N87-22704

LARGE SPACE STRUCTURES GROUND EXPERIMENT CHECKOUT

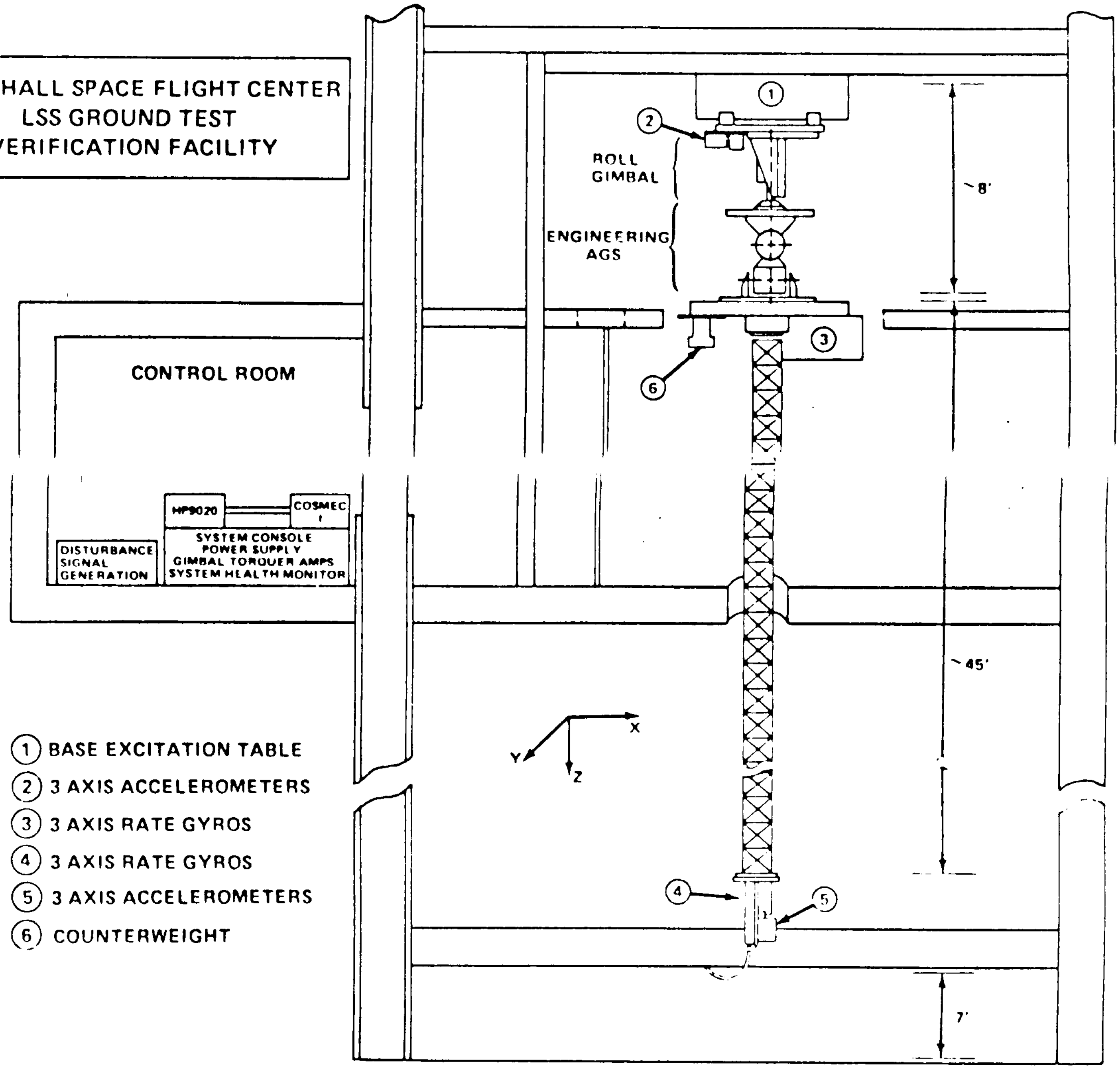
HENRY B. WAITES
NASA/MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, AL

WORKSHOP ON STRUCTURAL
DYNAMICS AND CONTROL INTERACTION
OF FLEXIBLE STRUCTURES
APRIL 22-24, 1986
MSFC, AL

NASA Marshall Space Flight Center has developed a facility in which closed loop control of Large Space Structures (LSS) can be demonstrated and verified. The main objective of the facility is to verify LSS control system techniques so that on-orbit performance can be ensured. The facility consists of an LSS test article or payload which is connected to a 3-axis angular pointing mount assembly that provides control torque commands. The angular pointing mount assembly is attached to a base excitation system which will simulate disturbances most likely to occur for Orbiter and DOD payloads. The control computer contains the calibration software, the reference systems, the alignment procedures, the telemetry software, and the control algorithms. The total system is suspended in such a fashion that the LSS test article has the characteristics common to all LSS.

The first version of the LSS/GTV facility is shown schematically on the facing page. It consisted of an ASTROMAST beam mounted to the faceplate of the Angular Pointing System (APS). The APS, in turn, is mounted to the Base Excitation Table (BET). Six separately packaged inertial measurement assemblies comprise the control system sensors. The signals from these sensors are received and processed in the COSMEC-I data gathering system. The COSMEC-I interfaces with a Hewlett Packard HP9020 desktop computer which processes the control algorithms, transmits control actuator commands to the COSMEC-I system, and stores data as they are collected during test runs; it then provides post-experiment data reduction and off-line displays. The COSMEC-I processes the control command from the HP9020 to the associated effector(s) to complete the closed loop system.

MARSHALL SPACE FLIGHT CENTER
LSS GROUND TEST
VERIFICATION FACILITY



1. BASE EXCITATION TABLE
2. 3 AXIS ACCELEROMETERS
3. 3 AXIS RATE GYROS
4. 3 AXIS RATE GYROS
5. 3 AXIS ACCELEROMETERS
6. COUNTERWEIGHT

Six separately packaged inertial measurement assemblies comprise the control system sensors. Two of the packages, containing 3-axis translational accelerometers, are identical. One is mounted on the mast tip and the other on the lower surface of the BET. Three other packages contain Skylab ATM (Apollo Telescope Mount) rate gyroscopes and are mounted on the APS faceplate (see top of facing page). The sixth package, the Kearfott Attitude Reference System (KARS), is located on the mast tip along with the remaining accelerometer package.

