WL-TR-92-3030

SPACE TRUSS ZERO GRAVITY DYNAMICS

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March 1993

Final Report for Period March 1989 - February 1990

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
MAR 93

3. REPORT TYPE AND DATES COVERED
FINAL: MAR 89 - FEB 90

4. TITLE AND SUBTITLE
SPACE TRUSS ZERO GRAVITY DYNAMICS

5. FUNDING NUMBERS
PE - 62201F
PR - 2401
TA - 04
WU - 32

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
FLIGHT DYNAMICS DIRECTORATE
WRIGHT LABORATORY (WL/FIBG)
WRIGHT-PATTERSON AFB OH 45433-7006

8. PERFORMING ORGANIZATION REPORT NUMBER
WL-TR-92-3030

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This technical report describes two truss experiments flown on the NASA KC-135 Reduced Gravity Aircraft. The purpose of these experiments was to investigate large space structure dynamics, ground test methods, and passive and active damping. A 2-meter truss was first flown to determine the rigid body dynamics in the aircraft during zero-gravity. The second flight's objective was to measure structural modes of a 12-meter truss, which represented a space structure component. Typically five to ten seconds of zero gravity data were recorded for each parabolic arc. Flight test results are compared with ground testing in which a low restraint spring mechanism was used to suspend the truss. Good correlation between ground and flight test results was achieved; the major differences were caused by suspension system friction, which coupled the frame modes with the bending and torsion modes.

14. SUBJECT TERMS
Zero Gravity, Rigid Body Dynamics, KC-135, Flexible Structures
Vibration, Damping

15. NUMBER OF PAGES
50

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT
UNCLASSIFIED

FOREWORD

This technical report describes the work performed by the Wright Laboratory, Flight Dynamics Directorate, Structures Division, Structural Dynamics Branch. Under the in-house Large Space Structure Technology Program (JON 24010432), two experiments were flown on the NASA KC-135 Reduced Gravity aircraft. The first set of experiments was flown on 20-21 March 1989, and the second set of experiments was flown on 1-2 February 1990. The Wright Laboratory flight test engineers were Captain Andrew Swanson, Wayne Yuen, Captain Jim Williams, and Lieutenant John Mackaman. Mike Banford, Gene Maddux, and Dave Banaszak provided instrumentation and field testing support. Joseph Hollkamp, Capt Swanson, Larry Dukate, and Dansen Brown performed data analyses. The authors would also like to acknowledge Bob Williams and Linda White from the NASA Reduced Gravity Office for their support in making the flight test feasible, and Gun-Shing Chen and Cassandra Lawrence from the Jet Propulsion Laboratory for their participation and contribution in the active control study performed on the second flight test.

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INTRODUCTION

The Structural Dynamics Branch of Wright Laboratory's Flight Dynamics Directorate conducted a series of zero-gravity dynamic tests in support of the in-house Large Space Structures Technology Program. These tests were conducted to study the dynamics of a truss beam in a zero-gravity environment. The NASA Lyndon B. Johnson Space Center (JSC) Reduced Gravity Office cooperated with the Air Force in conducting these tests. This report describes the program and presents all test results.

BACKGROUND AND OBJECTIVES

Space system missions using large radar and optical devices are leading towards larger spacecraft with more stringent requirements for line-of-sight and shape control. The high cost of transporting material into orbit causes large space structures to be lightweight, flexible, and lightly damped. The structural vibration control problem thus becomes a critical challenge. For active control of these structures, system modeling and modal parameter identification are very important, and error reduction is critical. The earth's gravity environment poses an additional problem to the control system designer by thwarting his attempts at pre-flight system validation tests. All methods of supporting or suspending a space structure for ground test alter its dynamic behavior to some degree. The Flight Dynamics Directorate's in-house Large Space Structures Technology Program (LSSTP) is currently investigating methods for ground test and analysis of large space structures to predict on-orbit dynamic behavior.

The Air Force fabricated two twelve-meter truss structures for analysis, modal characterization, and control studies. Damping was incorporated into one truss using visco-elastic material in the diagonal members. The second truss had diagonal members made from Lexan, which has low damping. With both trusses being identical except for the diagonal members, the effects of damping on structural parameters were distinct. LSSTP engineers tested these trusses in a cantilevered and a simulated free-free condition (see Figure 1) [1]. In addition to the damping research, the Structural Dynamics Branch has been studying different free-free ground suspension methods because of the uncertainties in how much a suspension system contributes to a flexible structure's dynamics. To resolve part of this uncertainty, branch engineers formulated a reduced gravity flight test program. The reduced gravity aircraft of the NASA Johnson Space Center provides a suitable environment for testing a twelve-meter truss in zero gravity. The primary aim of the test is to determine the effects the LSSTP ground suspension system has on this structure. A secondary objective is to evaluate NASA's aircraft for the testing of other large space structures. The undamped truss was used in the flight test.

The California Institute of Technology Jet Propulsion Laboratory (JPL) has similar objectives in large space structure control studies. Its work has focused mainly on active vibration control, and JPL engineers have been experimenting with a new type of piezoelectric actuator for force input. Because Structural Dynamics Branch and JPL were working in similar fields, both organizations were aware of each other's projects. JPL engineers realized that the twelve-meter truss was a good test structure for testing their new actuator, and proposed to incorporate their actuator in our flight test. JPL developed these active member actuators to replace two truss diagonals for open and closed loop control tests during the flights. JPL's objective was to actively control the torsion modes (as these were mainly affected by force input through the diagonal members). These active members consisted of piezoelectric actuators, eddy-current differential proximity sensors, and load cells. A more detailed discussion of the bridge (compound) feedback controller they used can be found in [2].

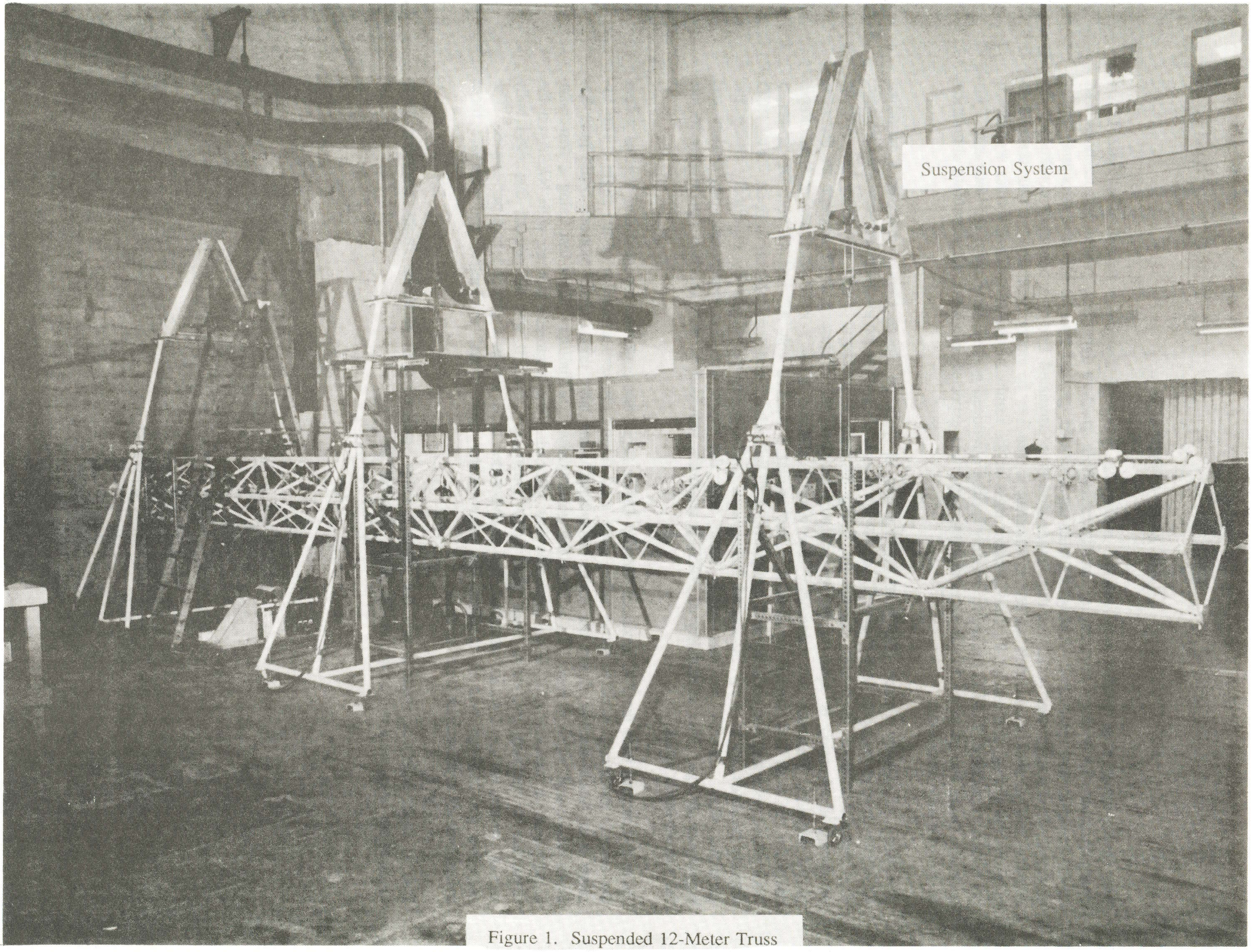

Figure 1. Suspended 12-Meter Truss

PLAN AND APPROACH

The twelve-meter truss project was initiated under the Structural Dynamics Branch's in-house Large Space Structure Technology Program to investigate flexible structure dynamics, ground test methods, and modal identification techniques. Using the truss as a testbed, ground tests to measure structural modal parameters were performed with the truss suspended in a simulated free-free boundary condition. To evaluate the ground suspension's ability to simulate a free-free boundary condition, it was planned to compare the ground test results for the 12-meter truss to the results measured while the truss was flown on NASA's modified KC-135 transport, which provides a reduced gravity (near zero) environment. This approach using the transport for flight testing the truss was expected to give a very accurate simulation of the free-free condition.

The Reduced Gravity Office (RGO) of the Lyndon B. Johnson Space Center operates a modified KC-135A turbojet transport (see Figure 2) to provide a reduced gravity environment for research projects. The aircraft achieves near-zero gravity by flying through a parabolic flight trajectory so that its downward acceleration is equal to the gravitational acceleration. Figure 3, a photograph of the nose of the KC-135, illustrates the trajectory. The aircraft offers a 60 x 7 x 10 foot test section, ample room for the truss and support equipment. Also available are 110 volt AC and 48 volt DC power, a floor attachment grid for securing test equipment, and audiovisual and test engineer support. The RGO aircraft provides up to forty 30-second intervals of zero gravity per flight by repeatedly flying the parabolic arcs. NASA provides ample room near the flight line for experiment preparation and equipment storage. The availability of NASA's resources provided us with the best opportunity to test the twelve-meter truss.

Early discussions with the JSC Reduced Gravity Office flight test engineers revealed that articles within the aircraft test-section tend to move about quite a bit during the zero-g portion of the flight. The 12-meter truss would occupy almost the entire cabin length, and large unrestrained motions could pose test performance and safety issues. To address this uncertainty, a preliminary flight test using a two-meter plastic truss to measure rigid body dynamics was planned. The engineers worked with NASA on the flight test to measure two-meter truss rigid body dynamics. Once it was determined that rigid body motion would not be a major problem, the twelve-meter truss test was planned and performed. The objective for this test was to measure the twelve-meter truss modal parameters and compare these measurements with ground test results.

Due to flight safety regulations and the physical stress involved with parabolic flight, engineers were required to have an Air Force class-III flight physical [3].

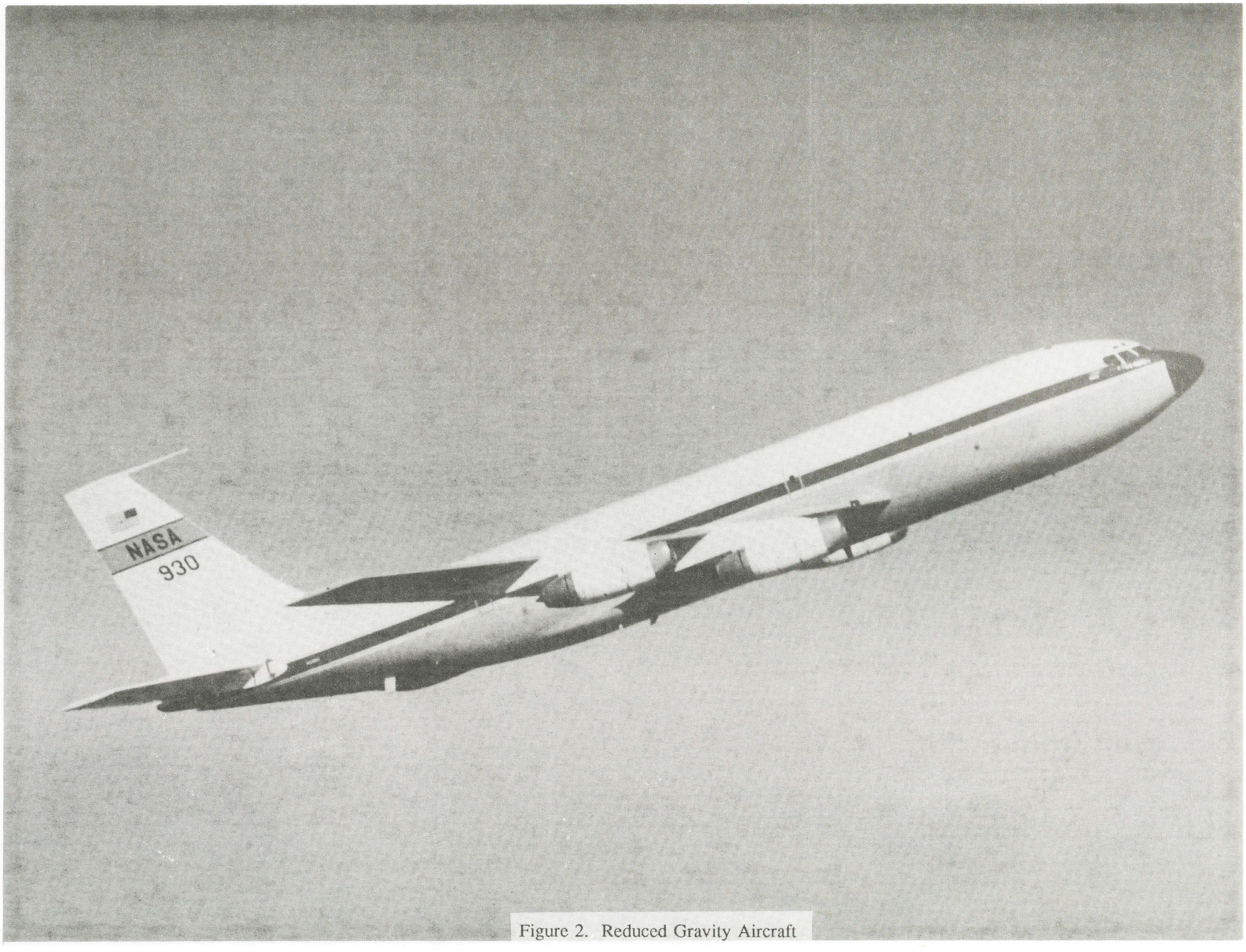

Figure 2. Reduced Gravity Aircraft

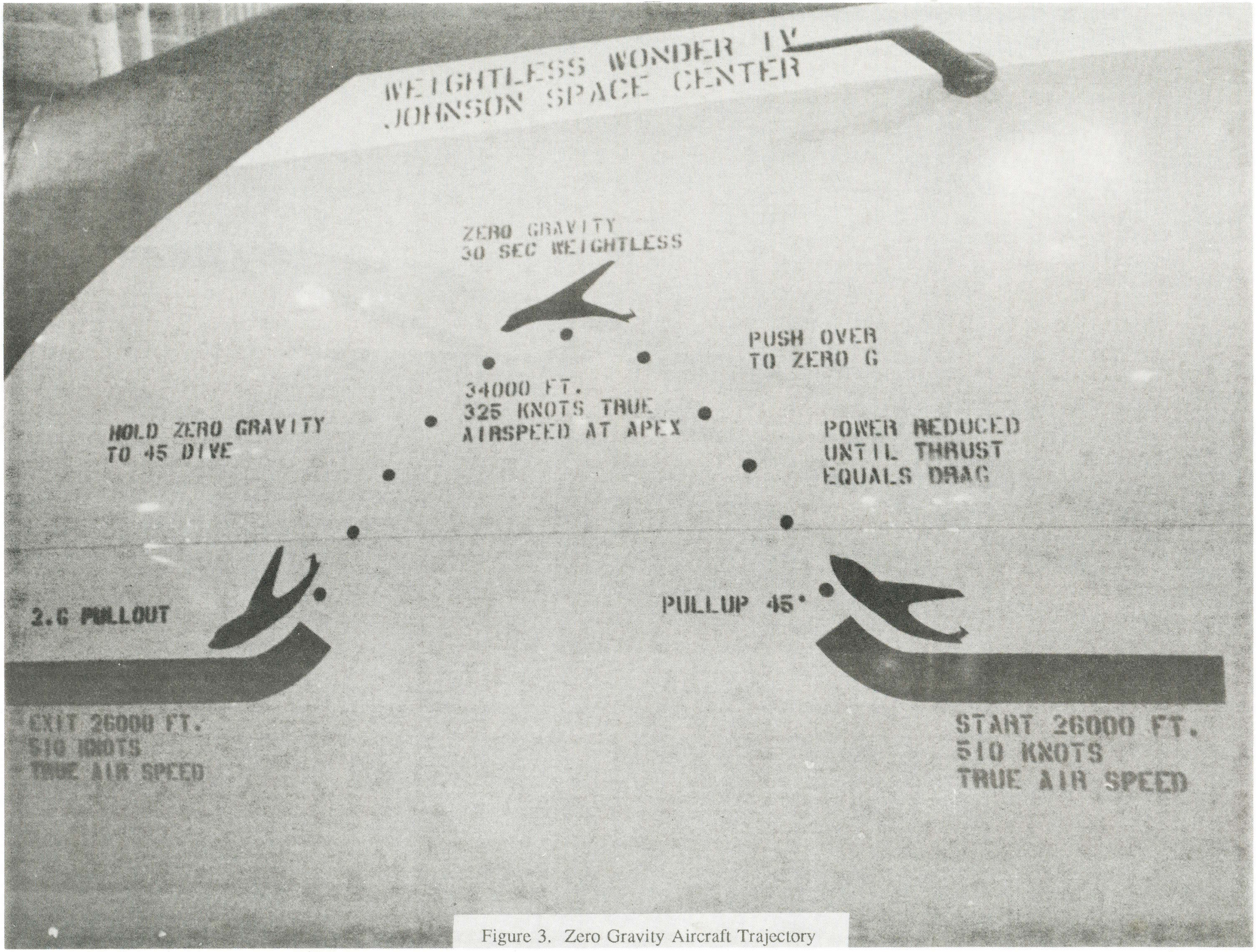

Figure 3. Zero Gravity Aircraft Trajectory

TWO-METER TRUSS FLIGHT TEST

Several characteristics of the aircraft and its trajectory cause test articles to have an apparent motion with respect to the test section. The Structural Dynamics Branch designed the two-meter truss test to determine how a test article behaves on the aircraft. Excessive motion reduces the amount of truss response, measurement time and changes dynamic response since any impact with aircraft walls adds excitation energy to the structure. A secondary objective was to determine what special test equipment and procedures are necessary to test a twelve-meter structure in such an environment.

