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# PIONEER F/G APPENDAGE DEPLOYMENT*

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This paper describes an integrated program of testing and analysis used to develop and flight qualify the appendage deployment systems of Pioneer F and G, a spin-stabilized spacecraft which will fly by Jupiter. Tests that exactly duplicate deployments from spinning spacecraft under zero-g in-flight conditions are not possible in the laboratory. Since representative spinning deployment test schemes would be very costly and complex, a combination of deployment system component tests, simplified non-spinning deployment tests, and analyses were used to develop the deployment system hardware. Analytical deployment models, verified by correlation with deployment test performance data and incorporating measured system parameters, were used to project in-flight deployment system performance over the expected range of environmental and hardware extremes.

## I. INTRODUCTION

The Pioneer F and G Spacecraft will be launched in 1972 and 1973 on fly by missions to the planet Jupiter. Shortly after boost the spinning spacecraft will deploy three appendages. First, two pairs of Radioisotope Thermoelectric Generators (RTG's) are each deployed 6 feet radially by centrifugal force to protect the spacecraft body from their nuclear and thermal radiation and to allow sufficient cooling of the RTG's. Then the four-segment 17 foot Magnetometer Boom is unfolded by centrifugal force assisted by hinge springs to position its tip mounted sensor away from the spacecraft stray magnetic fields. This boom also serves as a

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lever to activate the spacecraft nutation damper. Each boom deployment is controlled by a deployment damper to reduce deployment and latchup loads. The simultaneous deployment of the RTG Booms reduces the spacecraft spin rate from 22 to 5.7 rpm. The Magnetometer Boom deployment further reduces the spin rate to 5 rpm. Figure 1 shows the Pioneer F/G Spacecraft in-flight configuration with booms deployed and includes pertinent system parameters.

## II. DEPLOYMENT SYSTEM DESCRIPTION

Each RTG Boom is composed of two RTG's mounted back-to-back and supported by a truss attached at one end of three guide tubes. These guide tubes pass through a series of guides and rollers mounted on the spacecraft body. After deployment each guide tube latches with a simple leaf spring catch to insure that RTG Boom alignment is maintained. Electrical power is transmitted back to the spacecraft via a power cable which is stowed in a slack box and is extracted during RTG Boom deployment. A multilayered ribbon power cable construction is used to minimize stray magnetic fields and reduce mechanical resistance during RTG boom deployment.

Although the RTG Booms are released simultaneously by pyrotechnic bolt cutters, the deployment is assymetrical due to small variations in deployment system parameters from boom to boom. This assymetry is increased by the nonlinear deployment damper characteristics and is amplified by centrifugal force which drives the deployments. Considering a deployment damper force-velocity characteristic variation of ±10% from boom to boom, this assymetry can result in up to 50% higher loads for the faster boom and nearly double the deployment time for the slower boom.

The Magnetometer Boom is mounted to the spacecraft by two flexual pivots which allow the boom to pivot up and down relative to the spacecraft and pump the nutation damper. Prior to deployment, the folded boom is held in place by a preloaded tie-down mechanism and is released by pyrotechnic bolt cutters. The boom design incorporates an arrangement of control cables which gives the relative motion of the four boom segments the character of a pantograph. This design feature is required to ensure a satisfactory deployment envelope and permits the use of a single deployment damper to control boom deployment.

The 5/8 inch diameter magnetometer boom wire harness is composed of highly stranded wires using special silicon rubber insulation to reduce its stiffness. Hinge springs are required during the critical latchup phase to overcome hinge friction and wire harness torques. Analysis of the deployment indicated that using a conventional torsional spring designed to provide the required torque at latchup would result in unacceptable deployment loads due to high initial torque. The hinge spring design incorporated a coil spring on one side of the hinge attached to the other side by a cam and cable which provides an initial torque less than the latchup torque. Each hinge incorporated a simple leaf spring catch to maintain boom alignment after deployment.

## III. DEPLOYMENT DAMPERS

The three deployment dampers are of identical internal design and consist of a drum 2 inches in diameter by 0.6 inches long. The drum, which also serves as the pulley to stow the damper cable, is mounted on a shaft fixed to the damper mounting bracket. Inside the drum, immersed in silicon fluid, are a series of 15 discs alternately keyed to the shaft or the drum. When the drum rotates, the viscous fluid between the discs is placed in shear providing damping action.

The original damper design goal was to achieve a linear damper with minimum 4 lb-sec/in rate over the design temperature range 50 to 90°F. This rate was established by preliminary simulations of the RTG deployments. The initial damper design consisted of a single disc using 30,000 centistoke fluid with a 0.006 inch gap between the discs. Preliminary tests revealed that the damper's characteristics were very nonlinear, and the desired damping characteristic could not be achieved due to the non-Newtonian silicon fluid properties at higher shear rates.

