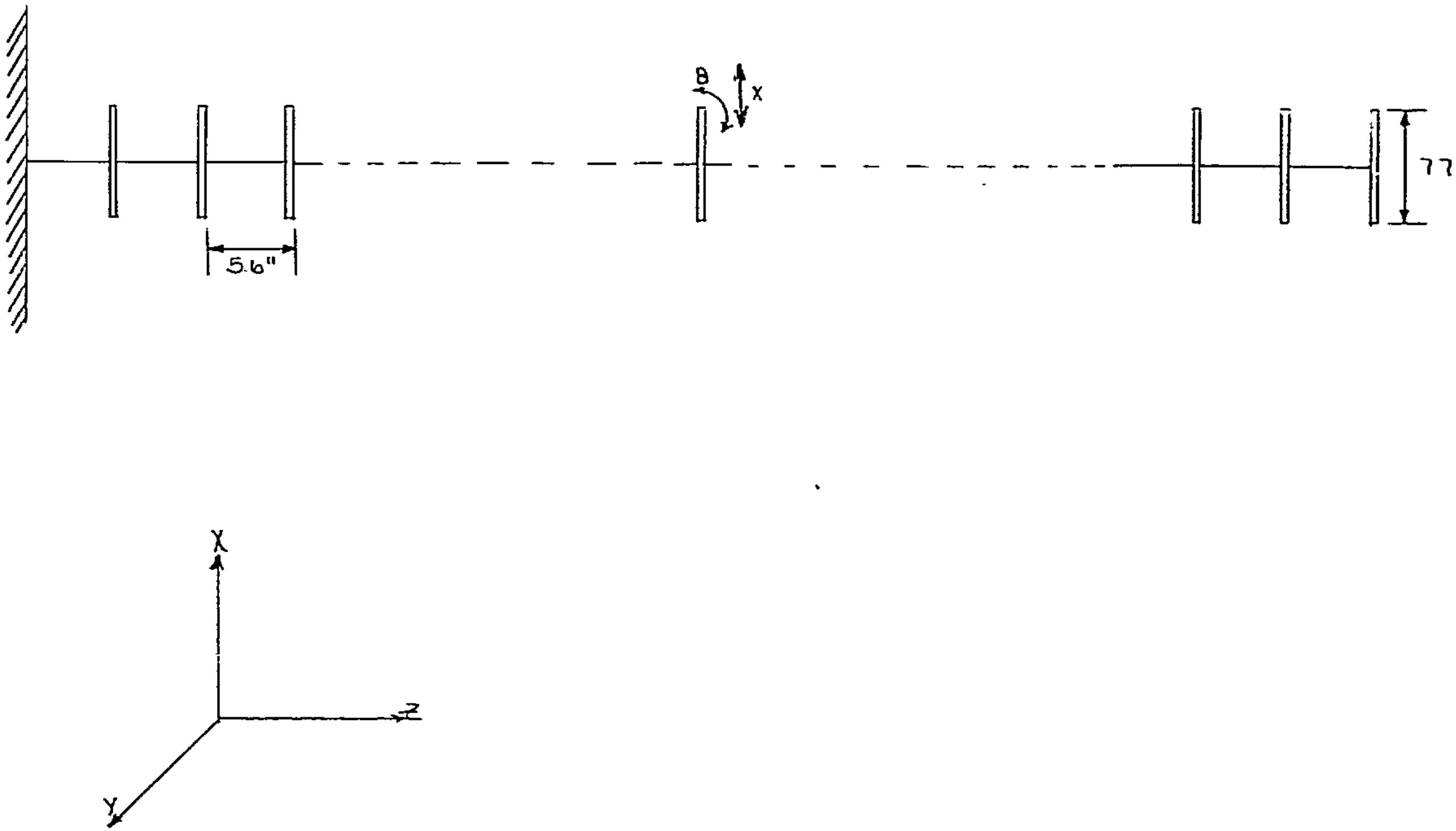

Figure 11. Simplified ASTROMAST beam description comprised of 91 mass lumps.