Rigid Body Dynamic Analysis

Dynamic equations to predict truss motion in the aircraft were developed before the test. The aircraft motion and the relative position of the truss and aircraft at release determined the truss motion with respect to the aircraft fuselage. During the zero-g portion of each parabola, the aircraft pitches downward at a constant rate of three degrees per second. With the truss cg initially at an arbitrary location in the aircraft and a certain distance from the aircraft cg, the equation of motion was developed. When the truss is released during this pitch-down maneuver, it also has the same angular velocity (ω) as the aircraft.

The following analysis was done to calculate truss translational motion (relative to the aircraft cg) after it was released during the constant pitch rate maneuver. With the truss cg about 8 inches above the floor and the aircraft cg 5 inches above the floor, the two cg's could not be physically collocated. This cg offset would result in relative motion between the truss and aircraft, which reduces zero-gravity test time during a parabolic maneuver. In an inertial reference frame, the truss translational velocity can be represented by $V = \omega r_{cg}$, where ω is the aircraft rotation rate and r_{cg} is the distance between the two cgs at release. At any instant, the truss velocity component that is perpendicular to the aircraft floor is :

$$V_y = \omega r_{cg} \sin(b) \qquad (1)$$

where b is the angle between the velocity vector and the aircraft floor (see Figure 4). Likewise, the velocity component parallel to the floor is :

$$V_x = \omega r_{cg} \cos(b) \qquad (2)$$

The relative velocity between the truss and aircraft floor is calculated by subtracting the aircraft rotational velocity from the truss velocity, giving the two relative velocity components:

$$V_{x_{rel}} = \omega r_{cg} \cos(b) - \omega y \qquad (3)$$

$$V_{y_{rel}} = \omega r_{cg} \sin(b) - \omega x \qquad (4)$$

where x and y represent instantaneous longitudinal and vertical distances between aircraft and truss cg's. The relative motion of the truss due to the cg offset is dependent on the initial position, as shown in Figure 5. Each curve begins at y = 25 inches and includes 25 data points, with one second between

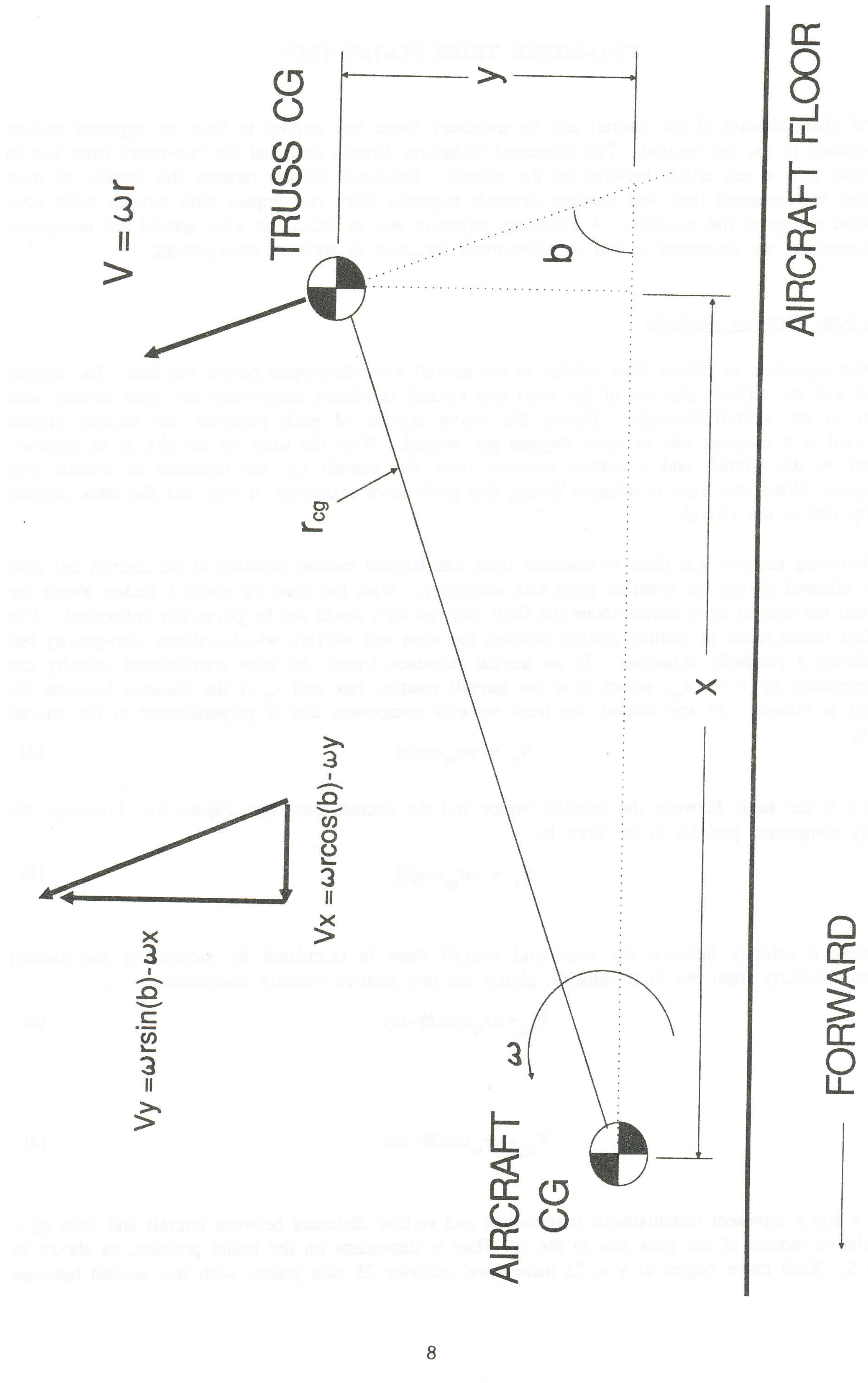

Figure 4. Truss Translation due to cg offset

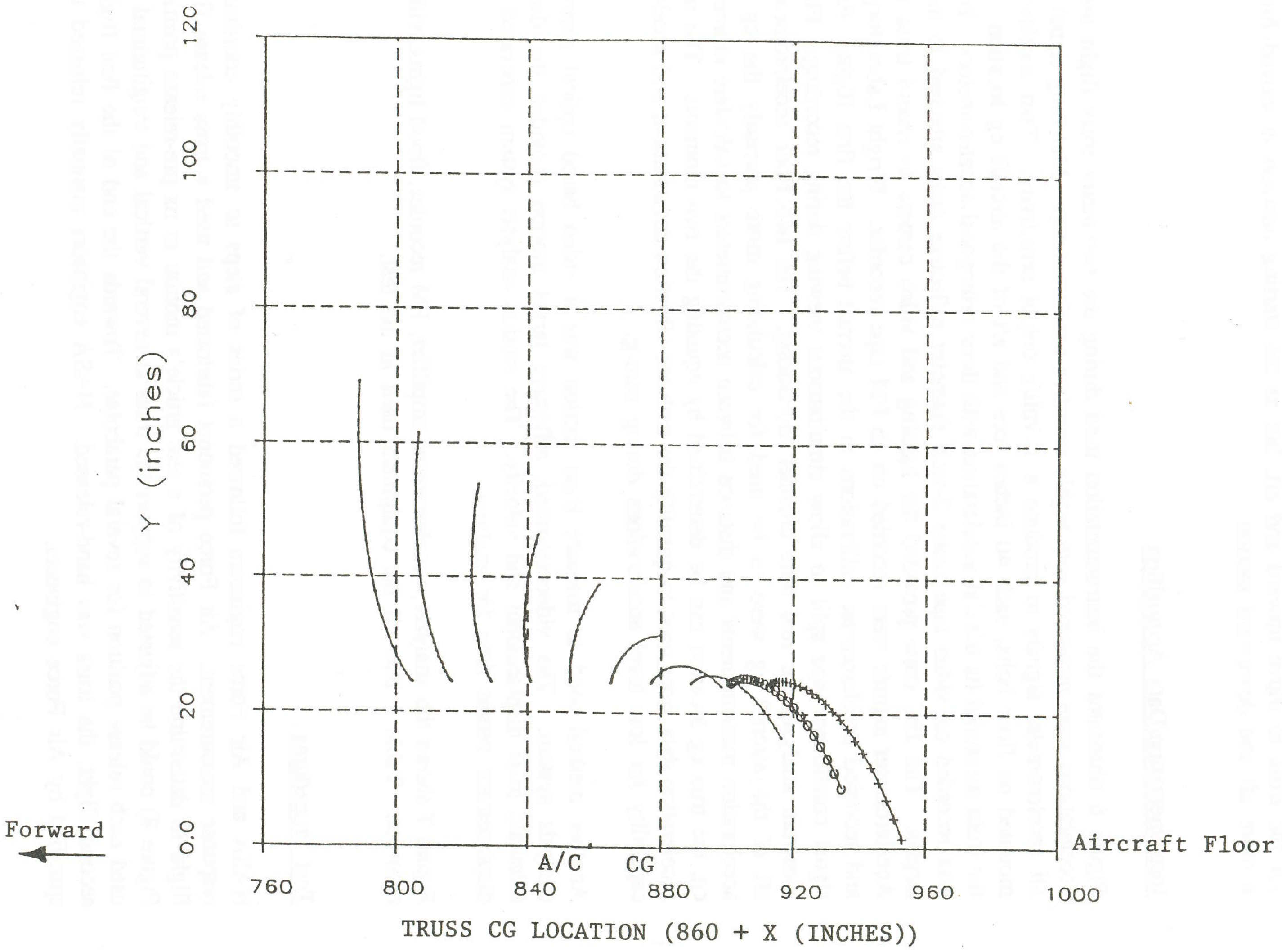

Figure 5. Truss Translation Versus Time

data points. The curves are generated as follows. At each time step, a new truss position (x and y) is calculated as the old position plus the distance travelled in one second. This distance is calculated as the instantaneous relative velocity multiplied by the elapsed time of one second (i.e., relative velocity is assumed to be constant over the time step). As shown, the truss generally moves in an upward and then aft direction relative to the aircraft cg. Based on the plot in Figure 5, the most desirable start position is to have the truss cg at 860 inches aft of the aircraft nose. This is also the aircraft longitudinal cg location. The relative vertical and longitudinal motion in the aircraft is minimized at this starting location, and at least 25 seconds of zero-gravity time can be achieved. The truss tends to move more rapidly upward toward the aircraft ceiling as the start position is moved forward and away from the aircraft cg. When the truss is released aft of the aircraft cg, there is initially a tendency for the truss to move upward and aft, but as the starting position is moved further aft, the truss has a more aft and downward motion.

Instrumentation/Data Acquisition

Figure 6 illustrates the instrumentation used during the two-meter truss flight test. Truss and aircraft accelerations were measured with highly sensitive accelerometers. Matching signal conditioners amplified all accelerometer signals to produce a 1 volt/g output sensitivity. Two accelerometers were hot-glue mounted on floor bolts, each 40 inches fore and aft of the aircraft cg location. Two blocks glued to the truss measured its triaxial acceleration with three orthogonal accelerometers. Truss rigid-body motion was recorded on video tape using 2-inch diameter reflective disks attached to the truss as illuminated targets. The JSC crew provided the lighting and video camera to record truss motion during zero-g. Accelerometer signals were recorded on an FM tape recorder. Wright Laboratory personnel performed and recorded accelerometer calibrations in the aircraft before the first flight. Each channel from the signal conditioner was split to allow simultaneous viewing during recording. Flight engineers used a spectrum analyzer for real time channel monitoring. The two floor accelerometers mounted fore and aft of the aircraft cg were to be used for calculating more precisely the cg location. Using the acceleration measurements and distance between accelerometers to calculate moments about an assumed cg, the true cg location can be determined by equating the two moments. The truss and aircraft floor acceleration data were used to quantify the ambient vibration environment and accelerometer measurement capability for low level accelerations during zero-g.

Another method used to measure truss motion was a video based optical system called the motion analysis system. The video-recorded, reflective target motion provided the data for the system to calculate truss displacement and velocity. The motion analysis system generated plots of velocity and displacement versus time for analysis.

Figure 7 shows the analyzer, accelerometer amplifier, FM recorder, flood lights, video camera, and video recorder. Table 1 lists all the equipment used in the test.

Test Procedures

NASA and Air Force engineers followed a series of steps to smoothly coordinate truss release and response measurement. Air Force personnel fabricated and used a truss release fixture during the first flight to determine the sensitivity of a test article's motion to its pre-release position. The fixture (see Figure 8) could be adjusted to support the truss at several vertical and longitudinal locations. Engineers used each release position for several parabolas. Towards the end of the first flight, and for the entire second flight, the truss was hand-released. NASA engineers manually released the truss at locations specified by Air Force engineers.