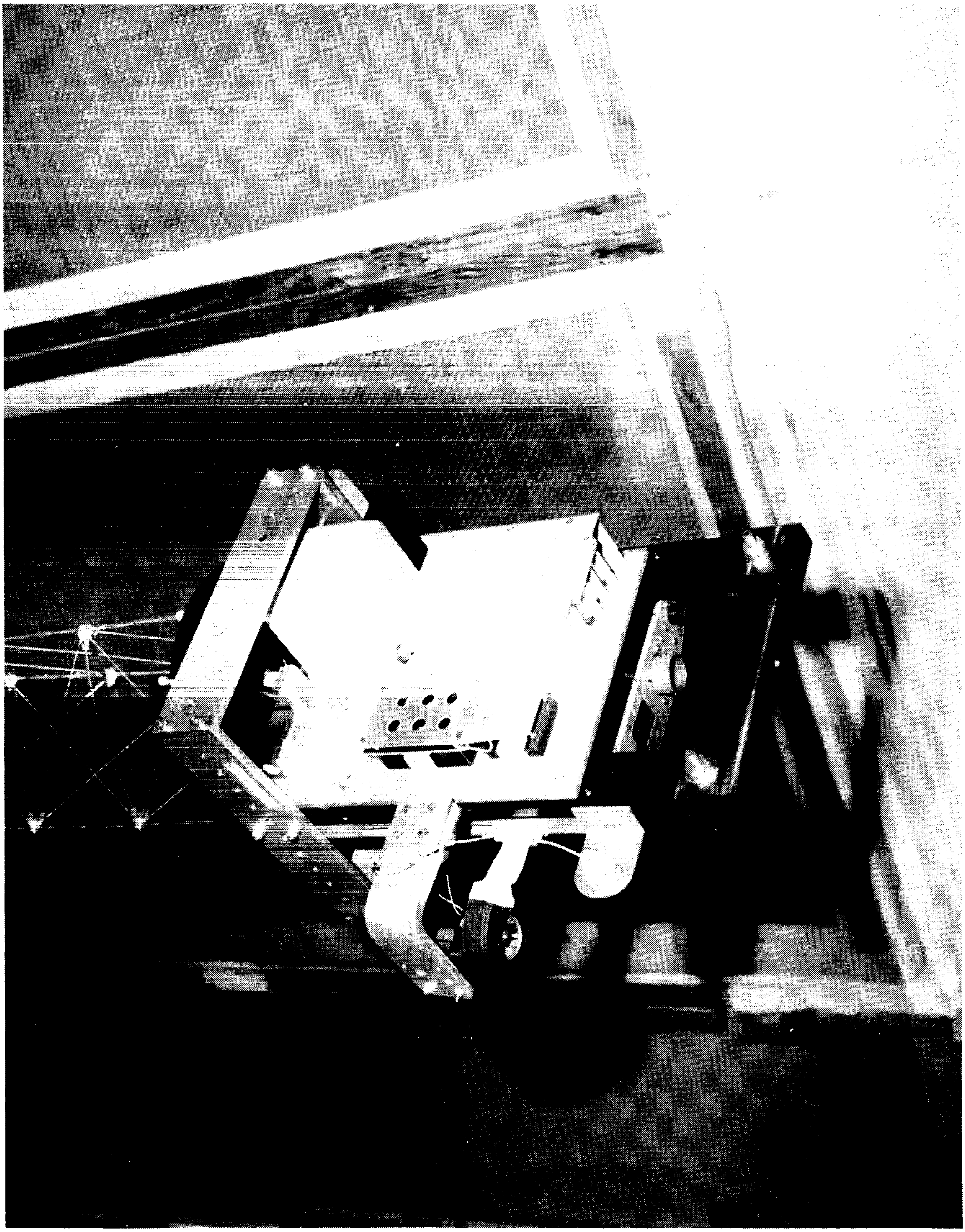
The Kearfott Attitude Reference System (KARS) includes three rate gyros and three accelerometers. The KARS unit is mounted to the test article tip as shown on the bottom of facing page, so that the sensors provide information about the tip motion. The rate gyros have a resolution of approximately 50 arc-sec/sec about two axes and 90 arc-sec/sec about the third axis. The KARS rate gyro bandwidth is about 70 Hz.

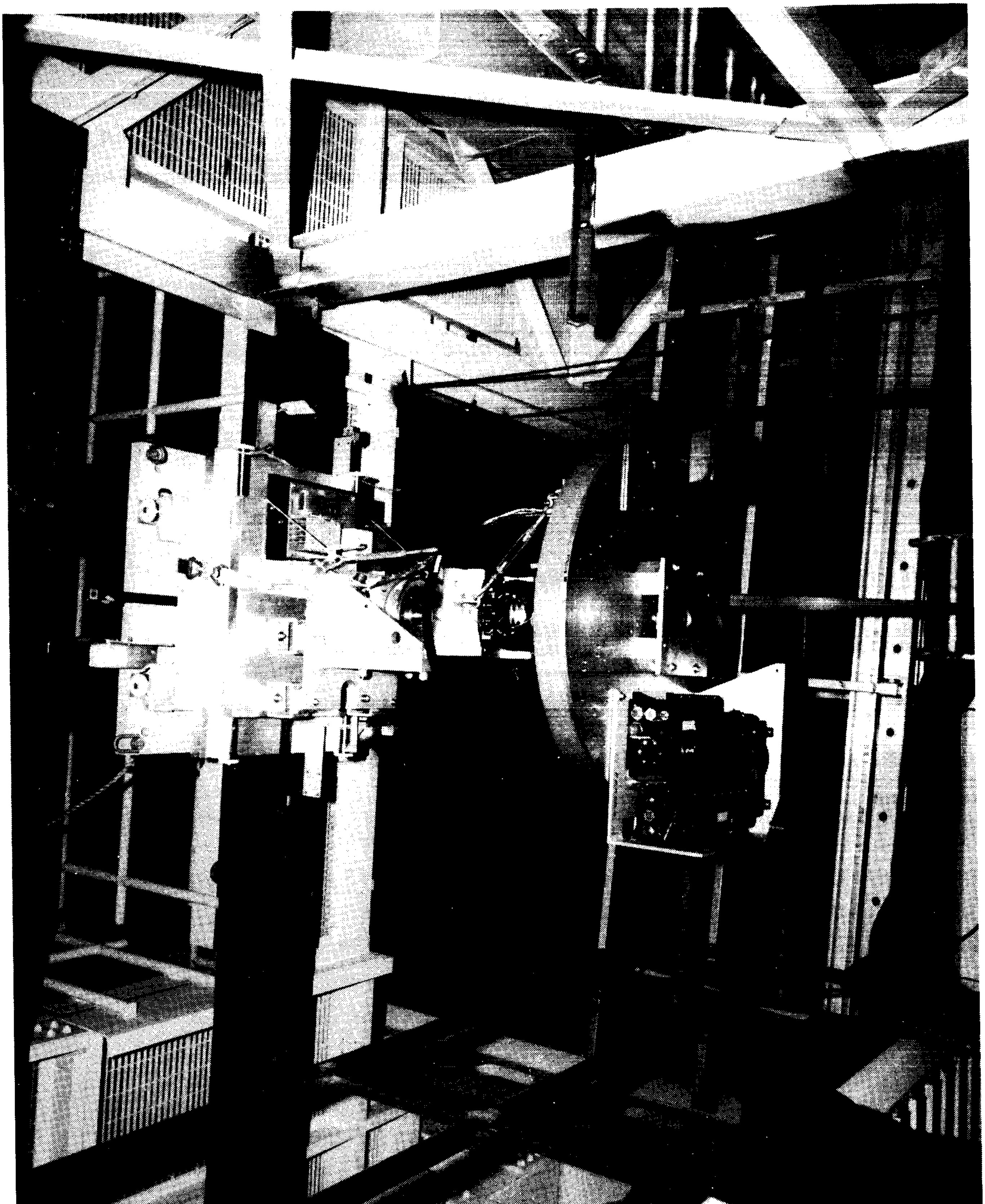
The ATM rate gyros are mounted to the APS payload mounting plate. The minimum resolution for the ATM gyros is approximately two arc-sec/sec. The gyros operate in a fine mode, which has a bandwidth of 12 Hz, and a coarse mode which has a bandwidth of 40 Hz.

The two 3-axis accelerometer packages incorporate six Kearfott 2401 accelerometers. The minimum resolution for each of these units is 11 microg's, and their bandwidth is 25 Hz.

The signals from these instruments are read by the COSMEC-I data gathering system and are processed by the HP9020 according to the particular control strategy under scrutiny. The control actuator signals are then transmitted to the APS as inputs to the dynamical system.