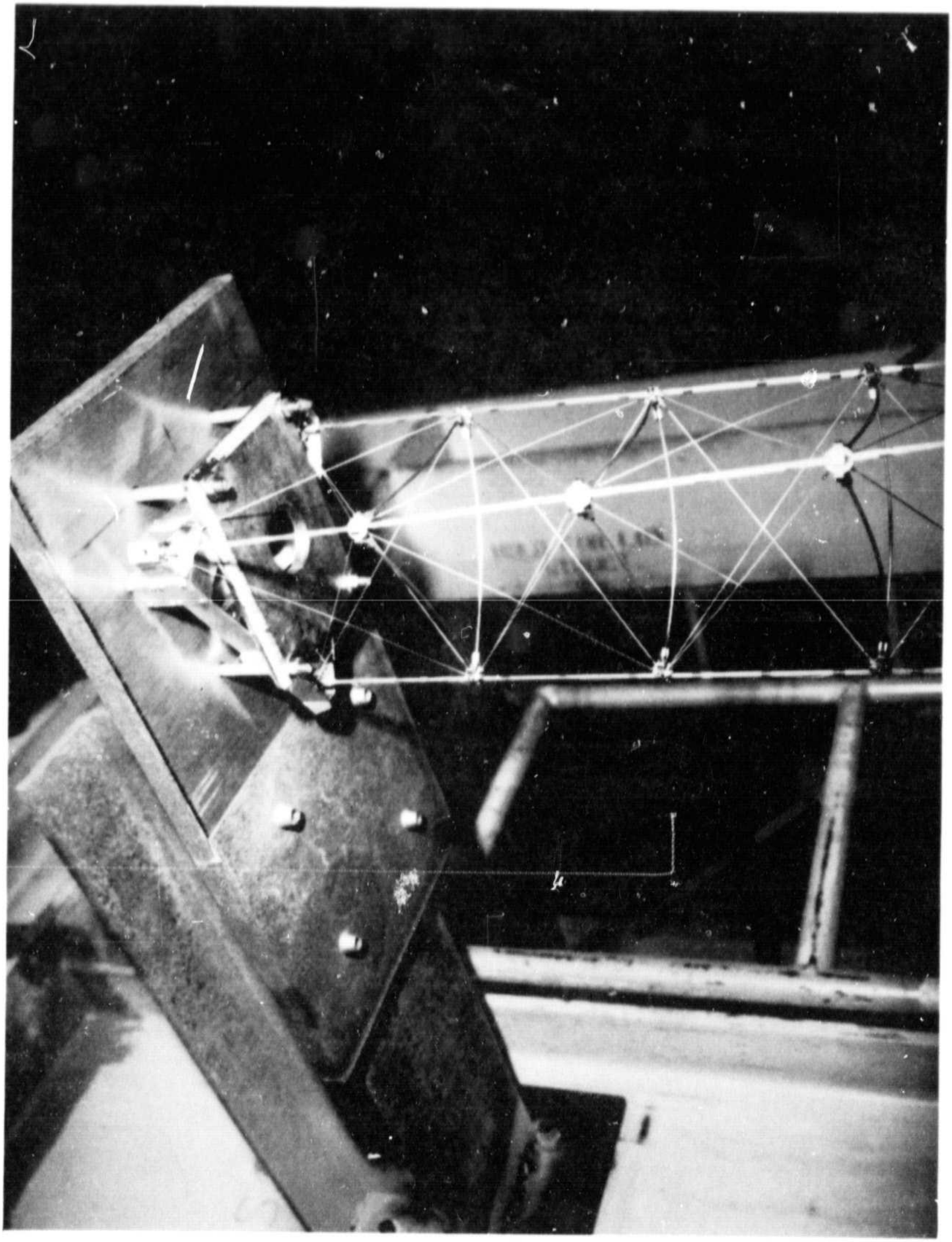

Figure 12. ASTROMAST base and mounting bracket for cantilevered modal test.