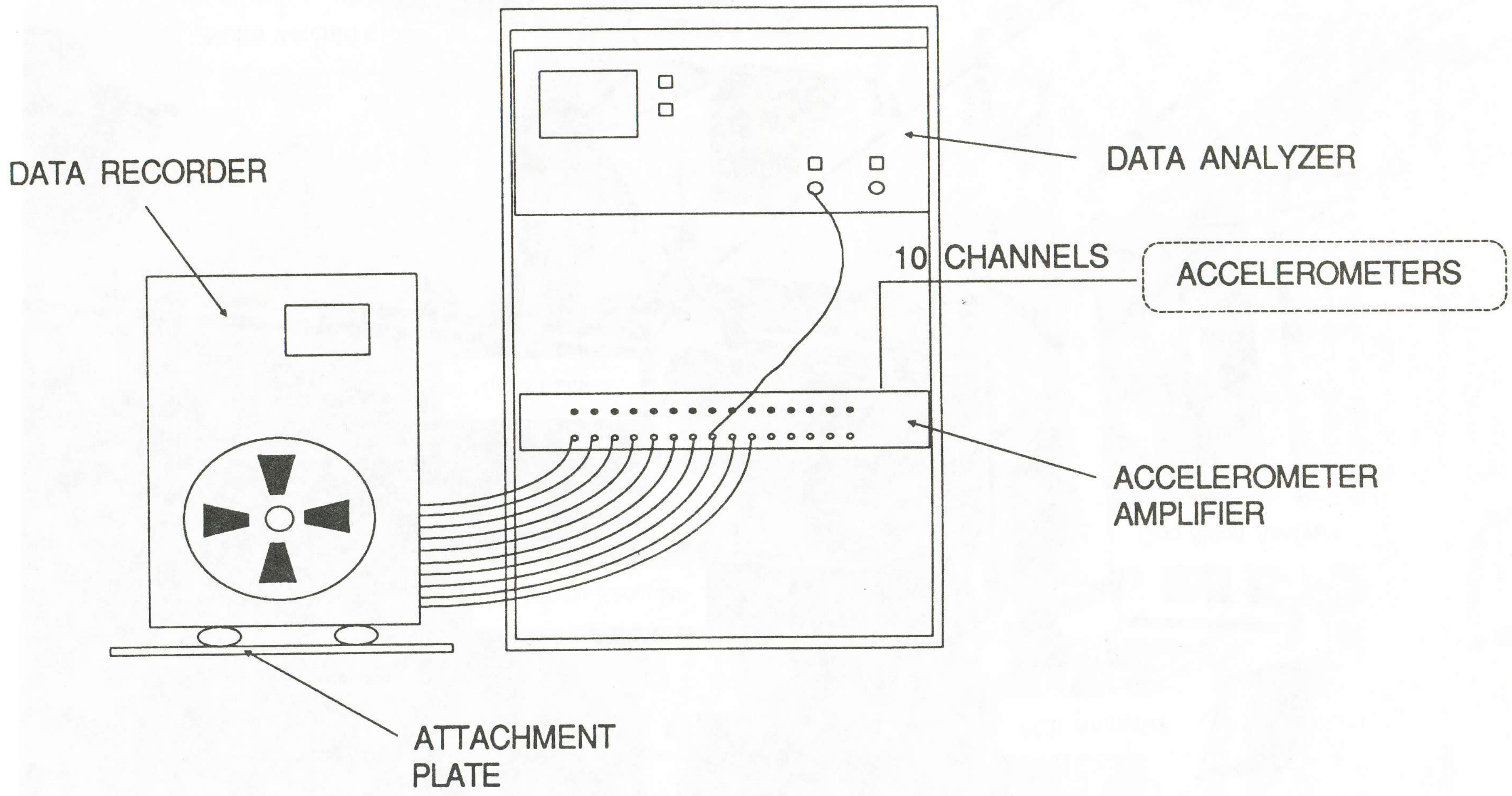

Figure 6. Two-Meter Truss Test Equipment Diagram

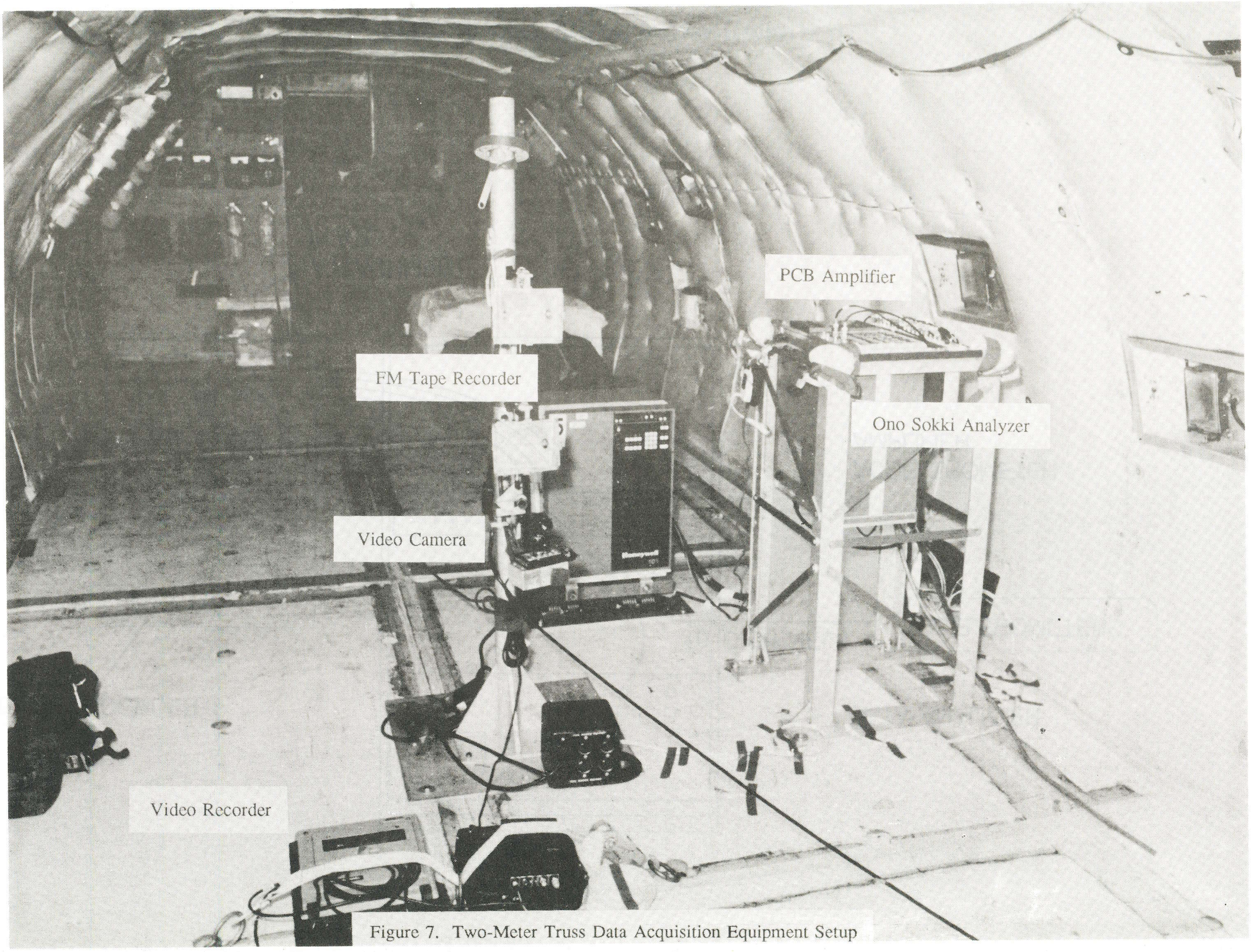

Figure 7. Two-Meter Truss Data Acquisition Equipment Setup

Table 1. Two-Meter Truss Flight Test Equipment List

ITEM #	DESCRIPTION	WEIGHT (lb)
1.	78 x 11.5 x 11.5 inch truss & accelerometers	40.0
2.	Truss support fixture	20.0
3.	Honeywell 101 recorder	120.0
4.	Ono Sokki FFT analyzer	50.0
5.	Four PCB accelerometers	0.3
6.	Two triaxial accelerometer blocks	0.5
7.	PCB amplifier	4.0
8.	Accelerometer cables	5.0
9.	VHS video cameras (2)	10.0
10.	Still camera	5.0
11.	Electronic equipment rack	30.0
12.	Headset intercom (2)	4.0
	TOTAL	288.8

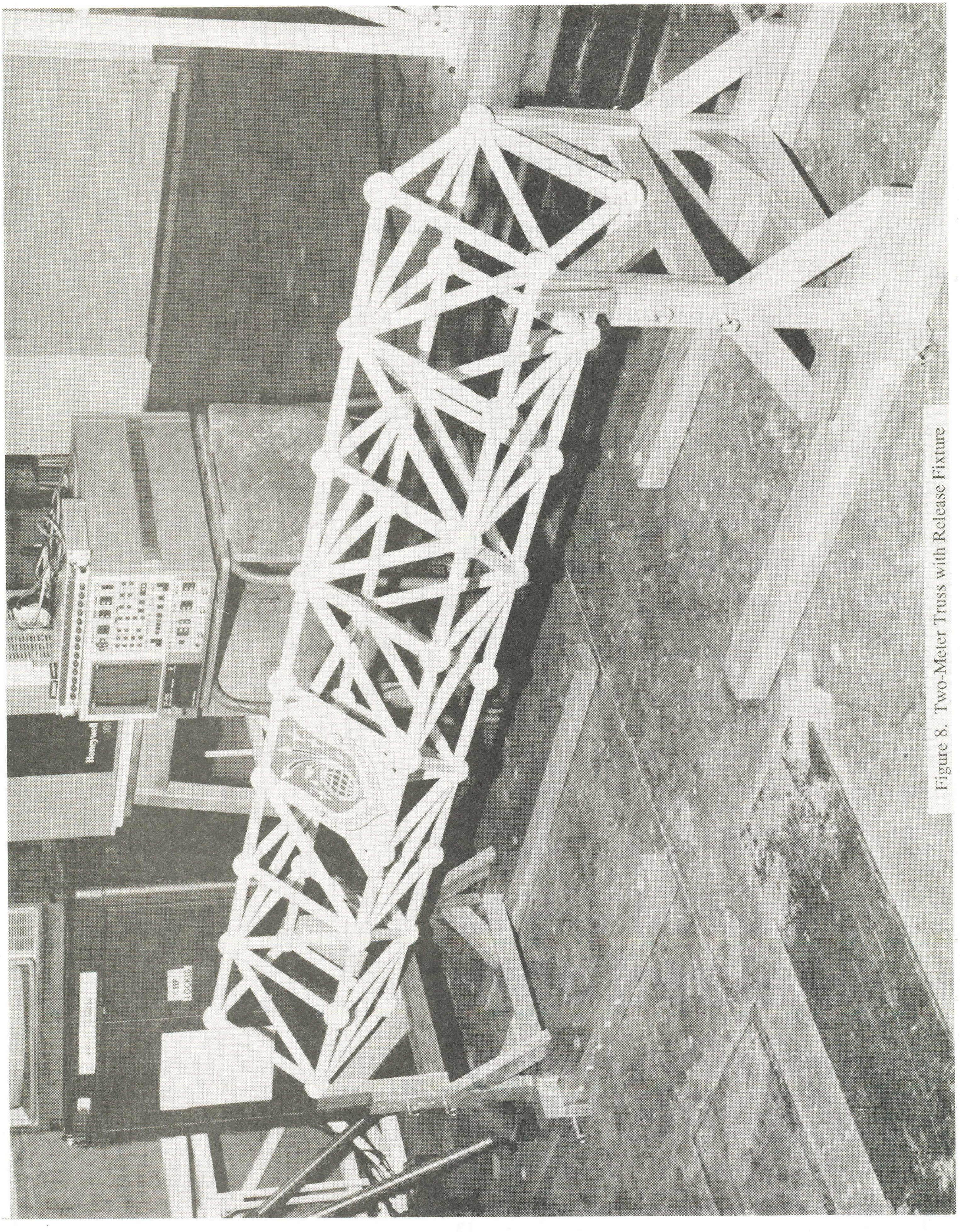

Figure 8. Two-Meter Truss with Release Fixture

Following takeoff, the truss and fixture were untied and raised into test position. The data recorders and analysis equipment were powered up and configured for testing, and it was verified that all equipment was operational. The accelerometers were verified to be securely fastened. The video camera was proven operational, focused, and the aperture was set. The test-crew/pilot intercom was checked. The truss cg was positioned at the prescribed distance from the aircraft cg. Approximately twenty seconds before zero-g onset, the data recorders and video camera were turned on. Once the three-degree-per-second pitch rate, zero-g condition was achieved, the truss was released from the fixture. The completion of this step was acknowledged verbally on tape. Vibration levels were monitored with the FFT analyzer. At the completion of the zero-g phase or when the truss struck the aircraft, voice annotations were made on tape at the time of impact or recovery. The truss was recovered and secured on the fixture. For the next parabola, the truss was positioned at a predetermined distance from the aircraft cg and the remaining steps were repeated. The truss was repositioned after each parabola. Following the last parabola, the truss was recovered and secured to the floor with cargo straps. The data recorder and analysis equipment were turned off.

Test Results

The two-meter truss tests were performed on 20 and 21 March 1989. Forty parabolas were flown on the first day and 20 on the second. The test was very helpful for assessing the amount and nature of travel to expect from the twelve-meter truss test. The small truss did not move in a predictable manner, as trajectory variations and cross winds were more of an influence than the cg offset. Free-float times were typically six to twelve seconds before the truss encountered a wall, floor or ceiling. Figure 9 shows the motion of the reflective targets mounted to the truss and aircraft floor as determined by the motion analysis system during a typical parabola. Curves 1, 3, and 4 are for the front end of the truss, curves 2 and 7 for the rear, and 5 and 6 are for the reflectors mounted on the floor. As shown by these curves, the truss did not always move in an upward direction. The release fixture would sometimes impede its motion. Manual release appeared to be the better method. For the second flight, the flight crew removed the fixture and used the intercom to inform the pilot of truss motions. The pilot compensated for flight path deviations by flying the aircraft such that the truss would stay centered in the cabin as much as possible. This resulted in longer float times. Since the truss accelerations appeared to be random and did not even grossly follow the analyses, the motion analysis system was not used to compare actual with predicted motion. A combination of external forces (crosswinds) and pilot control input to keep the truss centered affected the relative motion between the truss and aircraft, which resulted in the truss having a random trajectory. The system did provide the truss's average linear acceleration of .01 g's. Any spring device that might be used to keep the 230 lb 12-meter truss in the center of the test section would therefore need only impart, on the average, two pounds of force (.01 x 230lb). Acceleration data from the two-meter truss and aircraft floor provided a good record of aircraft ambient noise, but were not accurate enough to determine aircraft cg location or truss rigid body motion. The type of accelerometers used were not sensitive enough to measure the near zero-gravity experienced during the test. Figure 10 shows a typical truss response plot illustrating the inaccuracy in acceleration measurement.