ORIGINAL PAGE IS
OF POOR QUALITY

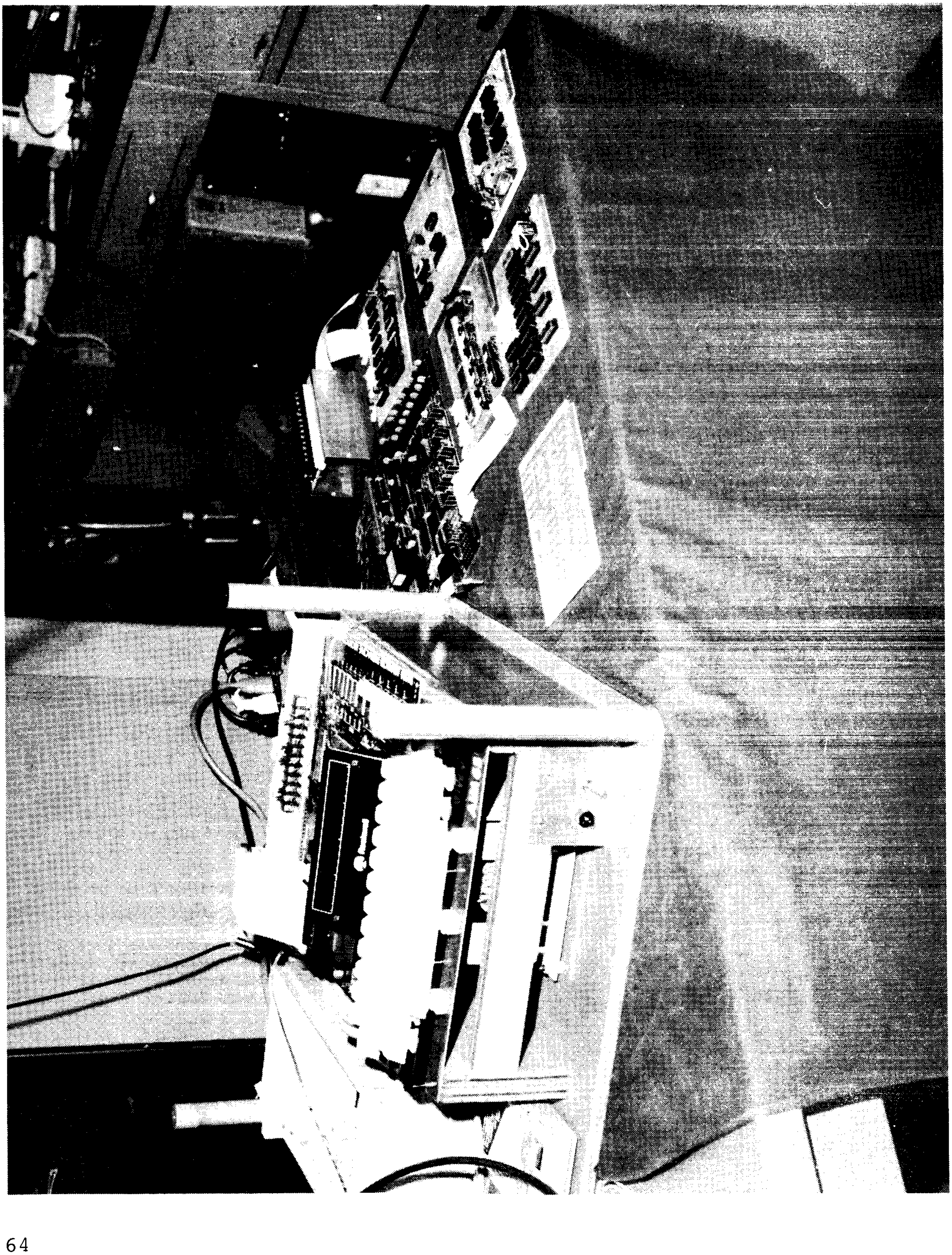




The signals from the sensors are utilized by the control computer and processed according to the control law under consideration. The COSMEC-I is the I/O computer which is used for data acquisition for the sensors and command output processing for the effectors. The COSMEC-I is a highly modified AIM-65 microcomputer system. It was developed originally by MSFC for the solar heating and cooling program. As a result, the development cost was not underwritten by the LSS/GTV facility.

The main purposes of the HP9020 control computer are to acquire the sensor inputs from the COSMEC-I, keep up with the laboratory coordinate system, process the control algorithm commands for the APS, and store control and sensor data for post-processing. The COSMEC-I and the HP9020 performs these tasks with twelve sensor inputs and three torque outputs, while maintaining a 50 Hz sampling rate. With the addition of the ANALOGIC array processor for the HP9020, the computational efficiency will increase by twenty-fold.

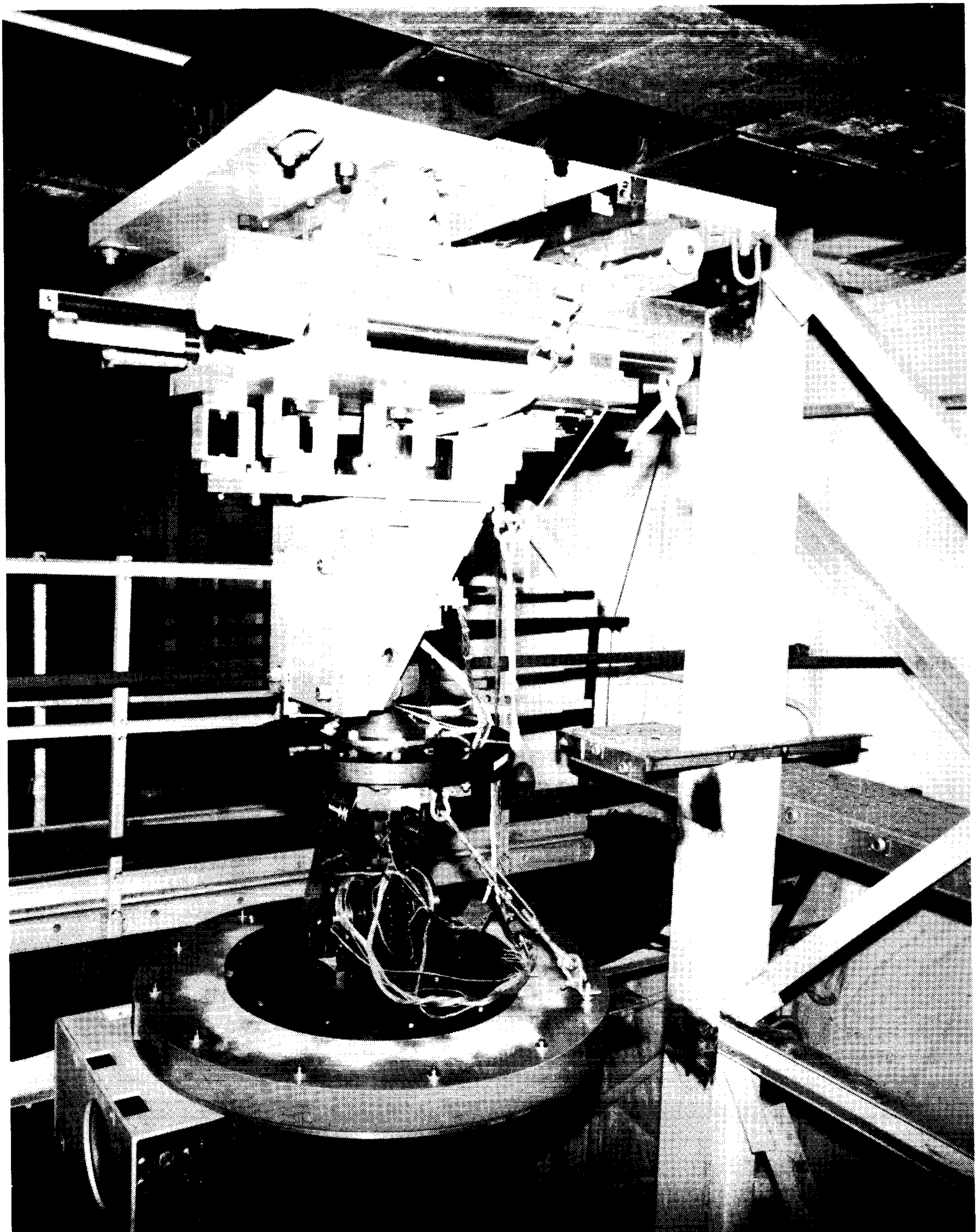
ORIGINAL PAGE IS
OF POOR QUALITY



The test structure is mounted to the payload mounting plate of an Angular Pointing System (APS). The APS provides the control inputs for the initial configuration system and the cruciform-modified system. The APS actuators are the Advanced Gimbal System engineering model, produced by Sperry for the Spacelab program, and a third (roll) gimbal designed and built inhouse (as were the amplifiers used to drive the gimbal torquers). The roll gimbal, serving the vertical axis, is suspended by an air bearing which requires approximately 85 psi to operate. The roll gimbal provides a means of rotating the entire system to produce different test scenarios. The air bearing is connected to a Base Excitation Table (BET) which is free to translate in two directions. This actuator assembly setup, with its low friction torques, permits control in three angular directions. With the added roll gimbal, the test article can be rotated about its center line so that different test setups can be achieved.