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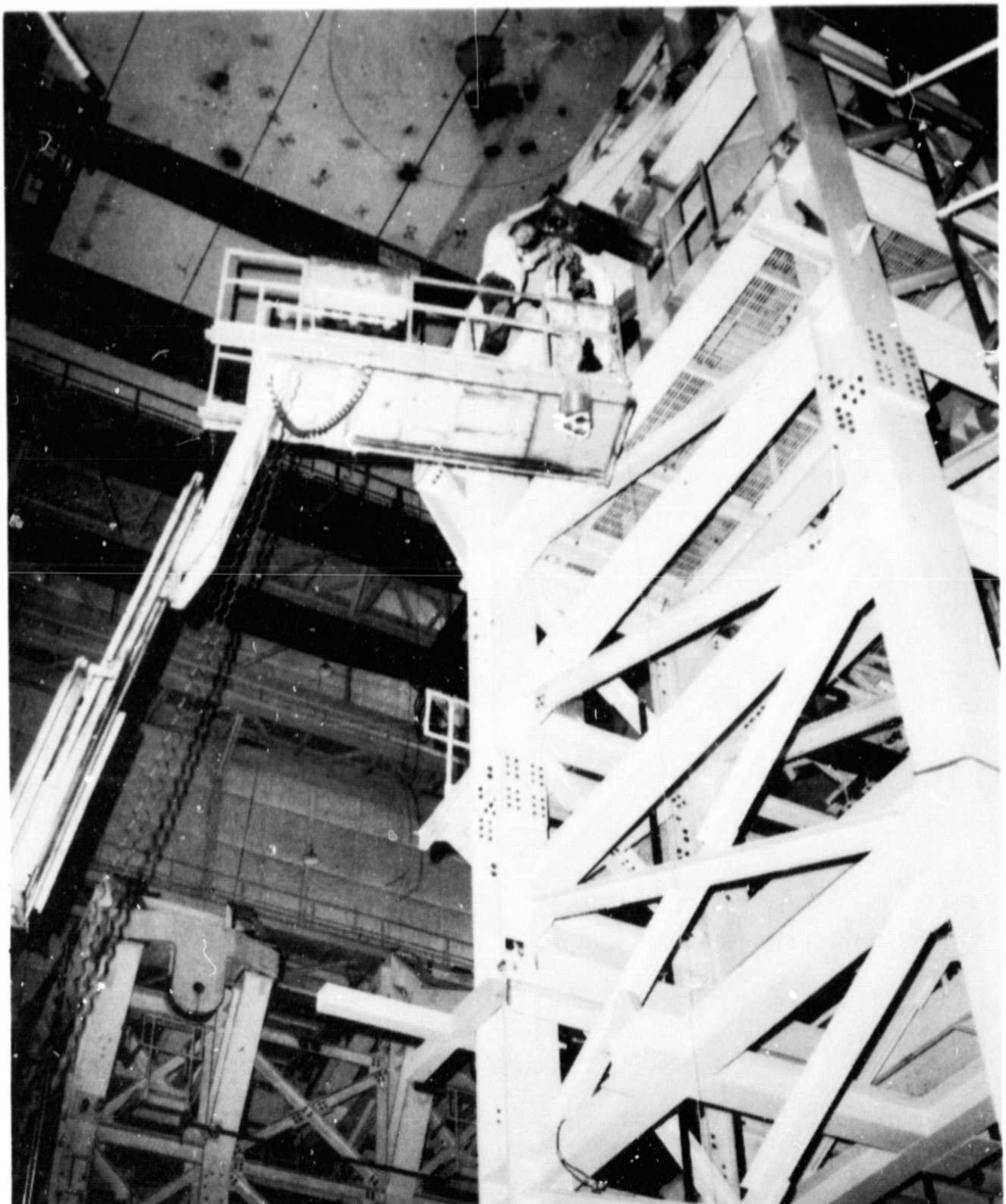

Figure 13. ASTROMAST beam at beginning of deployment.