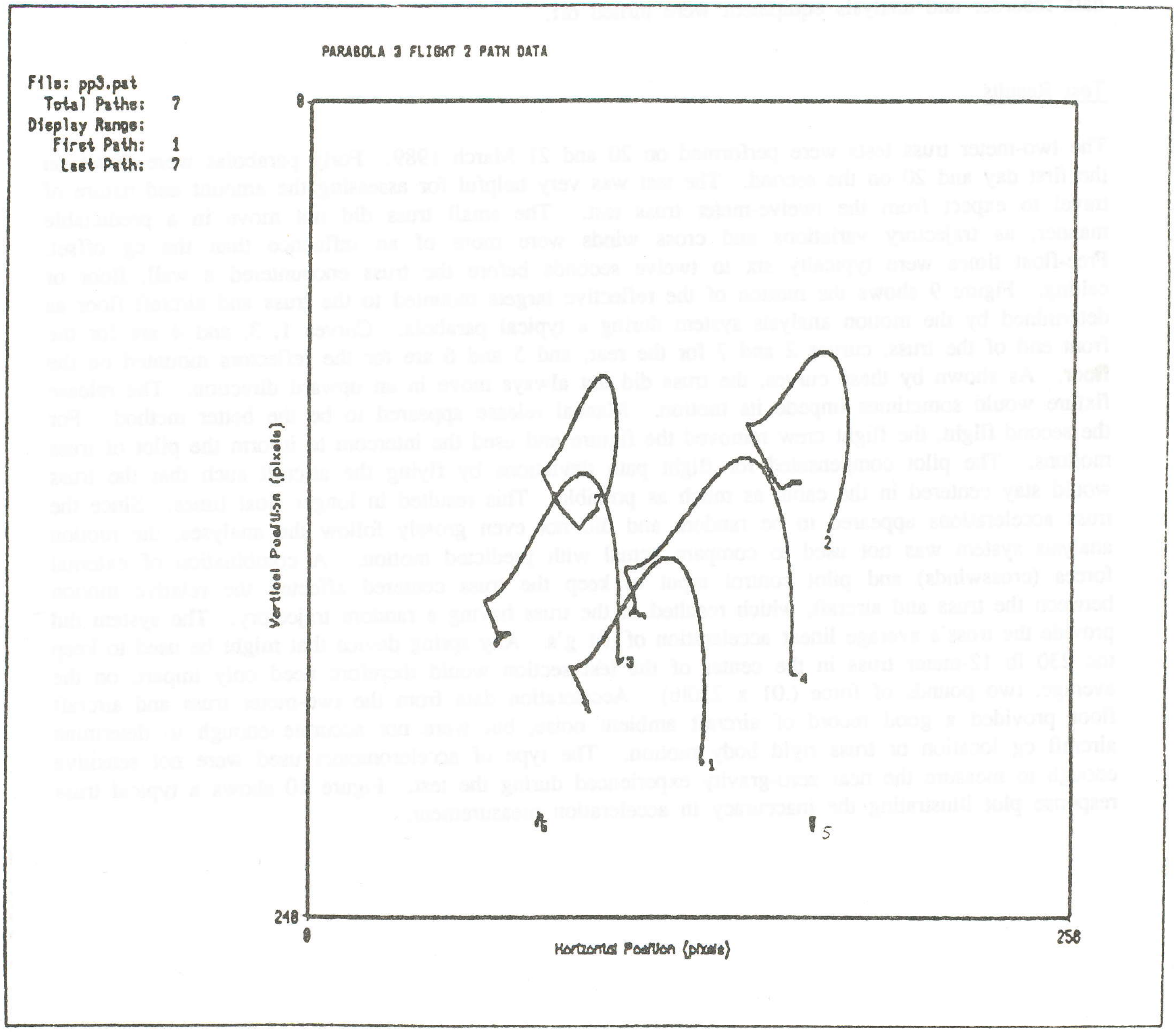

Figure 9. Two-Meter Truss Motion

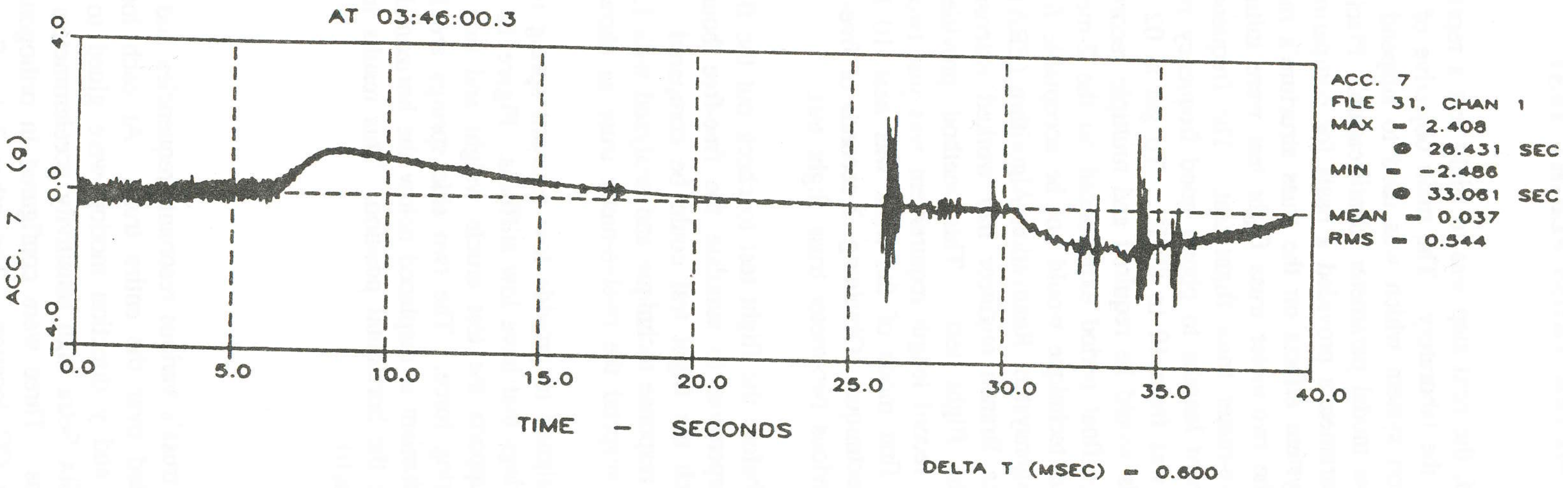

Figure 10. Truss Accelerometer Respons

TWELVE-METER TRUSS FLIGHT TEST

With the two-meter truss test completed, the next step was to flight test a representative space structure that had been studied on the ground in the laboratory. The main objective of the 12-meter truss flight test was to evaluate a ground suspension system which was used to suspend the truss in a simulated free-free boundary condition during truss modal parameter identification. Placing the truss in a zero-g environment and measuring the same parameters provided a basis for comparing ground and flight test data, and determining the suspension system effects on the truss structure's modal parameters.
The short float times experienced on the two-meter truss flight test were initially of great concern as engineers were preparing for the twelve-meter truss flight test. The frequency-domain data analysis techniques in use depend on longer record lengths to obtain good frequency resolution. For the truss modes, the frequency range of interest was from 10 to 40 Hz. To get a .02 Hz frequency resolution at 10 Hz, a record length of 50 seconds would be required and multiple records would be required to average out noise. Because the average float period experienced on the 2-meter truss flight test was 6 seconds, the frequency-domain analysis technique would not be acceptable for this test. To process the expected short record lengths, the Eigensystem Realization Algorithm (ERA) time domain technique [4] was used. An Structural Dynamics Branch engineer had worked extensively with this analysis technique and recommended it for the flight test. This method provided frequency resolution independent of data record length. The record length requirement was just two complete cycles at the lowest structural frequency. Since the first mode of the truss was near 10 Hz, this means only .2 seconds of data was required with this technique. Obtaining .2 seconds of free-float time was expected to be easy to achieve based on the previous two-meter truss flight test.

A ground vibration test was performed before the flight test to check out the flight test equipment and to record truss response using soft suspension to simulate the free-free boundary condition. This provided a structural baseline with which the flight test could be compared. The truss modes were excited and measured using the impulse response technique and analyzed with ERA. Three zero-spring rate mechanisms (ZSRM) were used to suspend the twelve-meter truss as shown in Figure 1.

The zero-spring rate mechanism was designed to provide low restraint spring forces without the large displacements associated with normal springs that have low stiffness. Figure 11 shows that each ZSRM consists of one vertical spring which supports the test article weight and two side horizontal springs which reduce the vertical spring's restoring force. The two side springs are in compression and act against the vertical spring when the mechanism is displaced below the horizontal position, and act with the vertical spring when displaced above the horizontal position. This results in a low restoring force for a linear vertical displacement (1 inch).

Instrumentation/Data Acquisition

To measure adequately the twelve-meter truss's various resonant frequencies and mode shapes, 73 PCB modal test accelerometers were distributed over the entire truss. At each location on the truss, 2 accelerometers configured to measure x and y direction motion were glued to the truss. Figure 12 shows all the accelerometer locations. Six Setra high sensitivity accelerometers were used to measure low frequency (below 1 Hz) accelerations. Three were configured in orthogonal (x,y,z) directions to measure rigid body motion at the truss CG location. The other 3 (configured orthogonally) were attached to the aircraft floor to measure the zero-gravity conditions. The accelerometer signals were filtered (100 Hz lowpass), multiplexed, and recorded on a Honeywell 101 FM tape recorder. A patch panel was configured to allow signal monitoring during recording. Table 2 lists all the equipment

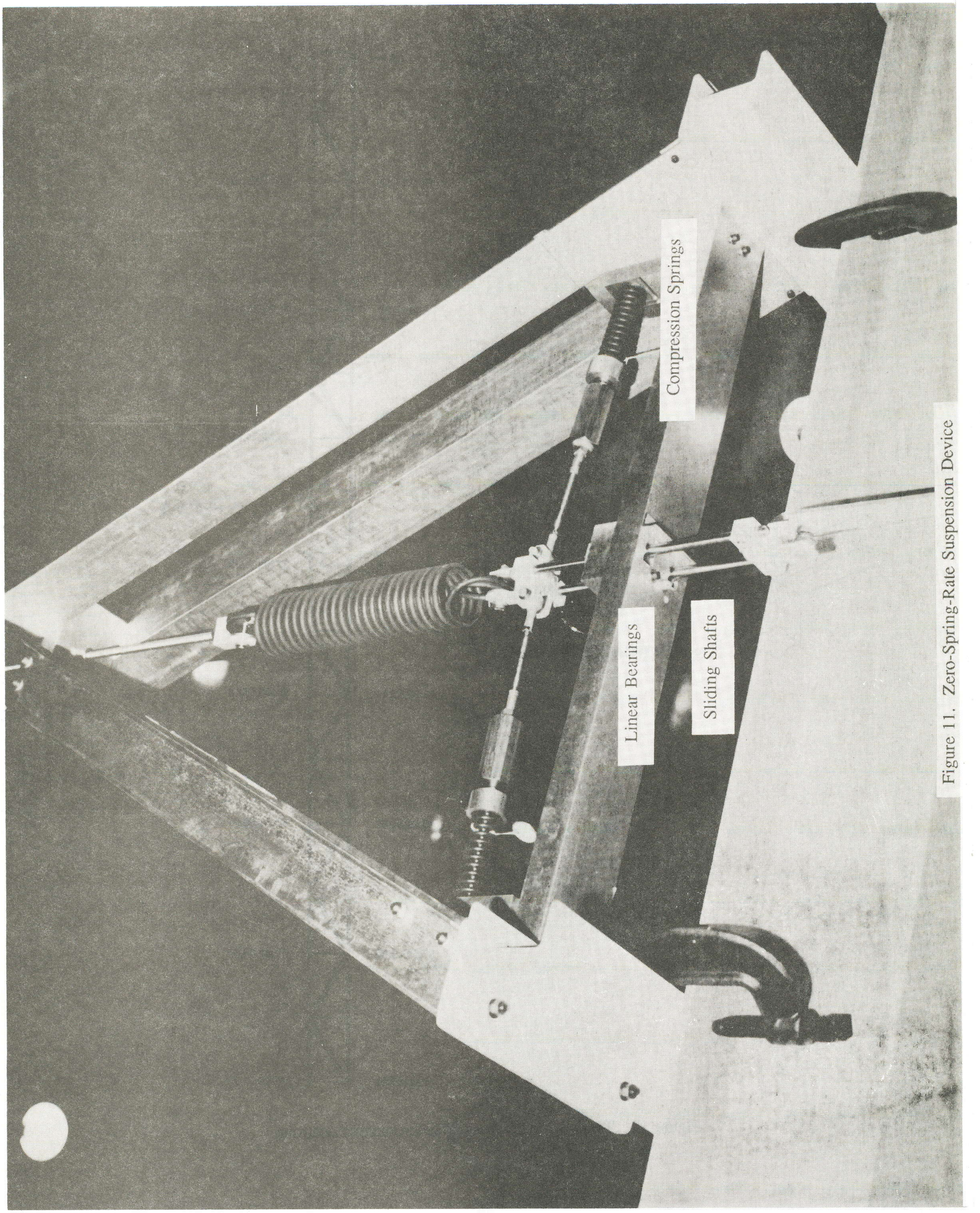

Figure 11. Zero-Spring-Rate Suspension Device

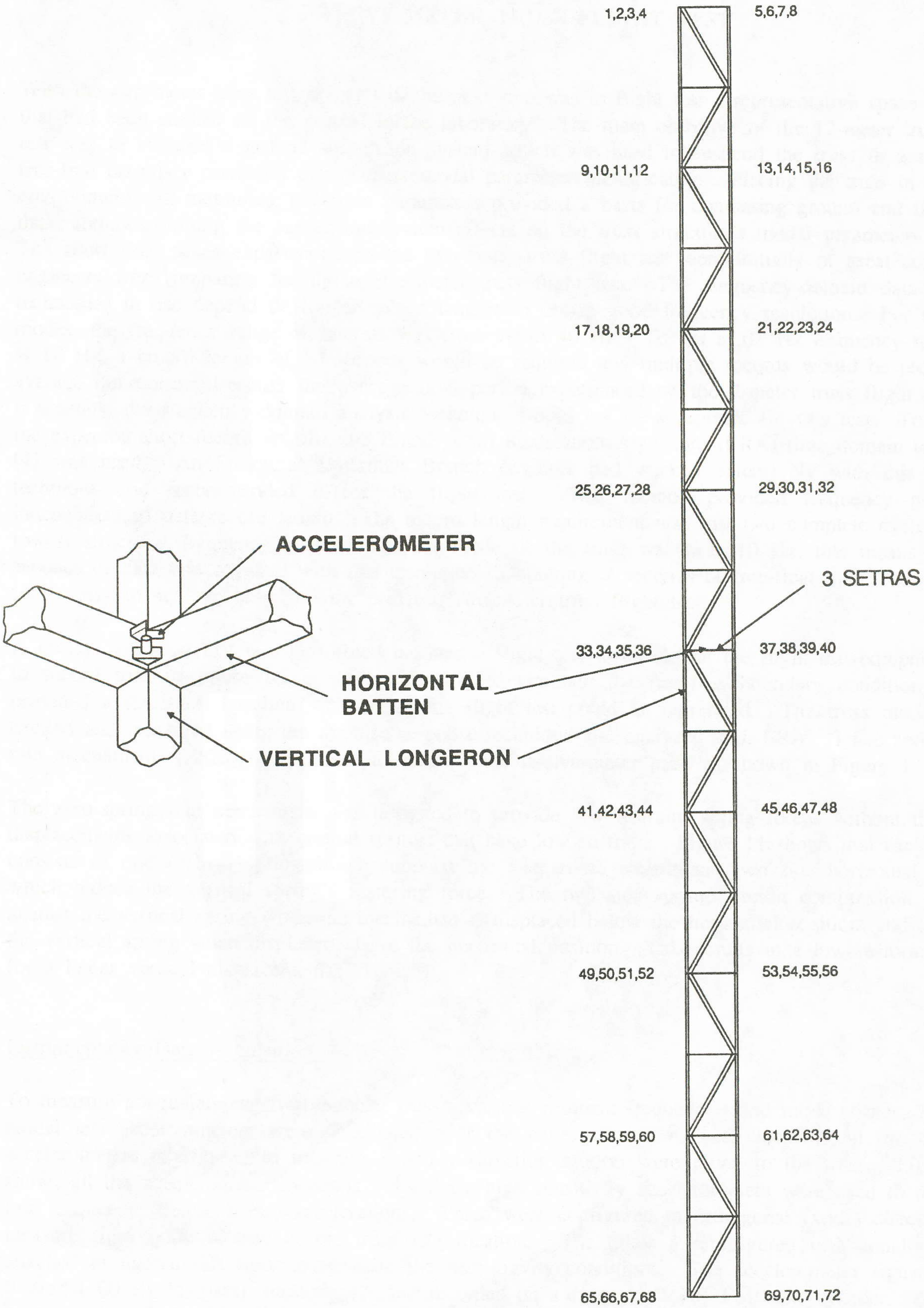

Figure 12. Twelve-Meter Truss Accelerometer Locations

Table 2. 12-Meter Truss Flight Test Equipment List

ITEM #	DESCRIPTION	WEIGHT (lb)
1.	12x.5x.5 meter truss and exciter	230.0
2.	Accelerometers (73)	.5
3.	Honeywell 101 recorder	125.0
4.	Ono Sokki FFT analyzer	55.0
5.	Three triaxial accelerometer blocks	0.8
6.	Accelerometer cables	20.0
7.	VHS video camera	10.0
8.	Still camera	5.0
9.	Electronic equipment rack	210.0
10.	Headset intercom (2)	4.0
11.	Multiplexer	5.0
12.	Accelerometer amplifiers (6)	24.0
13.	Power supplies (2)	80.0
14.	Filters	25.0
15.	Patch Panels	20.0
	TOTAL	814.3

used on the twelve-meter truss flight test. Figure 13 is a schematic representation of the data acquisition system, and Figure 14 shows the instrumentation rack. All of the accelerometers were calibrated individually with a one-g, calibrated shaker and the calibrations were recorded on tape and on paper. The force input mechanism used to excite the truss was a solenoid-powered impact device. With a 2-lb weight attached to the solenoid shaft, the device generated a 20-lb force.

The impact device was bolted to a truss longeron (Figure 15) at a location where both bending and torsion modes would be optimally excited. This location, at approximately 4 meters from one end, was determined through finite element model analyses. A PCB accelerometer was attached next to the impact device and positioned parallel to the force vector to measure acceleration levels at the impact point.

The Honeywell 101 recorder was mounted to the floor of the aircraft with shock mounts. A double-bay shock mounted rack supported the remaining electrical equipment.

Test Procedures

The procedures followed for the twelve-meter truss were the same as for the two-meter flight test with a few exceptions. The differences were the truss was always hand-released, the data recorder was turned off between parabolas, and an excitation device was turned on just after truss release. One half of the second flight was dedicated to testing the JPL active member control system. The tests required replacing two diagonals from a bay near the center of the truss with actuators (see Figure 16) and turning on a controller before each parabola. Otherwise the tests followed the procedures described above.

Test Results

The twelve-meter truss flight test was performed on 1 and 2 February 1990. NASA's aircraft flew twenty parabolas on the first day before weather conditions forced an early return to Ellington Field. On the second day, the first twenty parabolas were dedicated to the JPL tests. The final twenty parabolas were used for more truss impulse response tests with the original diagonal members replacing the actuators. During the first three to five parabolas of each flight, the pilot and test director practiced optimizing the duration of zero gravity through intercom communications. The test director floated a pen in the test section and relayed its motion to the pilot who would correct the flight trajectory to minimize pen drift. The truss remained secured to the floor during these maneuvers. For the remainder of the two flights, the truss achieved release-to-impact float times often greater than six seconds. Flight engineers activated the solenoid impact device about a second after the two NASA test engineers released the truss. Figure 17 shows the truss just before release. All the instrumentation operated during the flight as planned. An accelerometer broke off the truss during one parabola but was reattached with double-sided tape. After the completion of all the tests, two bolts on one end of a truss diagonal member were found to be loose. Data from the flight test were analyzed to determine what effects the loose diagonal had on truss parameters. The Eigensystem Realization Algorithm (ERA) and Test Data Analysis System (TDAS) were used to obtain natural frequencies and mode shapes. The effects of the loose diagonal member are very distinct when comparing the 12-meter truss flight test and ground test mode shapes. For the flight test, coupling between torsion and bending modes caused by the loose diagonal was apparent. The 12-meter truss finite element model was modified by removing the loose diagonal to match the flight test condition. The mode shapes from the updated model and the flight test corresponded better, indicating a significant effect of the loose diagonal on the truss's modal parameters. Since the flight test results with the loose diagonal could not be correlated with the ground test, a second ground test was performed in April with the same diagonal member loose. The following comparisons are between the second ground test and the flight test.