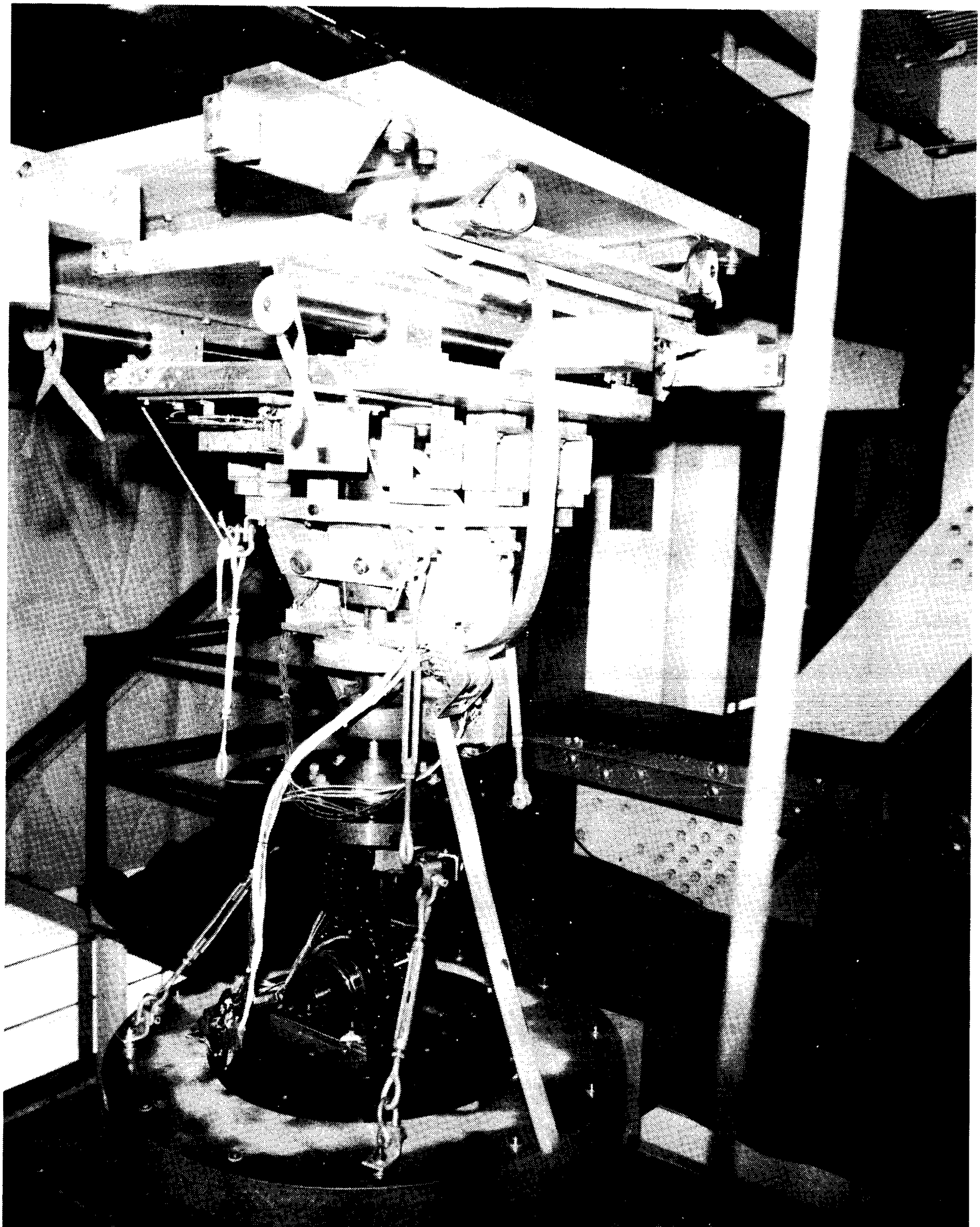
In the initial research and technology task, the effectors for the LSS/GTV control system are three torque motors which are capable of providing control torques about three axes. The bottom two gimbals can generate up to 51 N-M of torque, and the roll or azimuth gimbal can generate up to 10 N-M of torque. The bandwidth limitation for all three gimbals is 100 Hz. The APS amplifiers receive torque commands from the COSMEC-1 digital processor in the form of analog inputs over the range of -10 to +10 volts. This saturation represents the current limit of 27 amps which is built into the APS servo amplifiers. Because the APS servo amplifier outputs a current which is proportional to torque, the control law algorithm was designed to produce torque command signals. The gimbal torquers are shown on the facing page.

ORIGINAL PAGE IS OF POOR QUALITY



All of the GTV configurations need a device to excite the system in a consistent manner so that the effectiveness of the different control methodologies can be determined. Initially, these disturbances will represent either an astronaut pushoff, or a Reaction Control System thruster firing, or a free flyer disturbance. The Base Excitation Table (BET) which is attached to the building support structure, is shown on the facing page. It provides a means of producing such disturbance inputs. The BET is comprised of signal generators (deterministic or random noise), DC conditioning amplifiers, hydraulic servo controllers, and an oscillograph. The DC conditioning amplifiers are used to scale the signal generator while the signal conditioners are used to condition the electronic deflection indicator motion monitors for display. The oscillograph is used for recording the actual motion of the BET.

The precise motion of the BET is obtained by supplying a commanded voltage input to the BET servo control system. The BET movements are monitored by the directional feedback electronic deflection indicators which are fed back to the servo controllers. The servo controllers compare the commanded input voltage to the electronic deflection indicators and automatically adjust the position of the BET. The closed loop controller allows any type of BET movement within the frequency limitations of the hydraulic system.



One of the important aspects of the LSS/GTV is to verify the analytical model of the test article. The procedure is to describe the structure mathematically as well as possible, then perform structural tests on the test article, and finally to factor these results into the mathematical model.

One of several modeling efforts included the APS, BET, and instrument packages. This model was used as an aid in conducting the modal test on the structure in this configuration. Again, the test data were used to refine the corresponding structural model. The table, in the upper facing page, provides the corresponding synopsis of the modal frequencies as predicted pre-test, measured, and "tuned." Turning was accomplished by varying the inertial properties which were poorly known and the bending and torsional stiffness which change with the different gravity loading in this configuration. Examination of the percentage errors in table previously mentioned shows the refinement of the model.

The modeling was then expanded to include the cruciform structure at the ASTROMAST tip which was added to obtain more LSS-like pathologies, i.e., closely spaced modal frequencies. The "model-test-tune" procedure described in the previous paragraph was carried out for this configuration in order to produce a high fidelity model of the LSS/GTV experiment structure. The modal frequencies and damping for the two previous measured models are shown in bottom facing page table. The results described as "local modes," in this table primarily involve deformation of the cruciform arms.

The last modal test that was performed was to determine the effects of connecting cables to the various components on the test structure. All the cabling was stripped off the stiff external wrapping and sufficient length and coiling was provided to reduce any cabling effect on the structural dynamics. The acquired test data conclusion is that no significant modal shifts occurred when the cables were connected.

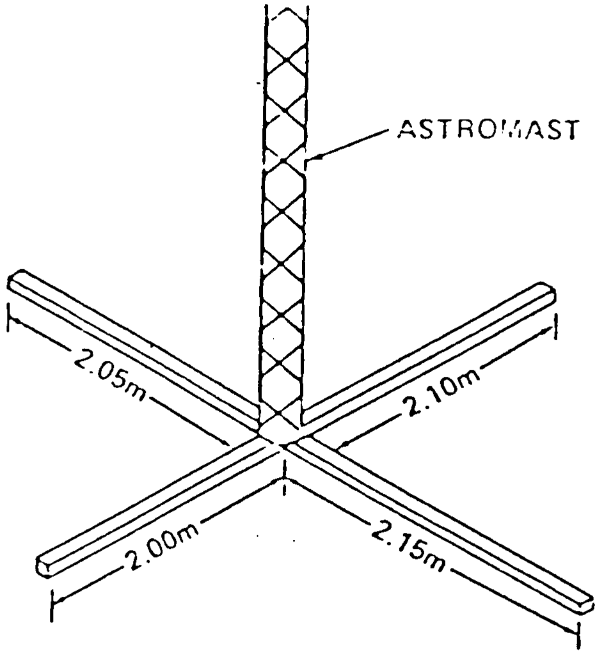
TABLE 1. Structural Natural Frequencies Without Cruciform

MODE #	DESCRIPTION	ORIGINAL ANALYTICAL	MEASURED	Δ(%)	TUNED ANALYTICAL	Δ(%)
1	RB (xy-plane)	0.00				
2	RB (yz-plane)	0.00				
3	RB (torsion)	0.00				
4	1st Bend (yz-plane)	0.14	0.14	0.0	0.14	0
5	1st Bend (xz-plane)	0.15	0.15	0.0	0.15	0
6	1st Torsion	1.18	0.99	19.0	1.02	3
7	2d Bend (xz-plane)	1.27	1.33	4.5	1.29	3
8	2d Bend (yz-plane)	1.40	1.80	22.0	1.64	9
9	3d Bend (xz-plane)	3.02	3.30	8.5	3.34	1
10	3d Bend (yz-plane)	3.91	3.94	0.0	4.31	11
11	4th Bend (xz-plane)	6.69	8.06	17.0	8.10	0
12	4th Bend (yz-plane)	7.03	8.13	14.0	8.21	1
13	2d Torsion	8.42	9.60	12.0	9.61	0