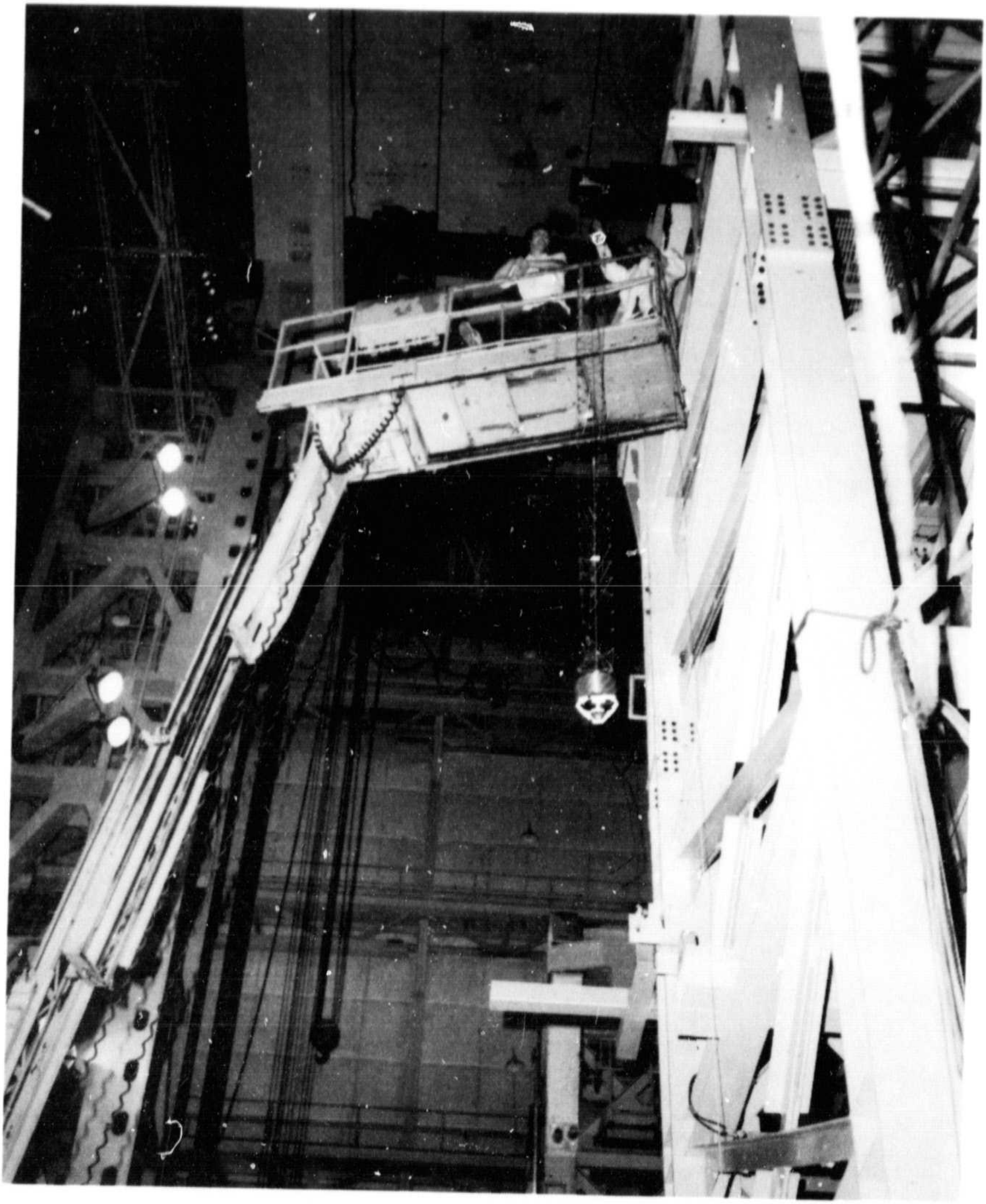

Figure 14. ASTROMAST beam about 50 percent deployed.