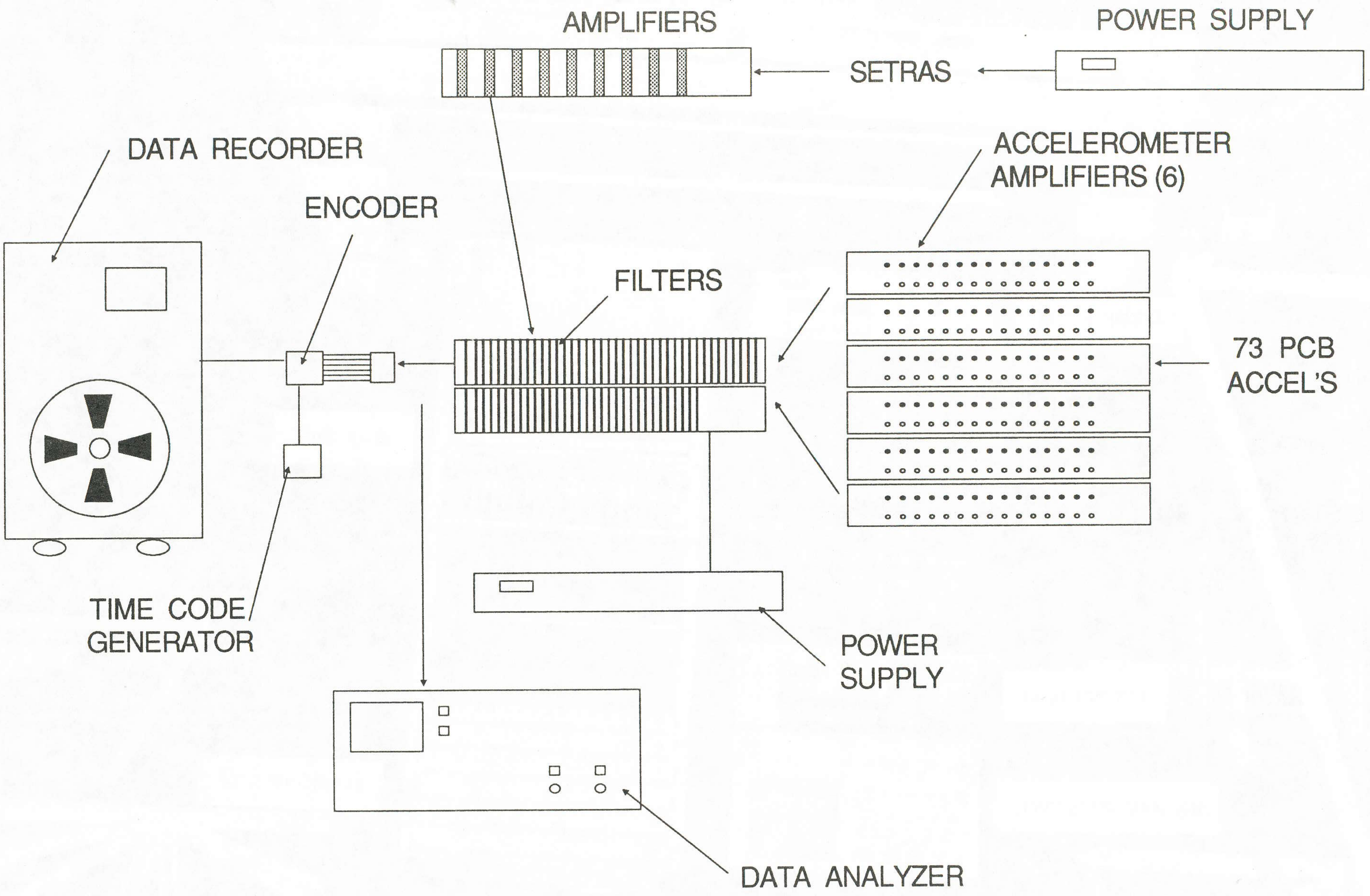

Figure 13. Twelve Meter Truss Data Acquisition System Diagram

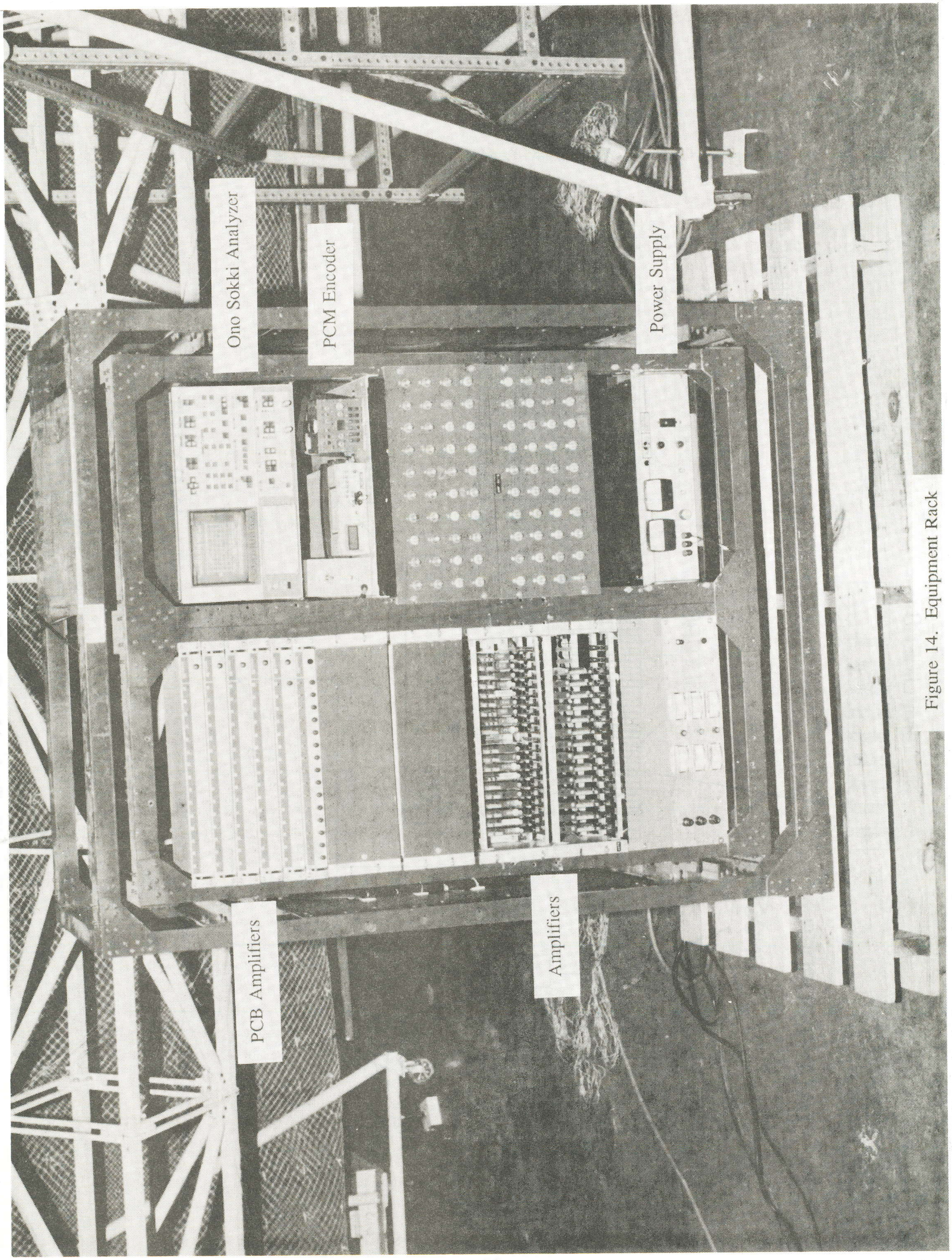

Figure 14. Equipment Rack

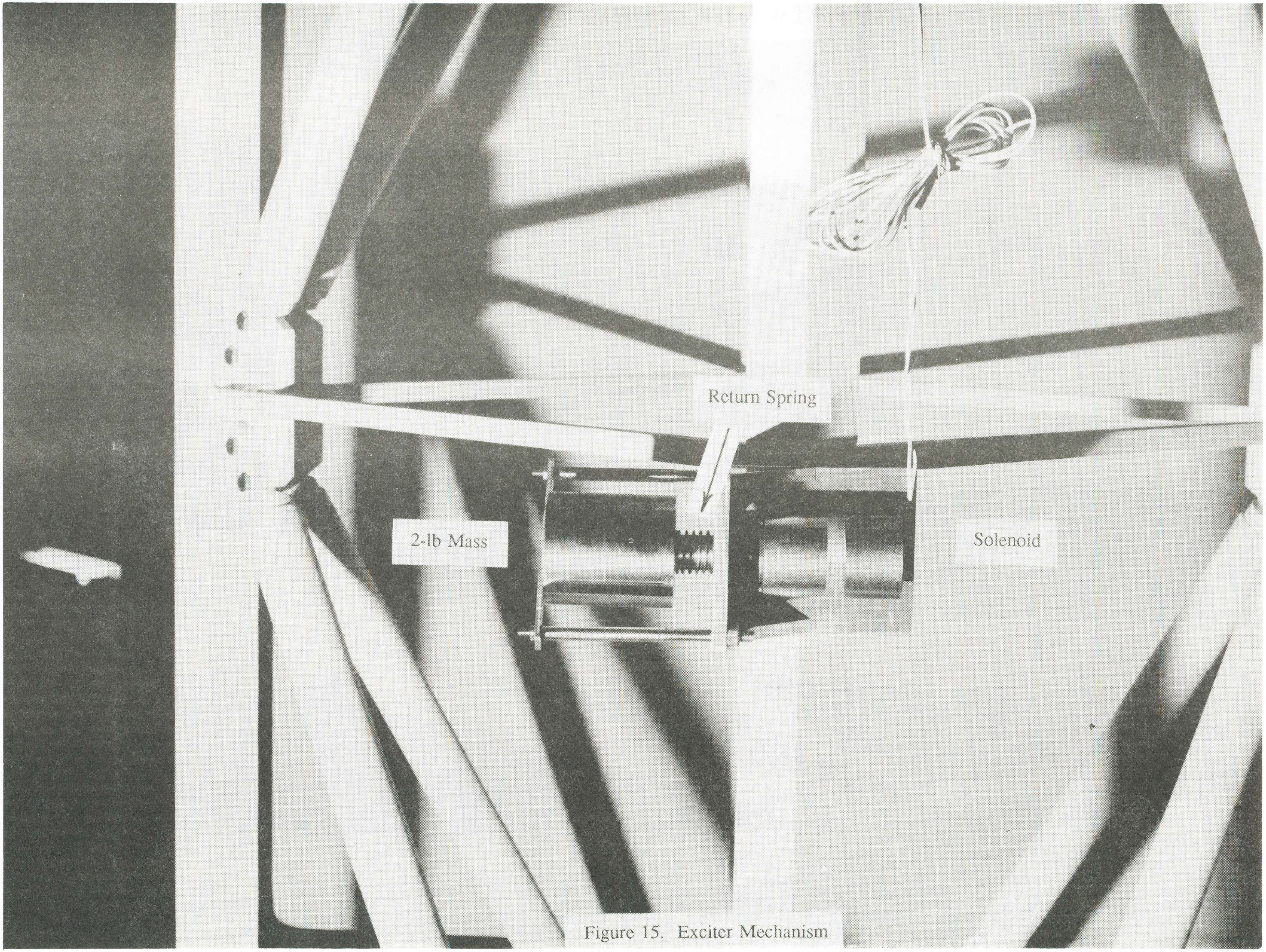

Figure 15. Exciter Mechanism

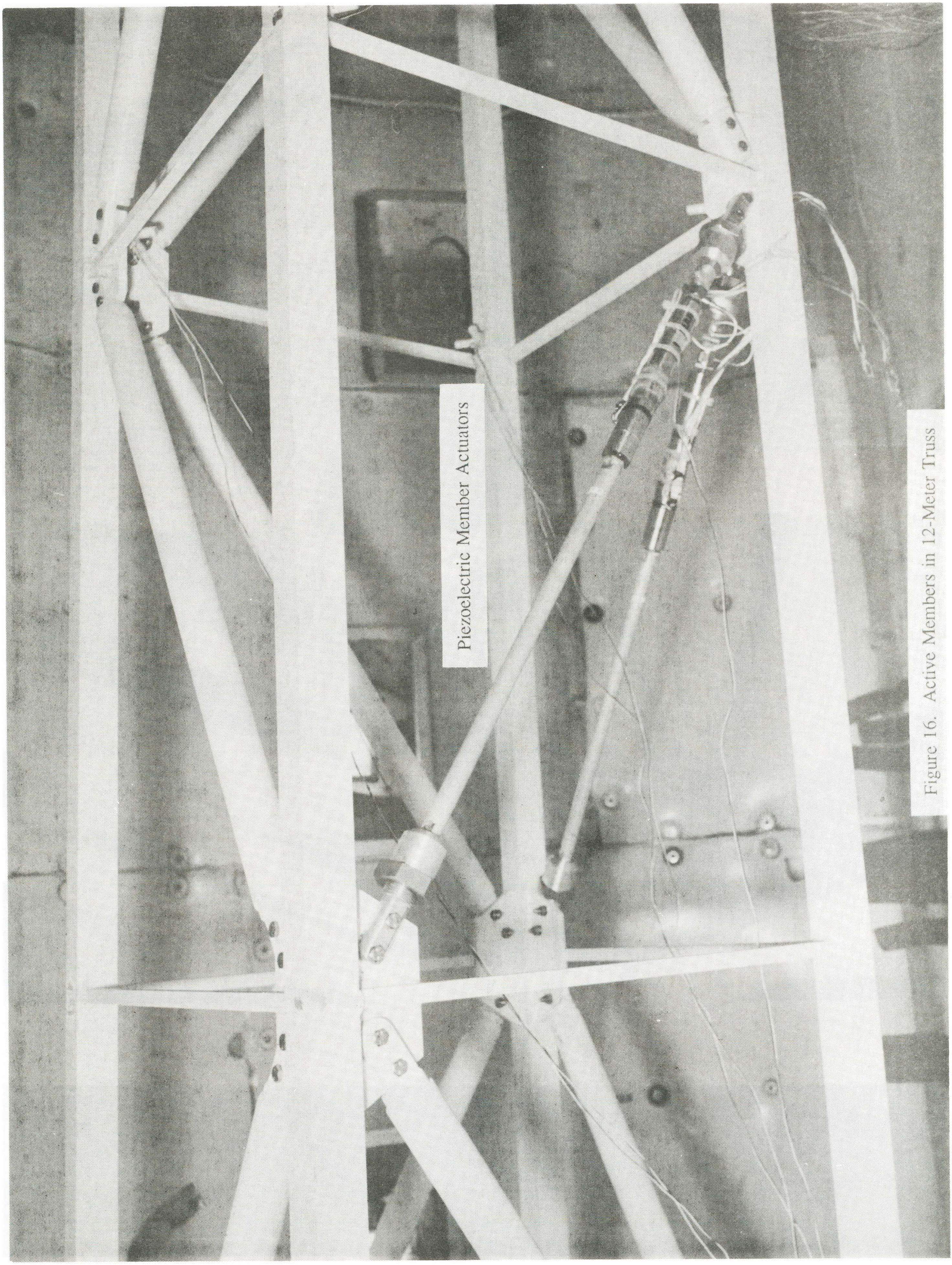

Figure 16. Active Members in 12-Meter Truss

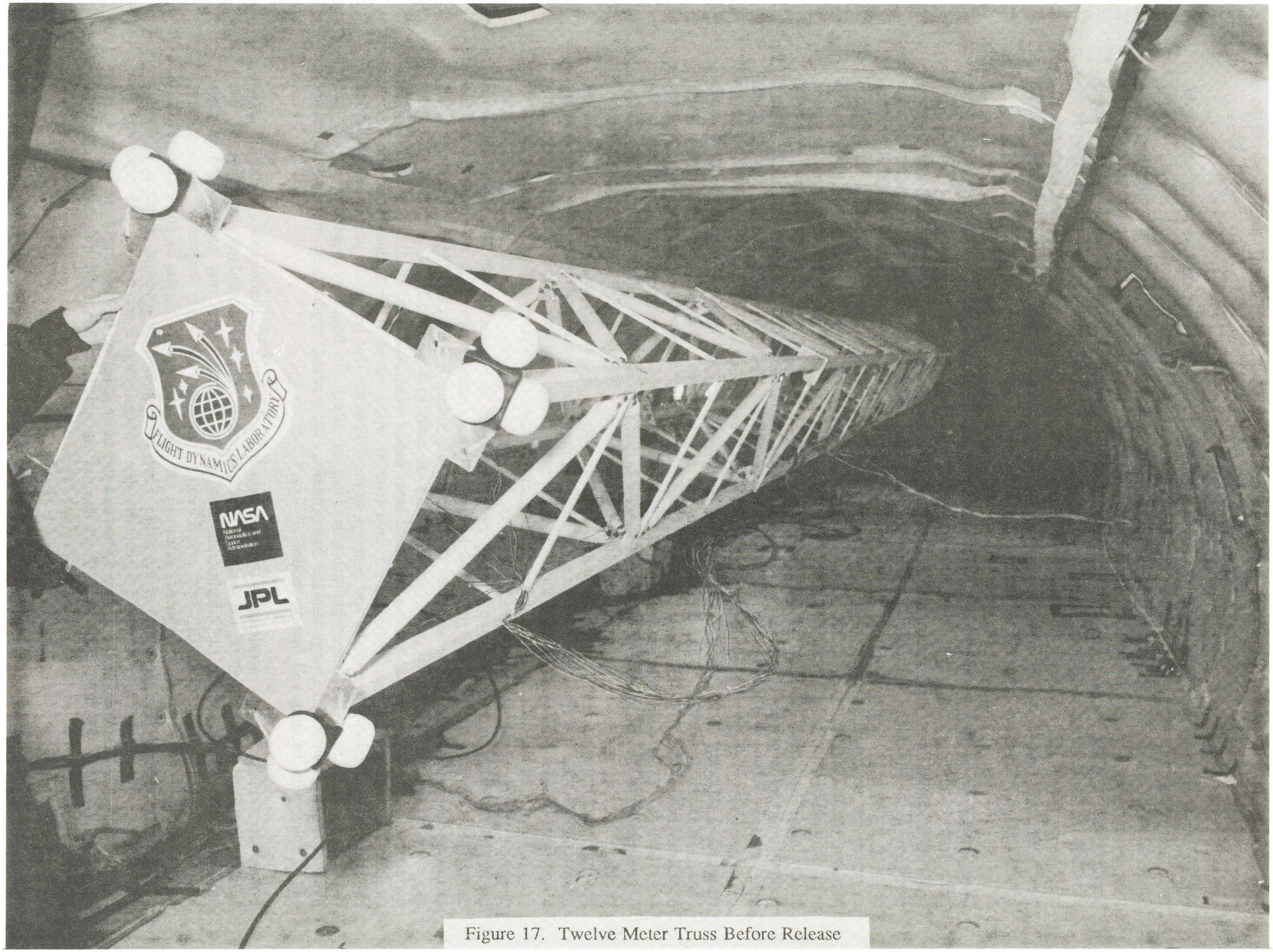

Figure 17. Twelve Meter Truss Before Release

The Eigensystem Realization Algorithm was used to estimate the modal parameters of the structure from both the ground and flight tests. The free response data were passed through 100 Hz anti-aliasing filters to provide a useable frequency range of 0 to 50 Hz. ERA used the filtered data directly to form the data matrices (Hankel Matrices) required by the program. In the analysis, the responses to several impacts were considered free responses to different initial conditions although actually, the impacts provided the same initial conditions. The response data sets were different because of the noise in the measurements and the variations in the digital sampling starting point. Data were not averaged and were somewhat noisy. To increase the accuracy of the parameter estimates in the presence of high noise, a large number of columns in the data matrices was chosen.