TABLE 2. Summary of LSS/GTV Modal Test Results

Description	W/o Cruciform			W/Cruciform		
System Mode	Freq Hz	% Damp	TSS	Freq Hz	% Damp	TSS
1st Bndg (x)	0.144	0.35	002	No Data	No Data	N/A
" (y)	No Data	No Data	N/A	No Data	No Data	N/A
2nd Bndg (x)	1.33	1.33	002B	1.36	1.9	005
" (y)	1.83	1.88	002A	1.83	1.9	004
3rd Bndg (x)	3.38	1.76	002B	3.24	1.7	005
" (y)	3.9	2.2	002A	3.74	2.0	004
4th Bndg (x)	8.06	2.9	003	6.36	1.1	005
" (y)	8.13	4.5	003	6.67	1.85	004
1st Torsion	0.991	0.44	001	0.377	0.56	006
2nd Torsion	9.6	1.1	001	3.02	0.34	007
Local Modes						
Y Bndg	N/A	N/A	N/A	0.38	0.53	008
"	"	"	"	1.149	0.53	008
"	"	"	"	6.418	0.70	008
"	"	"	"	6.876	0.44	008
"	"	"	"	7.326	0.415	008
				7.706	0.156	008
Z Bndg	N/A	N/A	N/A	1.143	0.79	008
"	"	"	"	6.756	1.09	008
"	"	"	"	7.062	1.23	008

The original test configuration had all the desired LSS characteristics except the densely-packed vibrational modes. Several design configuration changes were considered so that this important missing structural constraint could be implemented. The configuration change which could effect the densely-packed modes was the addition of a cruciform structure at the tip of the ASTROMAST. To a degree, the new configuration approximates an antenna or a radar system.



THE CRUCIFORM STRUCTURE

FOR SIMULATION PURPOSES, THE 4 ALUMINUM BARS WERE PLACED AT THE TIP OF THE BEAM, IN ACTUALITY, THEY ARE TO BE LOCATED AT THE END OF THE TIP BRACKET. THE RODS VARY IN LENGTH FROM 2.00m TO 2.15m. THEY ALL HAVE A CONSTANT CROSS-SECTION OF 1/4" x 1/4".

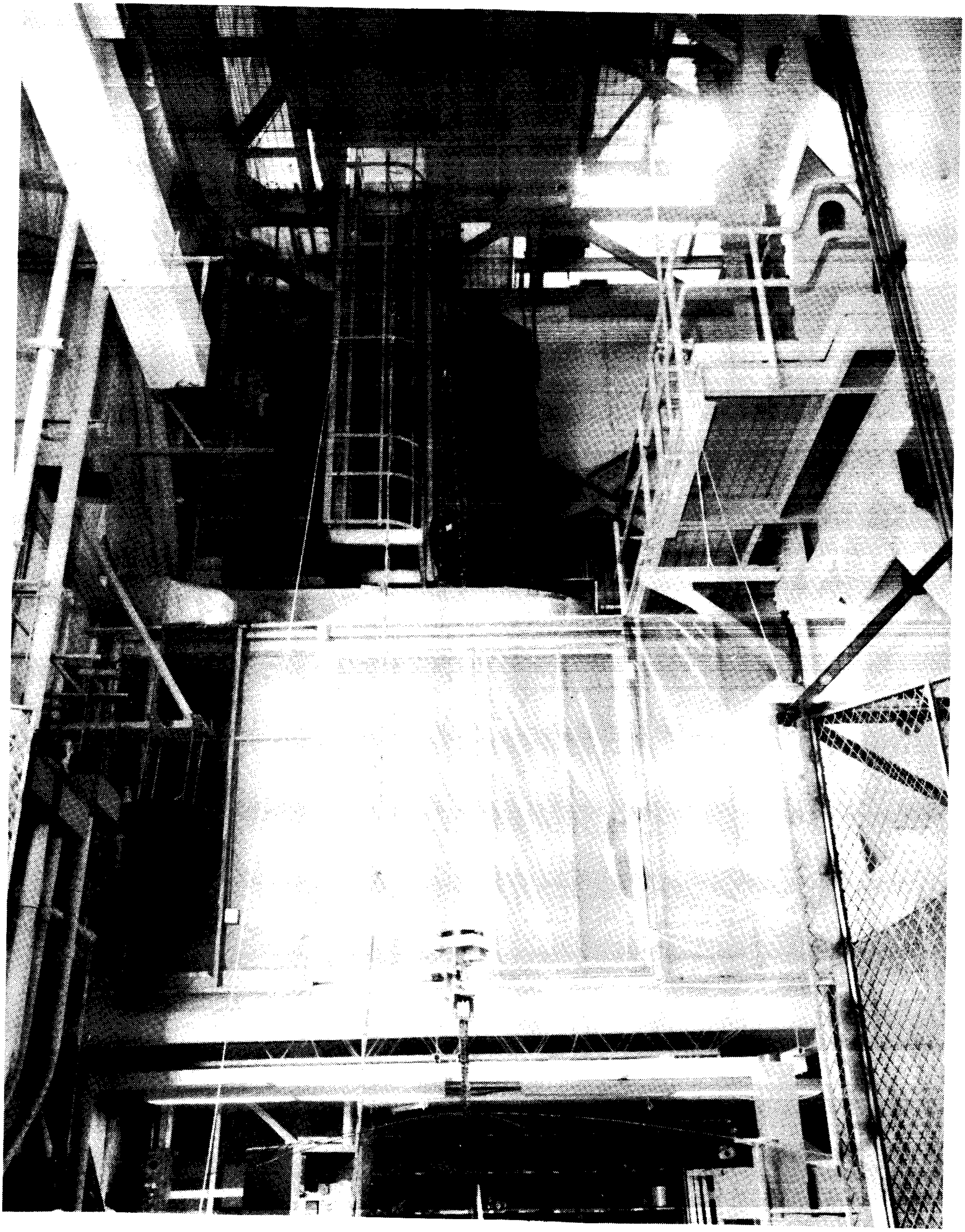
MODE #	FREQ. (Hz)
1–5	0.0 (RIGID BODY)
6	.382
7	1.052
8	1.149
9	1.154
10	1.157
11	1.219
12	1.254
13	1.266
14	1.287
15	1.409
16	2.973
17	3.520
18	3.870

MODES, MODAL, FREQUENCIES FOR COMBINED STRUCTURE

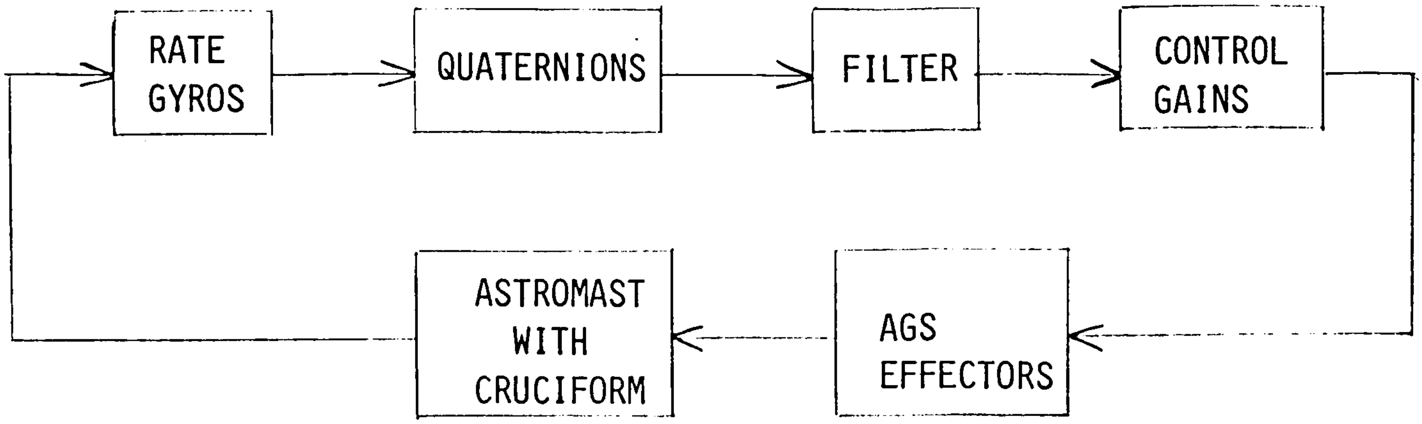
The first test article is a spare Voyager ASTROMAST built by ASTRO Research, Inc. It was supplied to MSFC by the Jet Propulsion Laboratory (JPL). The ASTROMAST is extremely lighweight (about five pounds) and approximately 45 feet in length. It is constructed almost entirely of S-GLASS. It is of the type flown on the Solar Array Flight Experiment-I (SAFE-I).