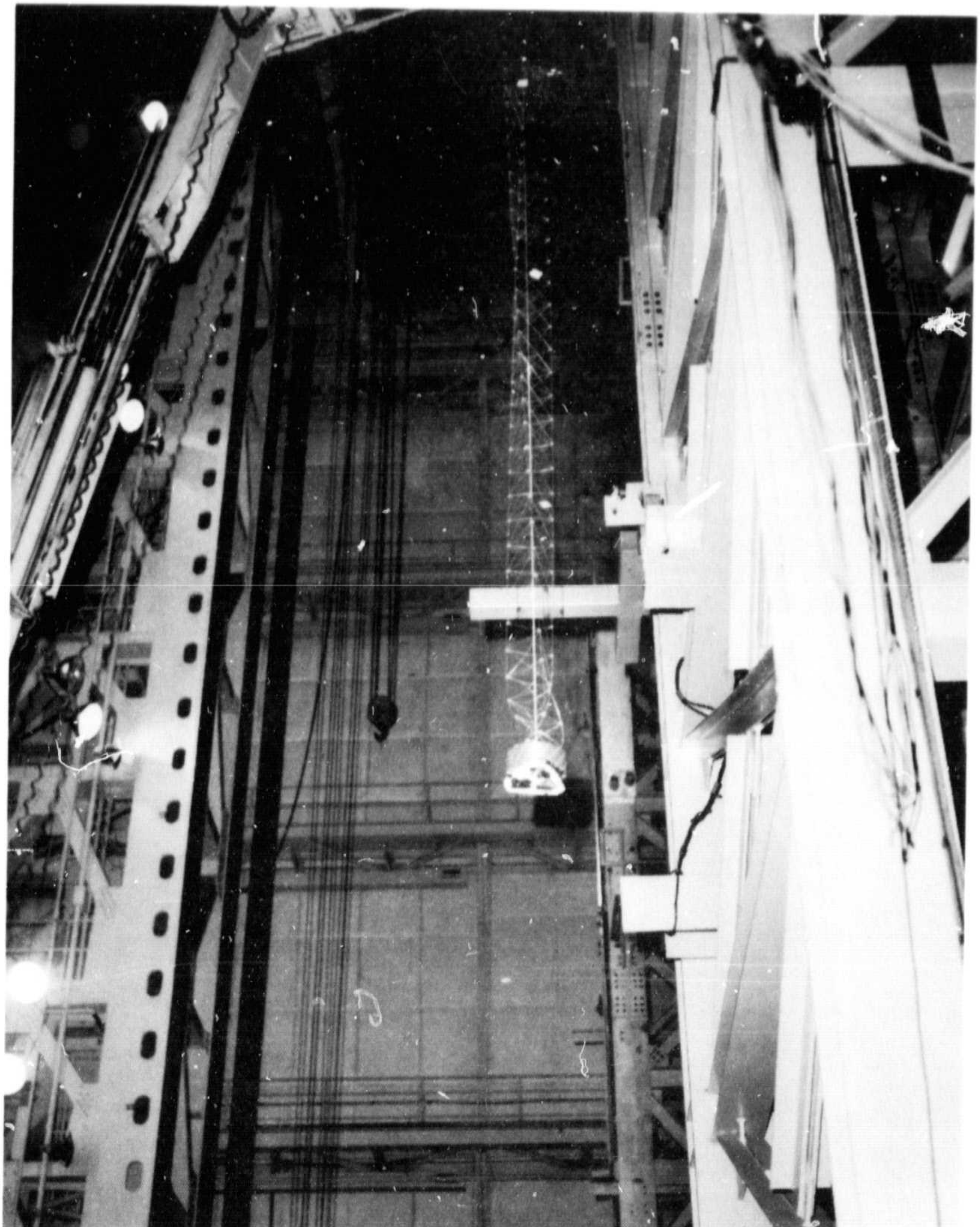

Figure 15. ASTROMAST beam about 75 percent deployed.

Figure 16. ASTROMAST beam fully deployed in cantilevered modal test configuration.

Figure 17. ASTROMAST beam showing 280 deg static twist about longitudinal axis.

APPROVAL

DEFINITION OF GROUND TEST FOR LARGE SPACE STRUCTURE (LSS) CONTROL VERIFICATION

By H. B. Waites, G. B. Doan, III, and Danny K. Tollison

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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