Table 3 lists the ground and flight test structural modes identified using ERA. The frequencies were taken from a single identification using multiple tests; 4 tests for ground and 6 tests for flight. The voids in the table were modes not identified by ERA. Figure 18 shows a frequency response function plot from truss measurement location 1y for the ground and flight tests. The peaks correspond to the bending, torsion, and frame modes listed in Table 3. Frame modes are truss cross-sectional distortions in which the cross-section expands in one diagonal direction and contracts in the other. Correlation between frame, bending and torsion modes for ground and flight tests was measured using modal assurance criterion (calculated with ERA). The Modal Assurance Criterion is calculated as the cosine of the angle between the modal vectors. Criterion values ranges from 0 to 100 percent, with 100 percent implying a perfect correlation between two modes. Tables 4 and 5 list these values for several truss modes. The off-diagonal low percentage terms indicate that the modes being compared are different modes. Bending and torsion modes compared well between the two tests with resonant frequencies differing less than 0.5 Hz. All modes except for the first x-direction bending mode correlated better than 80%. The frame modes did not correlate well; only the first frame mode correlated better than 80%. Figures 19, 20, 21, and 22 are four corresponding ground and flight test mode shapes. They were generated with SDRC's TDAS software. The dashed and solid lines in the figures represent the deformed and undeformed mode shapes respectively. Figure 19 shows the first y-direction bending mode coupled with the first torsion mode. Figure 20 shows the first x-direction bending mode coupled with the first torsion mode. Figure 21 shows the second x-direction bending mode coupled with a frame mode. Figure 22 shows a dominant frame mode from the flight test and a dominant second y-direction bending mode from the ground test. To illustrate the effects of the loose diagonal members on truss dynamics, corresponding mode shapes were computed from ground tests with diagonals tightened and are plotted in Figures 23, 24, and 25. Figure 23 is an off-diagonal bending mode that separated into the first two bending modes described in Figures 19 and 20. Figure 24 shows the second x-bending mode, and Figure 25 is an unsymmetric frame mode. With the tightened diagonal members, resonant frequencies were higher than the corresponding flight/ground test modes and bending modes were no longer coupled with torsion modes as seen in Figures 23, 24, and 25. The poor correlation in the frame modes can be explained from earlier tests performed on the truss and ZSRMs. Results had shown that truss frame modes were excited when vibration amplitudes were too low to overcome static friction in the shafts and bearings of the ZSRM's. This prevented unconstrained vertical motion, which allowed the suspension cable stiffness to affect the boundary condition in the truss dynamics. This transferred energy into the frame modes. As a result, more frame modes were excited and coupled with bending and torsion modes.

Figures 26 through 28 show acceleration response data from the Setra accelerometers. Figure 26 is for a triax mounted on the floor of the aircraft. Accelerometer 81 was positioned vertically, 82 was horizontal, and 83 was along the longitudinal axis of the aircraft. The rms accelerations in these directions are .15, .029, and .013 g's respectively. Besides the high frequency noise present, accelerometer 81 shows the low frequency errors in the flight trajectory. Figure 27 shows the response of the Setras mounted near the center of the truss. Each curve shows the solenoid impact at .6 seconds and the truss impact with the aircraft 5.5 seconds later. Magnifying .5 seconds of data preceding the initial impact (first large spike) in Figure 28 reveals the noise level of the floating truss. Root-mean-square accelerations are .008, .007, and .02 g's for the vertical, latitudinal, and longitudinal directions respectively.

Table 3: Ground and Flight Test Modes

Mode Description	Ground Test Freq. (Hz)	Flight Test Freq. (Hz)
1st Y-Bending + 1st Torsion	11.7	11.8
1st X-Bending + 1st Torsion	12.2	12.3
1st Torsion	12.7	12.9
Frame Mode, asymmetrical	22.5	22.4
Frame Mode, one end	23.2	---
Off Diag 2nd Bndng & Frame	23.3	---
2nd X-Bending + Frame	24.5	24.2
Frame Mode	25.2	25.2
Frame Mode, 2nd Tor One End	27.4	---
Frame Mode, Torsion, Bndng	31.3	---
Off Diagonal Bending	32.7	32.3
Frame Mode	35.1	---
3rd Bending, Off Diagonal	36.2	36.2
3rd Torsion, Frame	39.6	39.6

Table 4: Percent Correlation of Frame Modes

		Flight Modes (Hz)		
		22.4	25.2	32.3
	22.5	86	4	0
Grnd	23.2	17	45	0
Mode	23.3	14	31	0
(Hz)	25.2	4	44	1
	31.3	0	0	54
	32.7	2	25	6
	35.1	0	2	23

Table 5: Percent Correlation of Bending and Torsion Modes from Ground and Flight Tests

		Flight Mode (Hz)					
		11.8	12.3	12.9	24.2	36.2	39.6
	11.7	80	6	2	0	1	0
Grnd	12.2	4	60	8	0	1	0
Mode	12.7	0	0	88	1	0	0
(Hz)	24.5	0	0	1	82	0	0
	36.2	2	1	0	0	85	1
	39.6	0	0	0	0	0	85

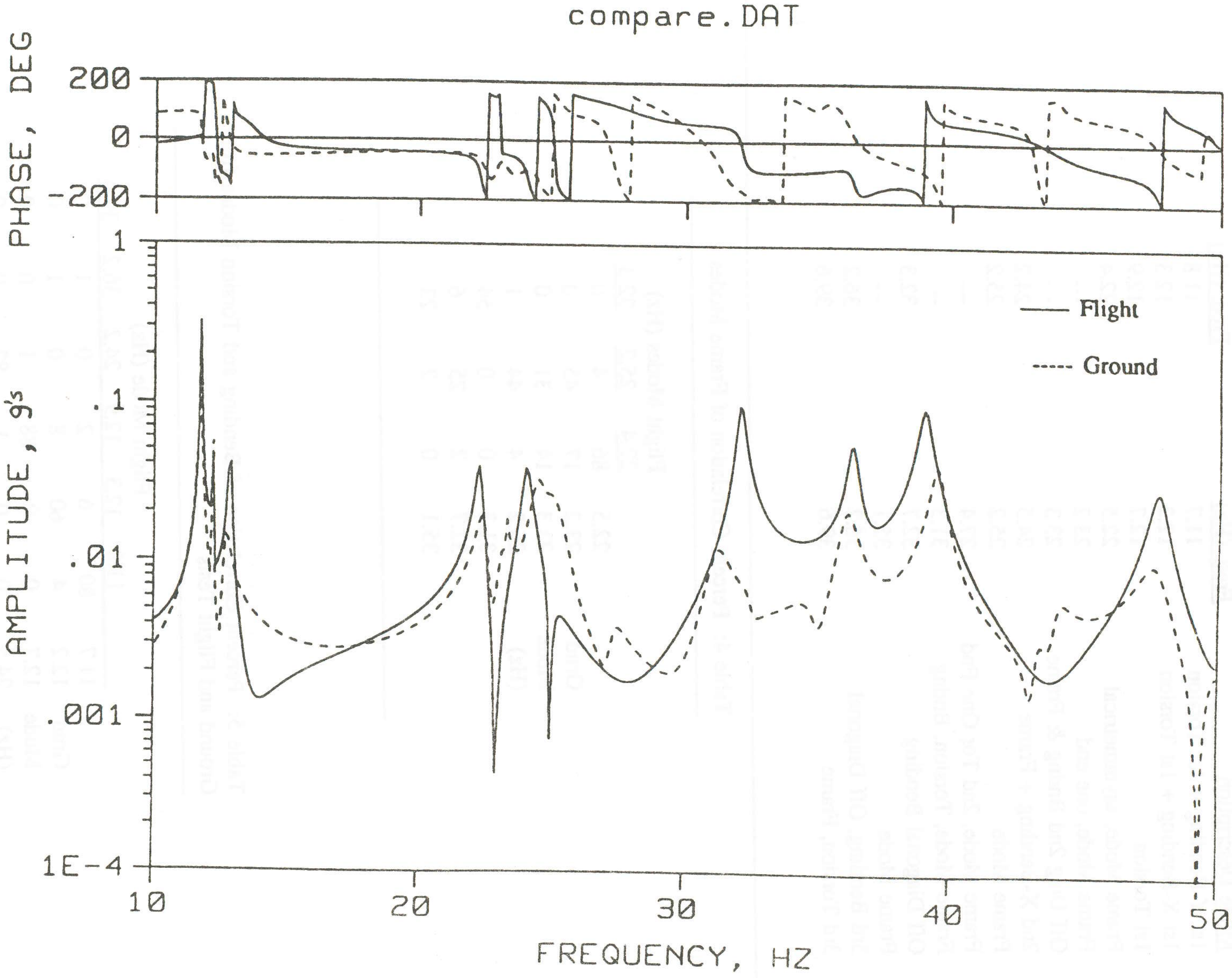

Figure 18. Accelerometer 1y Response for Ground and Flight Test

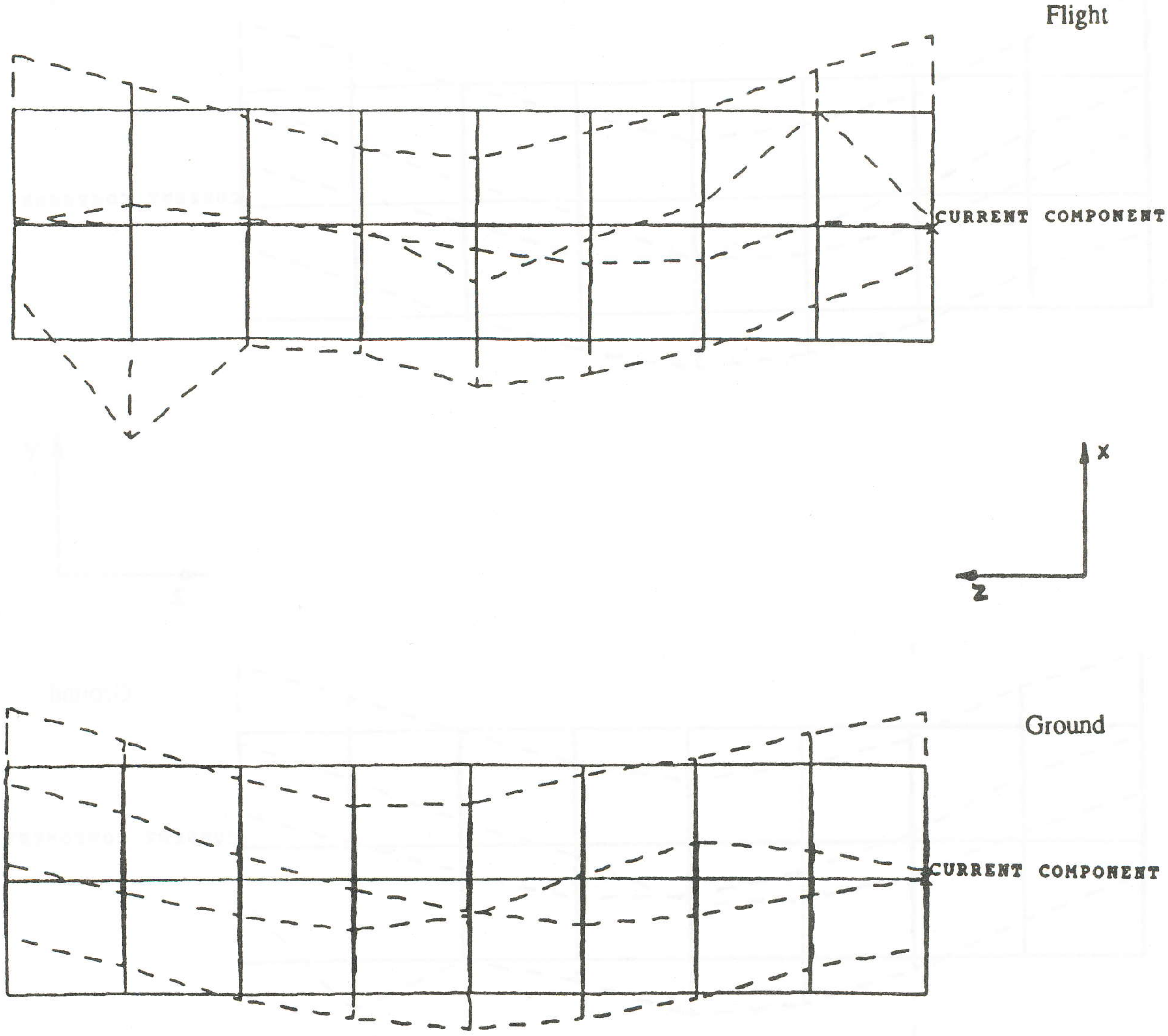

Figure 19. First y-Direction Bending Mode Coupled with First Torsion for Flight and Ground Tests

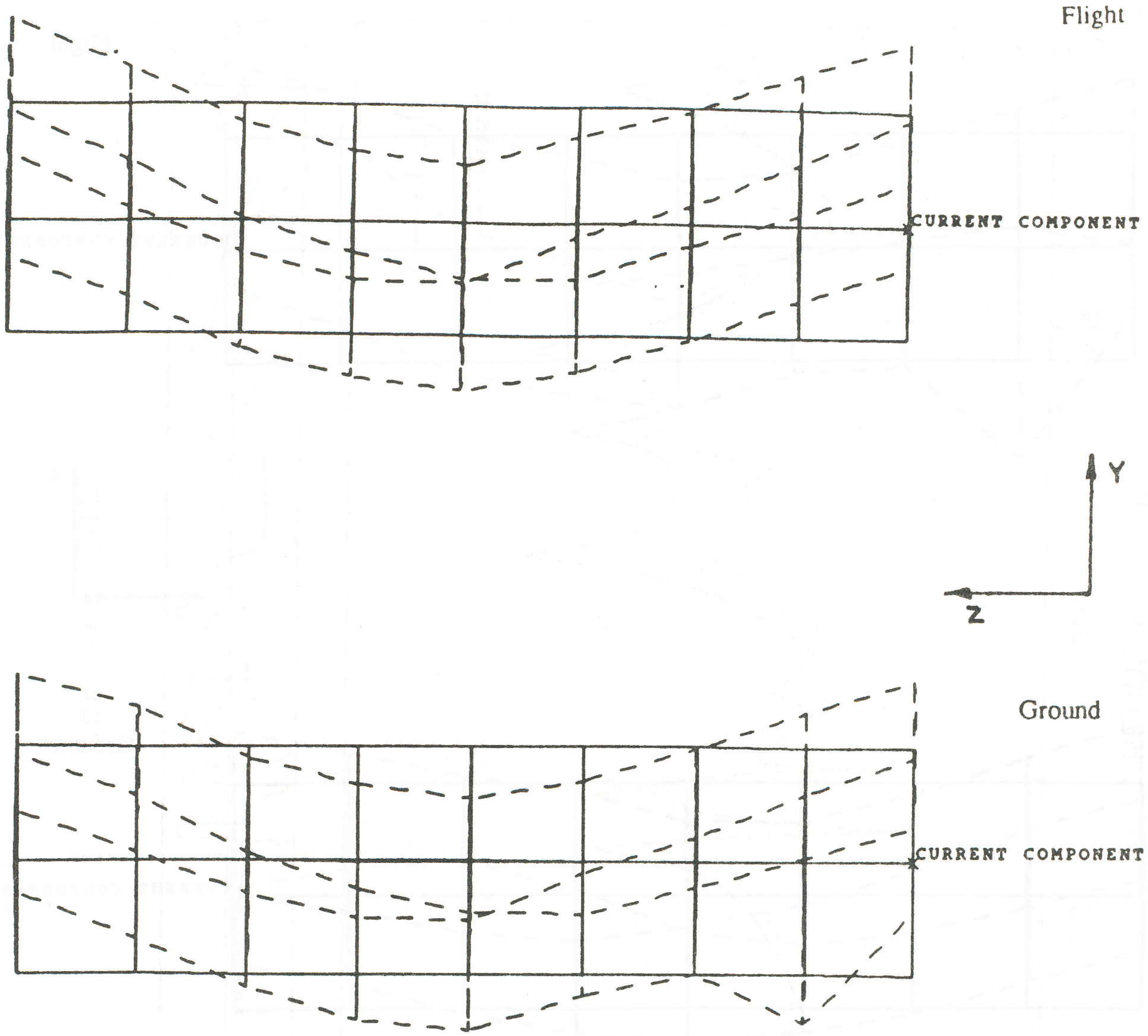

Figure 20. First x-Direction Bending Mode Coupled with First Torsion for Flight and Ground Tests