When fully developed, the ASTROMAST exhibits a longitudinal twist of about 280°. This twist contributes to the coupling between the torsional and bending modes.

As previously stated, the second test article consists of the ASTROMAST with a cruciform attached to the tip. The cruciform structure, which is made of aluminum, weighs eight pounds and is shown on the facing page. The cruciform rods vary in length from 2.00m to 2.15m. They all have constant cross-section of 1/4" X 1/4".



The initial control design for the Ground Facility for Large Space Structures Control Verification (GF/LSSCV) was a centralized control system. The initial centralized control system uses a triad of ATM rate gyros as sensors and the APS as the effectors. The closed loop block diagram is shown in the facing page viewgraph. The quaternions are input to filters which are used to "smooth" the position coordinates and derive a "smooth" rate. The position and rate are multiplied by constant gains to form the effector commands. The effector commands torque the APS gimbals so as to reduce the ATM rate gyro signals in an asymptotic manner. The generic control equations are also shown on the same facing page viewgraph.



$$Z(I+1) = DZ(I) + EQ(I)$$

$$W(I) = GZ(I)$$

$$U(I) = K\ W(I)$$

WHERE Q(I) : 3x1 QUATERNION VECTOR AT THE I^{TH} CYCLE

Z(I) : 6x1 FILTER STATE AT THE I^{TH} CYCLE

W(I) : 6x1 FILTER OUTPUTS

U(I) : 3x1 EFFECTOR COMMANDS

The modal control verification is tabularized on the facing page viewgraph. The table consists of the following: (1) axis (X,Y) see viewgraph 1 for axis identification, (2) open loop test giving modal frequency and damping, (3) analytic closed loop in terms of modal frequency and damping, and (4) closed loop tests which comprise modal frequency and damping.

The open loop test can be compared with the previous modal verification viewgraph. The open loop test was included with the modal control verification to show the amount of damping increase in both the analytical predictions and the actual test results. As can be seen from the table, the control system increases the damping in all of the modes that were tested. These results should not be too surprising. The pleasant results of the table are in the agreements in the analytically closed loop model and the test article. The worst error in frequency is 6.25% at 4.01 Hz and the worst error in damping is 60% at 0.139 Hz. Although the damping error is large, it is in the right direction i.e., more damping than predicted. Typical open and closed loop test plots are shown after the modal control verification table.

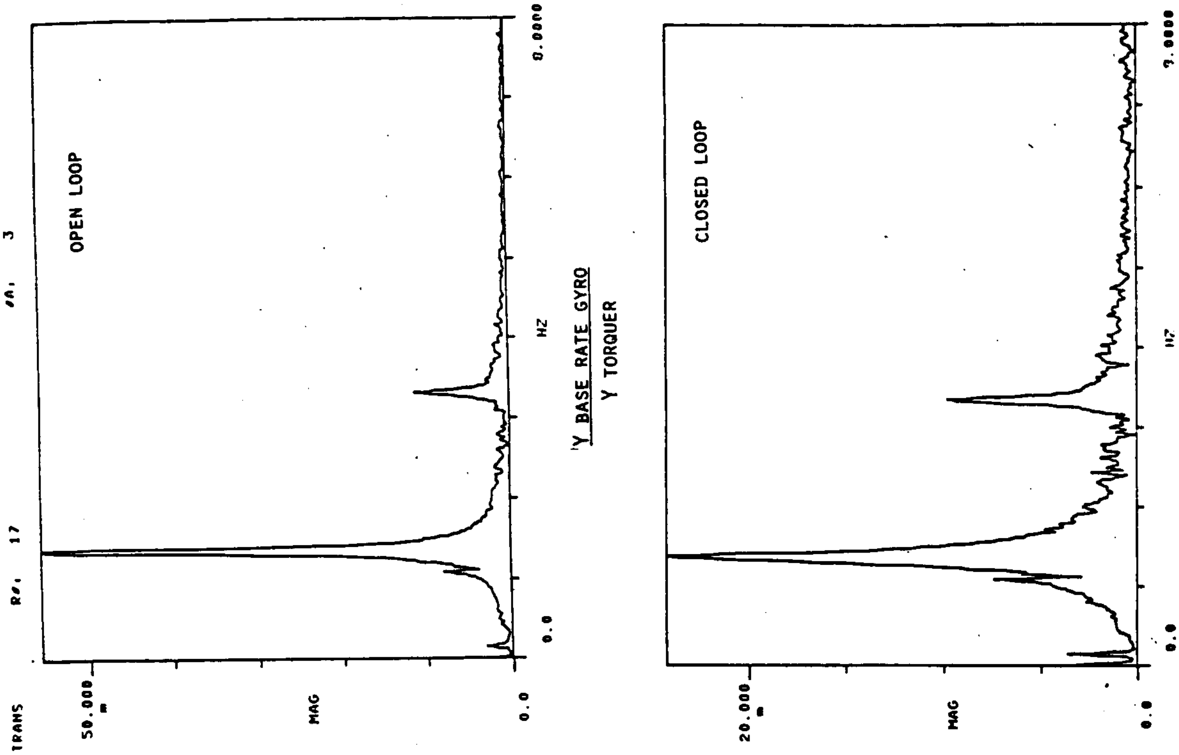
MODAL CONTROL VERIFICATION

AXIS X,Y	OPEN LOOP (T) Hz	OPEN LOOP (T) ζ	CLOSED LOOP (A) Hz	CLOSED LOOP (A) ζ	CLOSED LOOP (T) Hz	CLOSED LOOP (T) ζ
X	0.138	0.0187	0.135	0.023	0.138	0.0567
Y	0.138	0.0187	0.135	0.023	0.138	0.029
X	0.1515	0.041	0.139	0.028	0.1515	0.064
Y	0.1515	0.0167	0.139	0.028	0.1515	0.0567
X	1.33	0.0233	1.38	0.0933	1.6	0.085
Y	1.33	0.0233	1.38	0.0933	1.33	0.11
X	1.66	0.0355	1.85	0.051	1.83	0.085
Y	1.66	0.0258	1.85	0.051	1.739	0.11
Y	3	0.01	3.04	0.096	3	0.045
X	3.75	0.032	4.01	0.066	4.25	0.065