Prior to the system deployment tests, analytical deployment simulations using the measured damper performance data indicated the damper performance was unacceptable. The damper design was modified by increasing the number of discs. The performance was still somewhat nonlinear, however, simulations indicated (and later deployment tests demonstrated) that the performance was acceptable for the deployments.

## IV. ANALYTICAL MODELS

The main objectives of the analytical deployment models were to:

- Evaluate deployment system designs to identify critical problem areas and provide design loads.
- Evaluate component performance prior to system deployment tests.
- Analytically predict measured test performance within 15%.
- Establish the range of performance and loads under in-flight conditions for flight hardware.

Generalized deployment analytical models were formulated to simulate both test and in-flight deployment of the RTG and Magnetometer Booms. Both deployment models consisted of a spacecraft body with three degrees of rotational freedom. All structural elements were assumed rigid and the appropriate viscous damping function controlled boom deployments.

Each RTG Boom had one degree of linear freedom relative to the spacecraft body. These deployments were retarded by various specified drag forces due to guide tube/roller friction and RTG power cable drag force.

The Magnetometer Boom inner segment had two degrees of angular freedom relative to the spacecraft body, one about the inner hinge axis and one about nutation damper flexure axis. Each of the three outer segments had one degree of angular freedom about its hinge axis.

Torques due to control cables, wire harness mechanical resistance, and hinge deployment spring, were combined into a single torque-theta forcing function for each hinge. There was also a torque function for motion of the inner segment about the nutation damper flexure axis. Tests and measurements of these various forces and torques were made early in the development phase. Analytical functions were fitted to the data and these functions were incorporated into the deployment models.

Equations of motion consistent with the above models were derived and computer programs written to numerically integrate these equations of motion. The equations were integrated using a fifth order Kutta-Merson technique with a variable time step. The computer simulations provided detailed deployment time histories and loads. The in-orbit deployment simulation results also provided spacecraft stability and pointing information.

## V. DEPLOYMENT SYSTEM TESTS

The main objectives of the system deployment tests were:

- Demonstrate that boom release, deployment and latchup function as intended.
- Establish repeatability of the boom deployed position.
- Obtain hardware deployment performance data for correlation with deployment analytical models.

The ability of the structure to withstand design limit and ultimate loads was demonstrated in separate static loading tests of the structure. Detailed analytical deployment simulations were used to demonstrate that adequate structural loads margins existed for deployment and latchup loads.

Simplified non-spinning deployment tests were selected for the boom deployment system tests. Gravity, which is normally a handicap in testing of spacecraft deployment systems, was used to replace centrifugal force present during a spinning in-flight deployment. Aerodynamics, which might have been a factor in a spinning test, was not significant in the non-spinning deployment tests. Tests for both deployment systems were conducted for several combinations of the extremes in expected in-flight centrifugal force and temperature ranges. This was necessary since there is no single combination of extremes that would result in a worst case condition for all aspects of the deployment.

RTG Boom deployment performance tests were conducted by mounting an RTG Boom support structure to an overhead fixture (Figure 2A). A mass simulated RTG Boom was deployed downward, retarded by both a counterbalance load and the deployment damper. The counterbalance load was increased during deployment so that the RTG Boom mass minus the counterbalance load simulated the centrifugal force computed for an in-flight deployment. Side loads which encompassed expected in-flight load ranges were applied to the RTG Boom center of mass during deployment by a bungee cord. The deployment damper and structure were heated or cooled to simulate expected in-flight temperatures. This deployment test method could not truly represent the interaction between the RTG deployments, however, it did represent the anticipated interaction as determined by the simulation of in-flight deployments which were used to generate the counterbalance load versus distance curves.

The Magnetometer Boom deployment performance tests were conducted by deploying the boom over a smooth Plexiglas floor with each segment supported by low-friction, pivotable, caster bearings (Figure 2B). The range of centrifugal forces expected during in-flight deployments was approximated by slanting the support floor and performing deployment tests at several different slant angles from 0 to 5.4 degrees. The component of gravity force acting parallel to the slanted floor along the line of deployment simulated centrifugal force. As in the RTG tests, the deployment damper and hinge areas were heated or cooled to simulate expected in-flight temperatures. The slanted floor test was selected since the presence of counterbalance loads would significantly alter the boom response. Low centrifugal force levels enabled the use of this test method. Table slant angles were selected to impart the same energy to the deployment as centrifugal force imparts to an in-flight deployment. Castor bearings were used to support the boom rather than air bearings because of size, weight, and cost considerations. Their use, as expected, caused rapid damping of boom segment oscillations which occur after boom release but did not significantly affect peak loading values nor deployment times. The test setup was sensitive to castor misalignments and dust particles on the table which tended to bias and/or stop deployment. Careful castor alignment and thorough cleaning of the floor prior to each test run eliminated these difficulties.