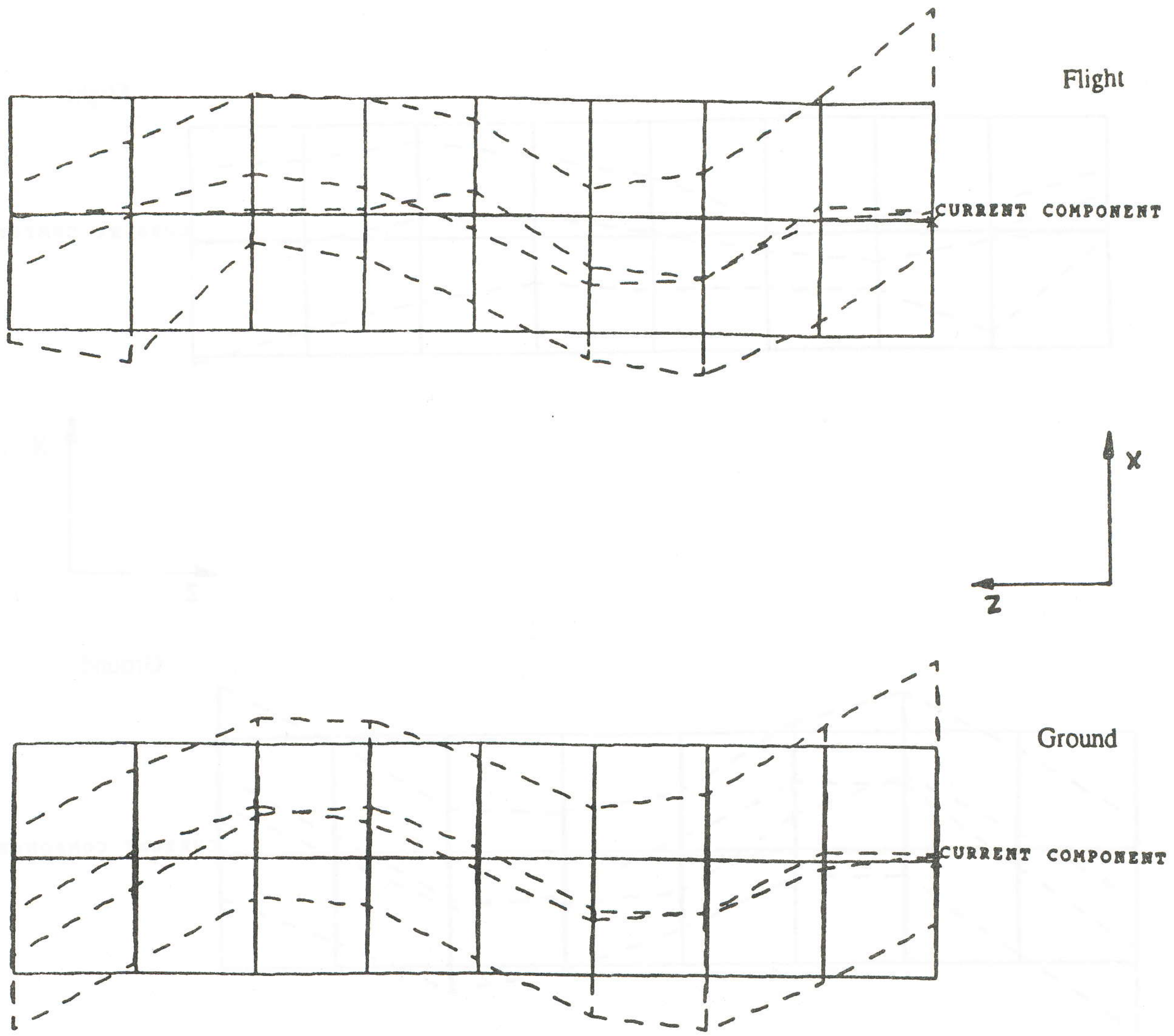

Figure 21. Second x-Direction Bending Mode Coupled with Frame for Flight and Ground Tests

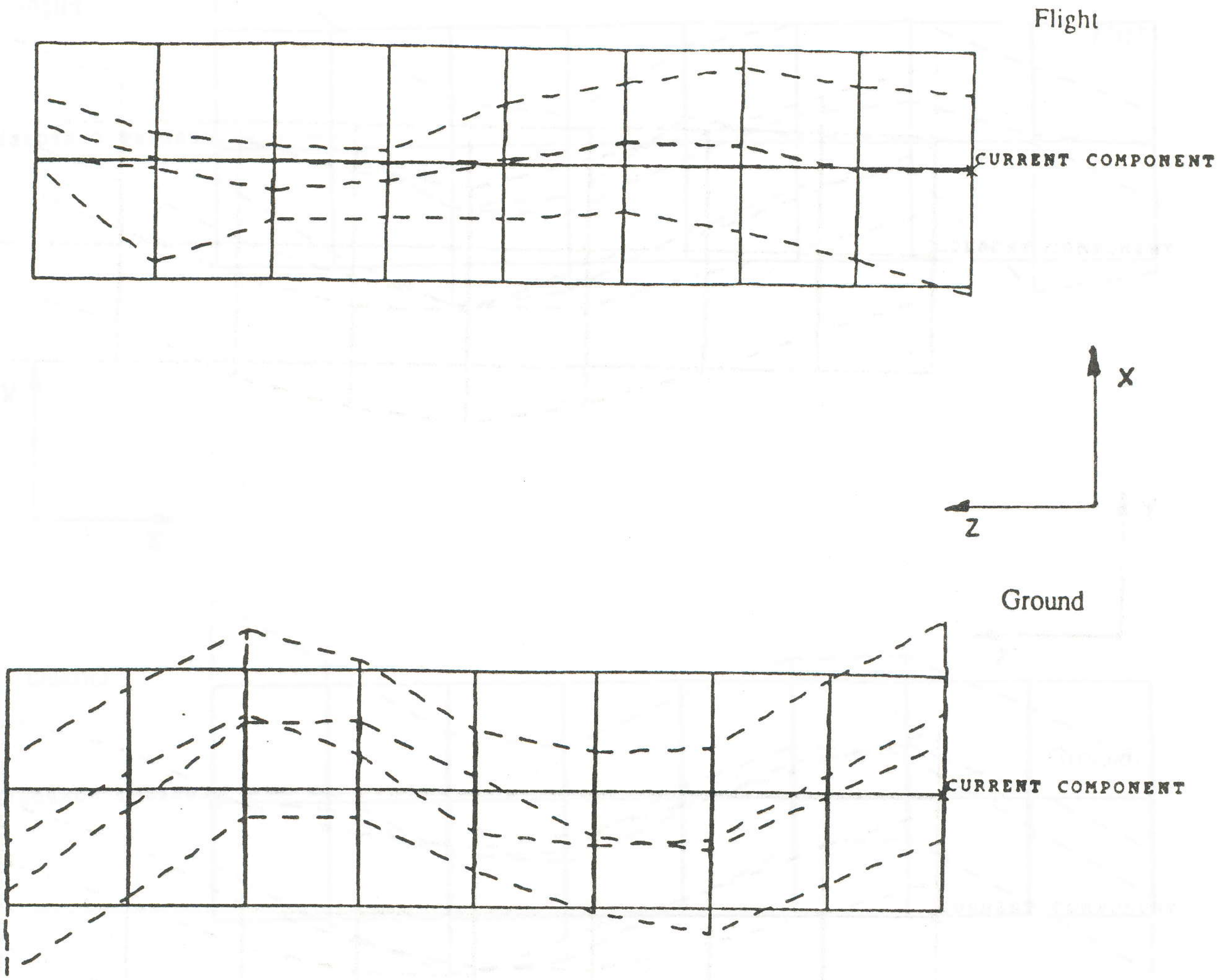

Figure 22. Frame Mode and 2nd y-Direction Bending Modes for Flight and Ground Tests