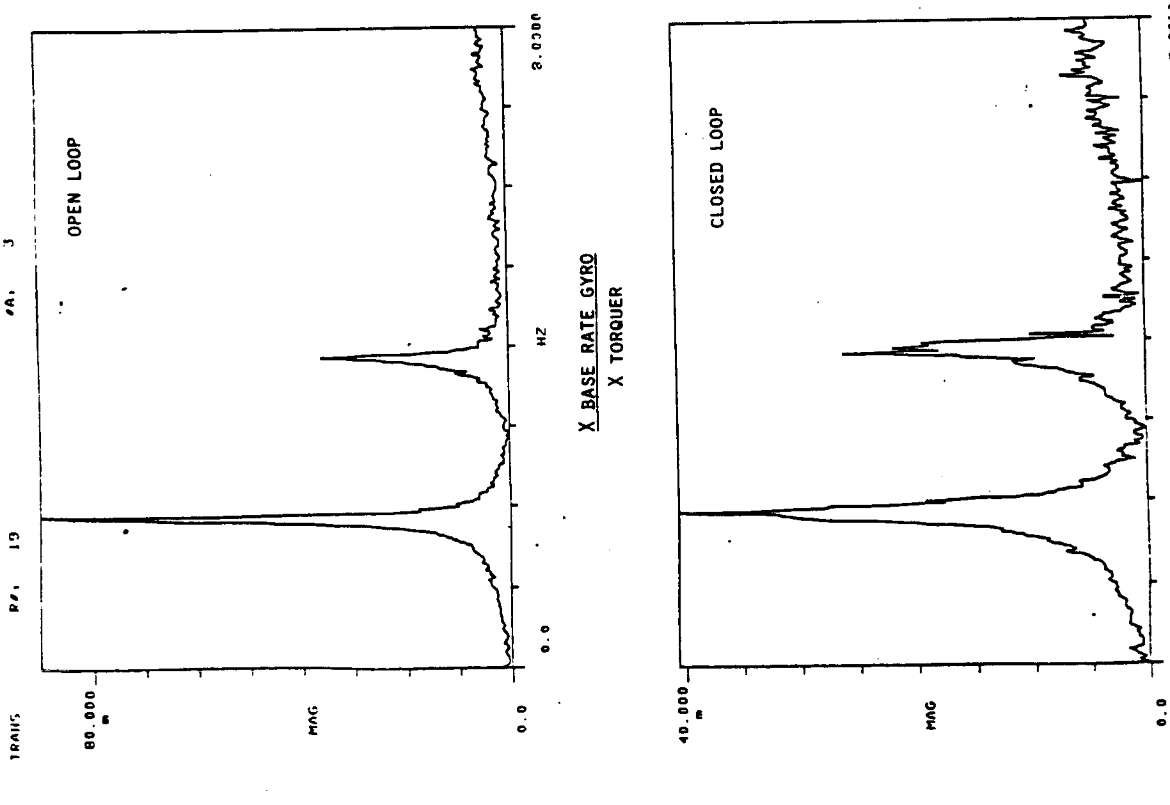
T IMPLIES TEST

A IMPLIES ANALYTIC

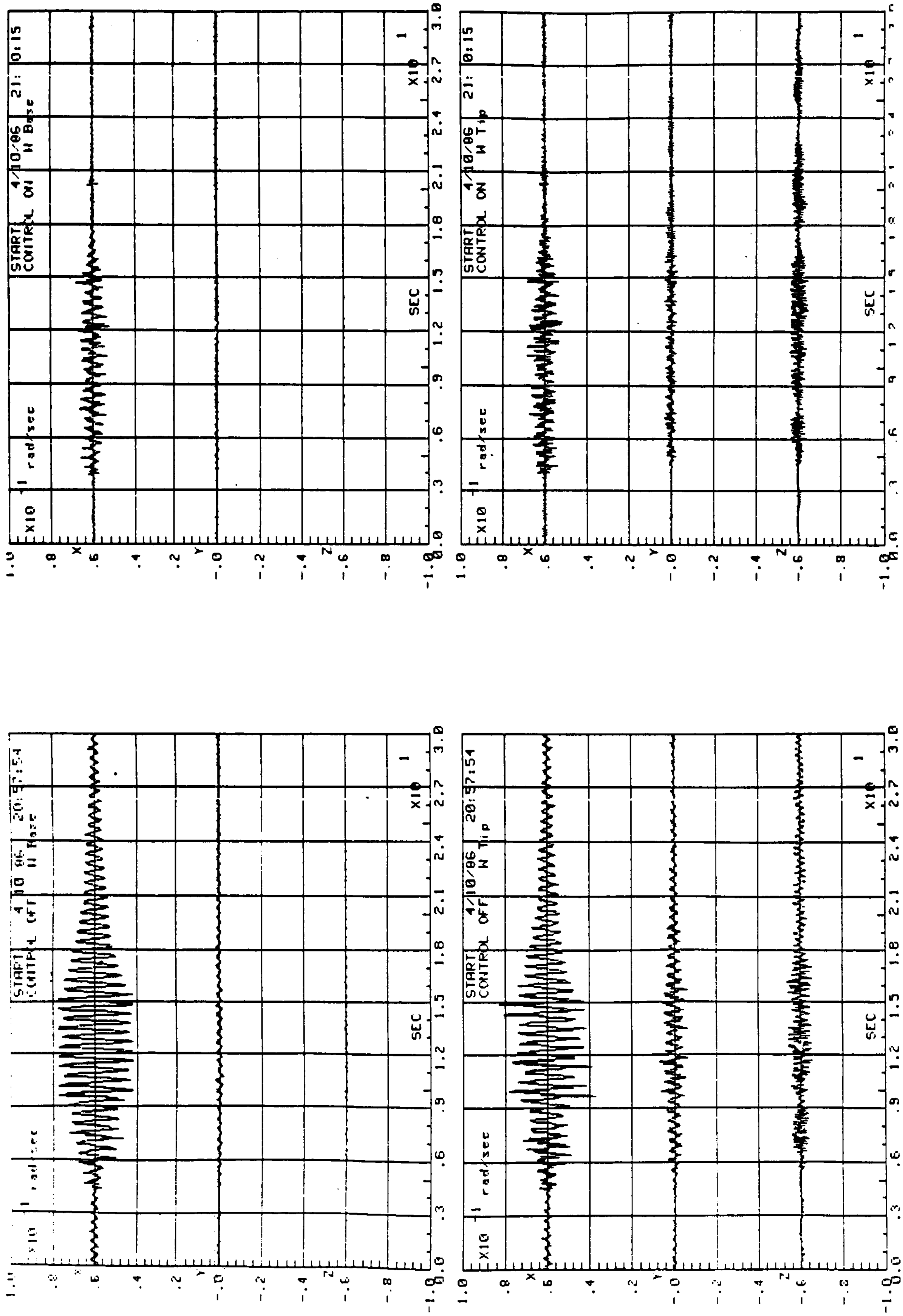
ORIGINAL PAGE IS
OF POOR QUALITY



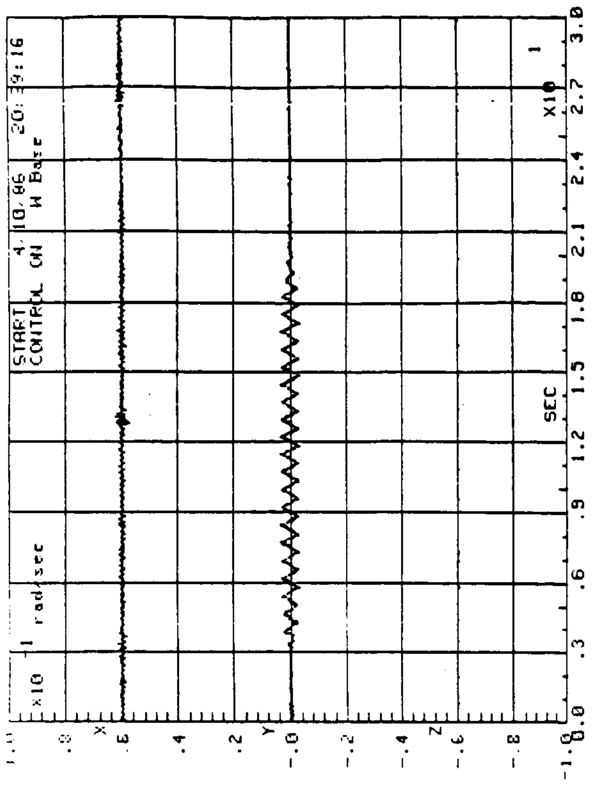
Y BASE RATE GYRO
Y TORQUER

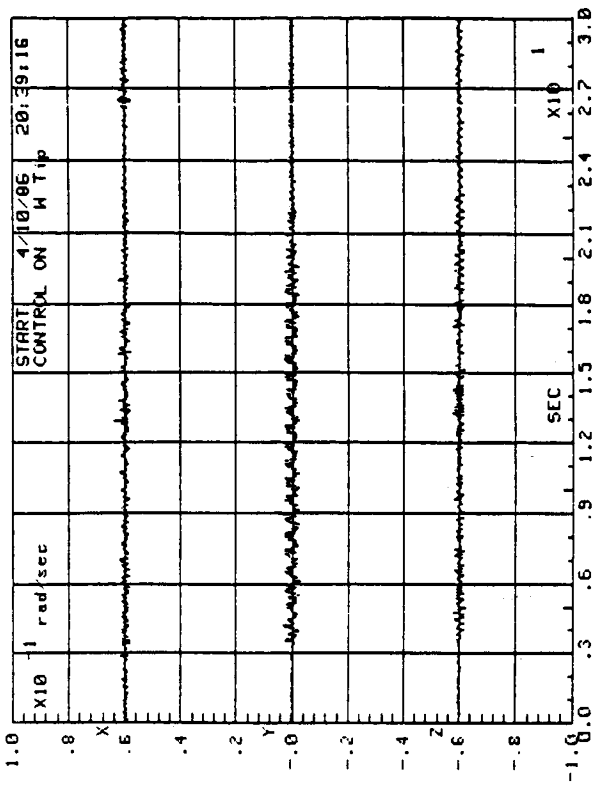


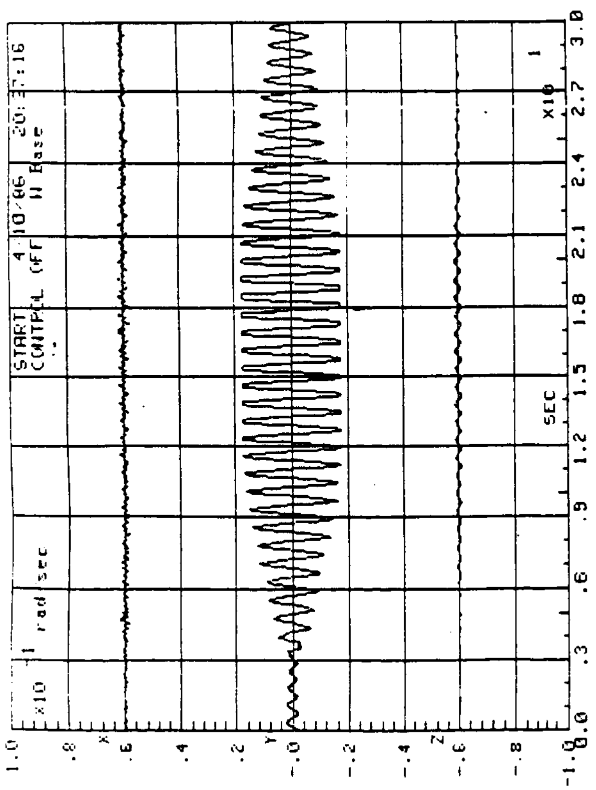
X BASE RATE GYRO
X TORQUER

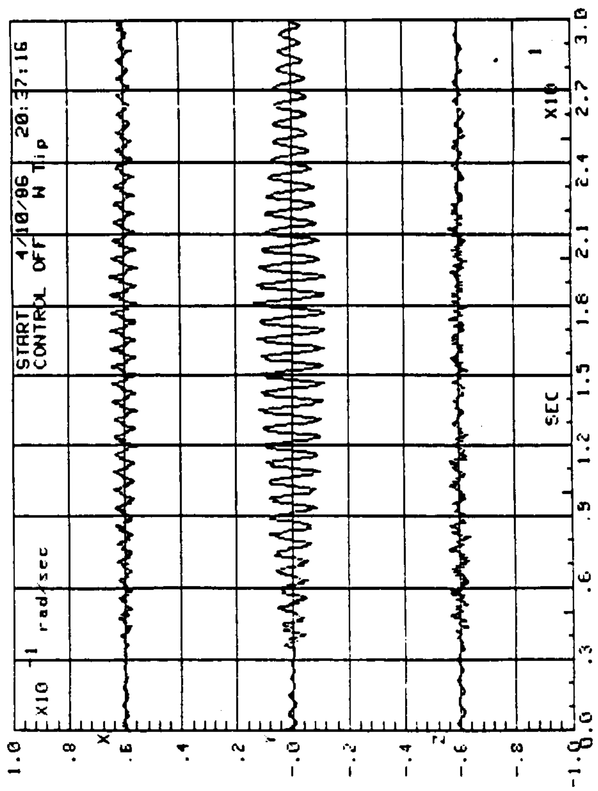

START CONTROL ON 4/10/86 21: 0:15
W Base
X10 -1 rad/sec
SEC
X10 1
START CONTROL ON 4/10/86 21: 0:15
W Tip
X10 -1 rad/sec
SEC
X10 1
START CONTROL OFF 4/10/86 20:57:54
W Base
SEC
X10 1
START CONTROL OFF 4/10/86 20:57:54
W Tip
X10 -1 rad/sec
SEC
X10 1

ORIGINAL PAGE IS
OF POOR QUALITY









A future configuration change will be the addition of a three meter offset antenna to the ASTROMAST tip and an antenna feed located on the payload mounting plate. In addition, the Vibrational Control of Space Structures (VCOSS)-II Linear Momentum Exchange Devices will be placed on the ASTROMAST at two different locations. These additions will facilitate both decentralized and distributive control methodologies. Also, a bi-directional linear thruster system is planned for location at the ASTROMAST tip so that active vibration suppression can be tested using these thrusters. The integration of the previously mentioned LSS/GTV modifications will provide adequate sensors, effectors, and LSS dynamic pathologies so that the test facility can encompass many facets of dynamics and control verification.

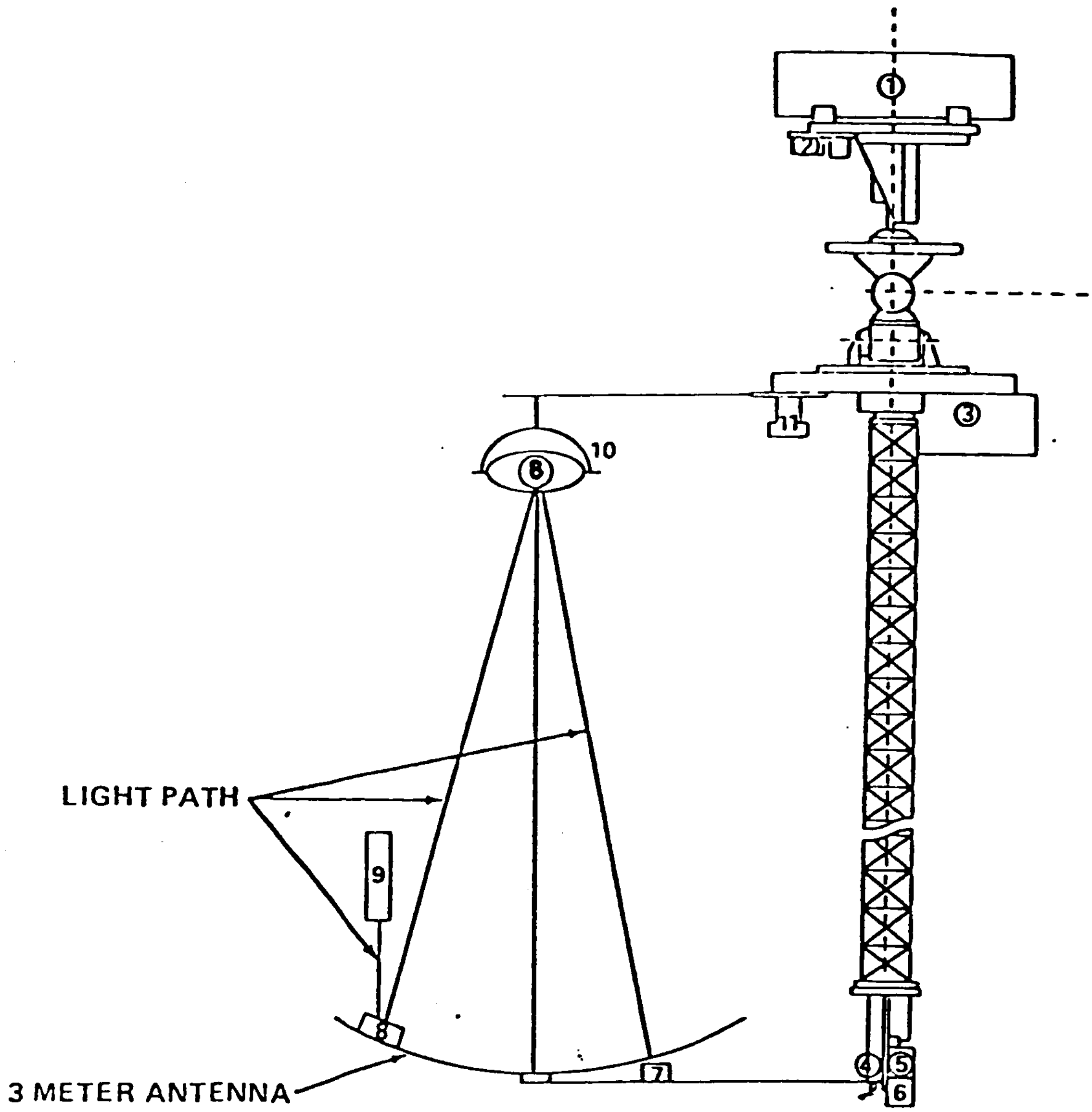


FIGURE FUTURE LSS/GTV SETUP

1. SHAKE TABLE
2. 3 AXIS BASE ACCELEROMETERS
3. 3 AXIS BASE RATE GYROS
4. 3 AXIS TIP RATE GYROS
5. 3 AXIS TIP ACCELEROMETERS
6. BIDIRECTIONAL THRUSTERS
7. OPTICAL DETECTOR
8. REFLECTORS
9. LASER
10. 2 GIMBAL SYSTEM
11. N_2 BOTTLES