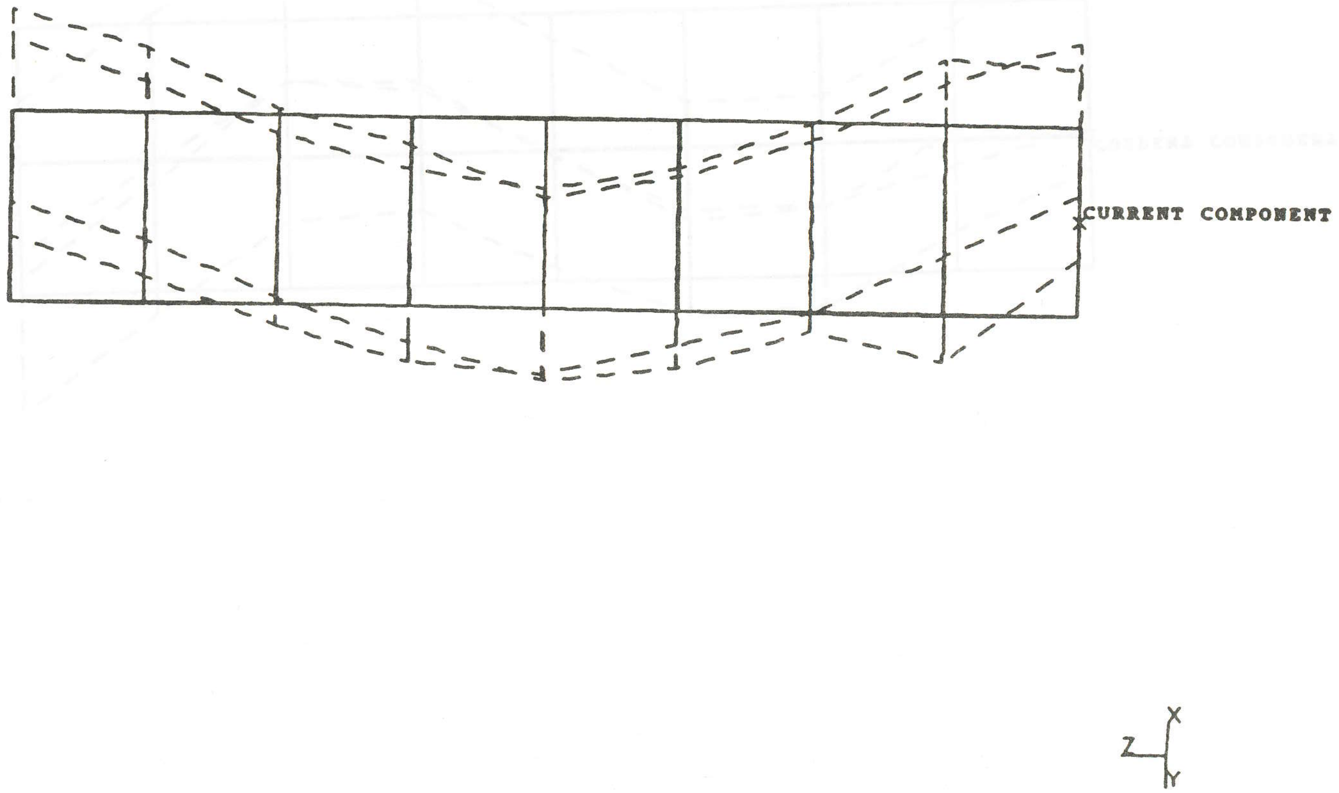

Figure 23. Off-Diagonal Bending Mode for Ground Test with Diagonals Tight

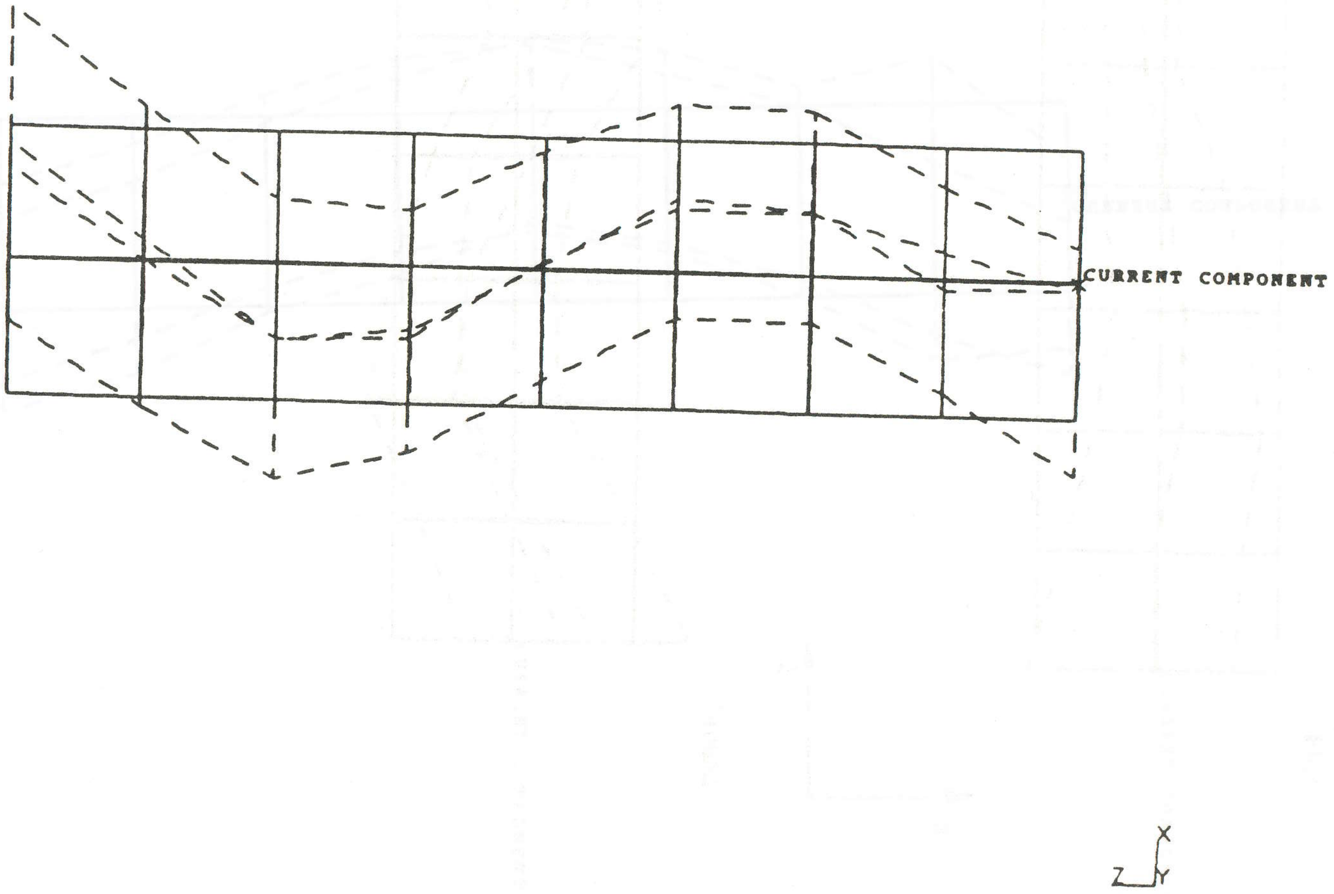

Figure 24. Second x-Direction Bending Mode for Ground Test with Diagonals Tight

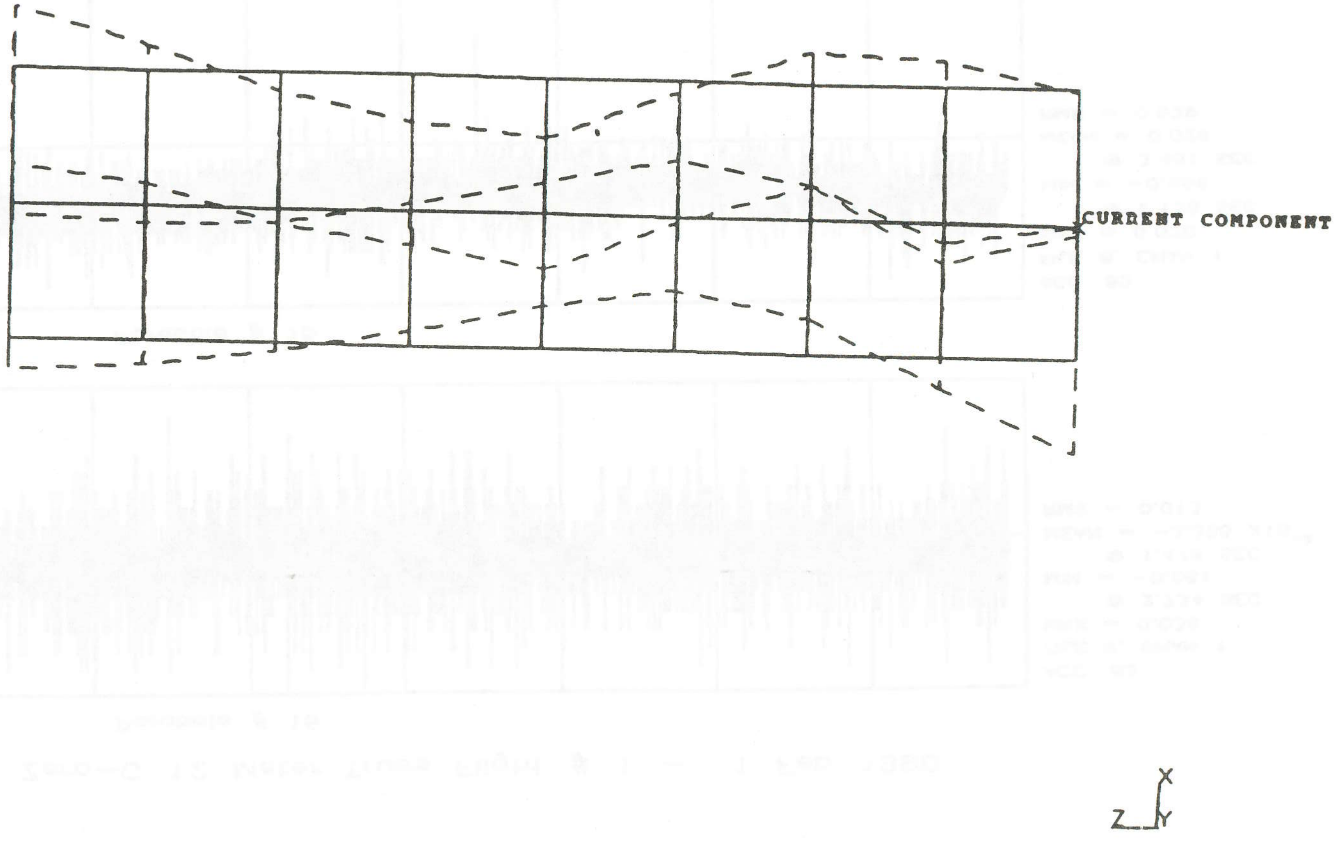

Figure 25. Unsymmetrical Frame Mode for Ground Test with Diagonals Tight

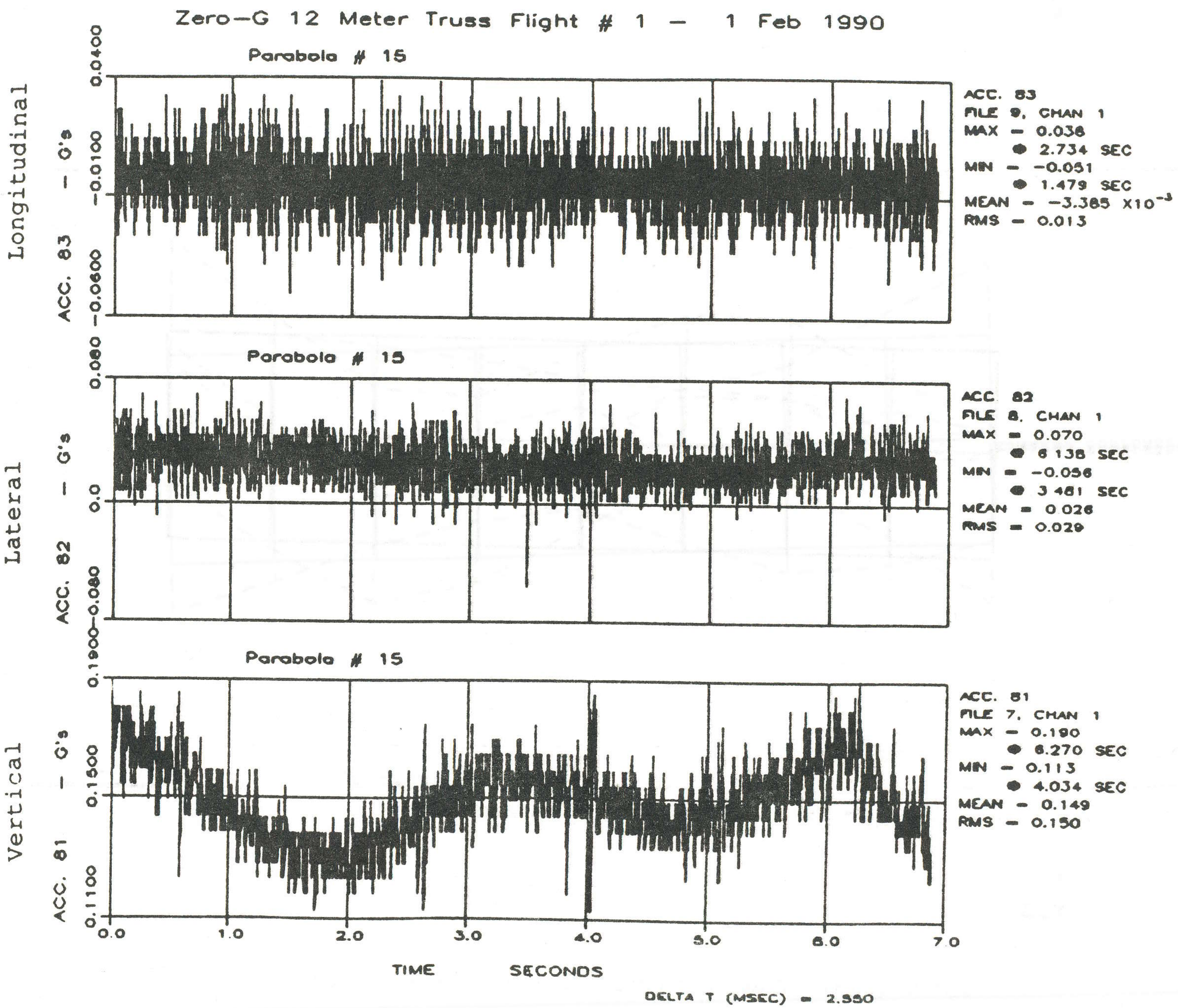

Figure 26. Floor-Mounted Triax Response

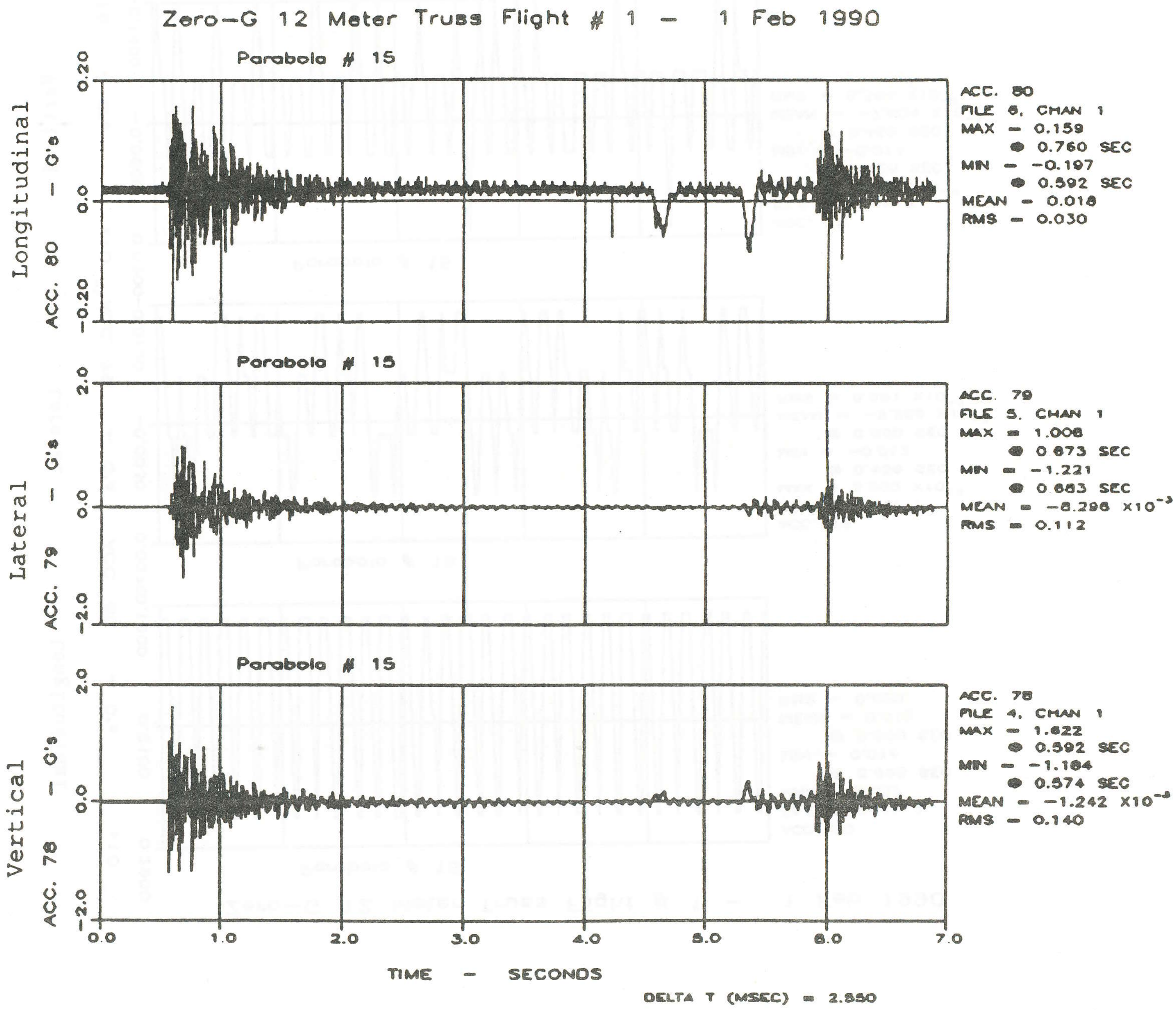

Figure 27. Truss-Mounted Triax Response

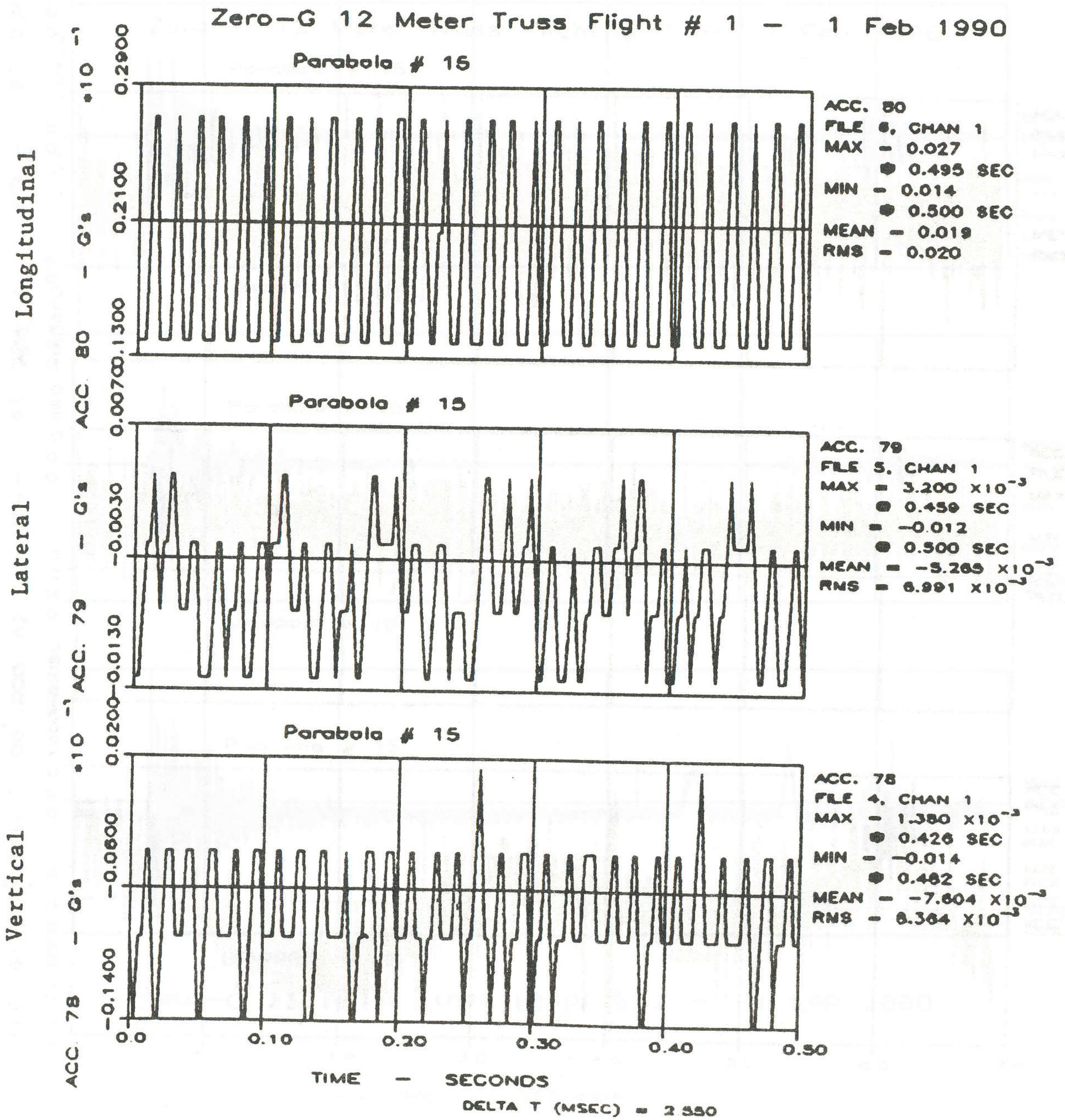

Figure 28. Triax Noise Level for Floating Truss

CONCLUSIONS AND RECOMMENDATIONS

The objective of this flight test, to evaluate ground testing techniques, was met successfully. Good correlation between ground and flight test results was achieved, confirming that laboratory zero-g test techniques are valid. The differences between ground and flight test results were caused mainly by the ZSRM friction and dynamics, which coupled the frame modes with the bending and torsion modes. The twelve-meter truss is relatively stiff and massive compared with many real space truss beams, and its dynamic response would not be as easily affected by the suspension dynamics as a lighter, more flexible structure might be. With careful engineering and analysis procedures, discrepancies and inaccuracies encountered in measured structural parameters can be avoided or accounted for. If a test structure is extremely flexible and light-weight, and if suspension system parameters can be quantified for a particular free-free simulation system, good results can be obtained.

The NASA KC-135A provided a very good reduced gravity environment for the twelve-meter truss dynamic tests. Experiments that require more than 5 to 10 seconds of free float time, however, may require a simple restraining device (soft springs or rubber bands) to keep the test article away from the fuselage. In any case, test procedures should remain simple, because the fast pace and the physiological effects on the experimenters make complex tasks even more difficult. These difficulties became apparent for the flight test engineer in charge of the instrumentation on the twelve-meter truss test. During each period of zero-g, the recorder needed to be turned on; voice annotation made of the parabola number, tape footage, and truss position; and the exciter activated. The flight engineer had to operate the recorder while fighting to maintain an upright attitude close to the equipment and while closely watching the truss's motion.

The good correlation between the bending and torsion modes from the flight and second ground tests indicates the suspension system friction and modal mass had minimal effect on these modes. The frame modes, however, were excited by the suspension system dynamics. When vibration amplitudes were too low to overcome static friction in the ZSRM shafts and bearings, free vertical motion was impeded. Thus, the suspension cable stiffness affected the boundary condition in the truss dynamics which allowed energy transfer into the frame modes. Since there was no friction affecting the truss in zero-g, there were fewer frame modes and negligible coupling. A solution to achieving better frame mode correlation would be to suspend the truss in a vertical position, which puts the frame mode displacement axis perpendicular to the suspension system bearing's line of action. This configuration requires a tall facility to suspend the twelve-meter truss on a cable from one end. Alternatively, a second generation suspension system [5] has already been developed and is being used in space structure experiments. The design is a pneumatic system that uses an air spring and air bearing to support loads. These units possess low friction and stiffness, making them potential replacements for the existing mechanical systems.

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