## VI. TEST RESULTS

Appropriate instrumentation, including motion picture coverage, was used to monitor displacements, velocities, accelerations, loads, and temperatures during both deployment systems performance tests.

The RTG Boom test results indicated generally satisfactory deployment system performance and repeatability. However, because of indicated marginal capability to latchup at the end of deployment, a damper release feature was incorporated into the RTG deployment dampers subsequent to the completion of deployment testing. The external damper design was modified to release the damper cable about 1.25 in. before RTG boom latchup. Analysis showed that this change provided sufficient momentum to the RTG Boom for a positive latchup for very slow deployment conditions, but at the same time did not result in overstressing the RTG guide tubes and support structure during fast deployment conditions. The Magnetometer Boom test results indicated potential problems in the release mechanism and support structure. Minor modifications in the boom release mechanism design eliminated the interference problems, and the tests continued without any significant problems. The deployment tests demonstrated the functionality of the boom deployment system as well as adequate repeatability of final boom orientations.

## VII. DEPLOYMENT TEST SIMULATIONS

Preliminary simulations of the deployment system tests verified test concept feasibility and aided in selection of test parameters. These results were used to provide quick-look appraisals of test data and proved valuable in spotting test setup and hardware anomalies. The initial runs of the RTG deployment test resulted in deployment times somewhat shorter than predicted by preliminary RTG test setup simulations. A quick check of the damper force versus velocity data revealed that its force-velocity characteristics were 10% lower than expected. This decrease was attributed to wear and tear the damper had undergone in the many previous component level tests. The deployment tests were continued without interruption and revised damper performance characteristics were incorporated into the RTG test simulations. Tables I and II compare analytical results with measured test performance for the RTG and Magnetometer Boom deployment tests.

Agreement between analytical and test results was within 10% for both the RTG and Magnetometer Boom. This agreement over a representative range of deployment conditions established the validity of the analytical deployment models and provided a firm basis for their use in projecting in-flight performance of the deployment system.

## TABLE I

### Summary of RTG Boom Deployment Test and Analysis Correlation

| Condition | Damper Temp. °F | Results - Test/Analytical<br>Maximum Velocity ips | Maximum Damper Load lbs | Deployment Time sec. |
|---|---|---|---|---|
| Nominal Deployment | 78 | 7.0/7.1 | 30/34 | 42.9/42.5 |
| Max. Latchup Loading w/o side loads | 120 | 14.1/14.0 | 35/35 | 12.3/12.3 |
| Max. Latchup Loading with side loads | 120 | 12.2/12.3 | 34/35 | 14.0/12.9 |
| Max. Deployment Time | 20 | 3.3/2.8 | 25/27 | 156/156 |

## TABLE II

### Summary of Magnetometer Boom Deployment Test and Analysis Correlation

| Condition | Damper Temp. °F | Results - Test/Analytical<br>Max. Control Cable Loads lbs | Maximum Damper Load lbs | Deployment Time sec. |
|---|---|---|---|---|
| Nominal Deployment | 78 | 80/85 | 13/16 | 12/14 |
| Max. Latchup Loading | 120 | 80/77 | 14/17 | 7/9 |
| Max. Surge Loading | 20 | 118/111 | 19/22 | 21/20 |
| Max. Deployment Time | 20 | 38/33 | 7/6 | 82/70 |

## VIII. IN-FLIGHT DEPLOYMENT ANALYSES

The analytical deployment models were updated to reflect parameter differences between the test articles and flight hardware. The RTG deployment analytical model was also modified to simulate the damper release feature which was incorporated into the RTG deployment system design.

In-flight deployment performance for the range of expected in-flight environmental and hardware extremes was predicted using the analytical models. These analyses incorporated the effects of spacecraft spin rate and wobble angle. In addition the RTG deployment analysis incorporated the interaction between RTG Booms, and expected differences in the deployment system parameters from boom to boom. The Magnetometer Boom deployment analysis incorporated the interaction between boom deployment and boom motion about the nutation damper axis.

These results verified satisfactory deployment system performance with adequate structural margins over the range of in-flight conditions.

## IX. CONCLUSIONS

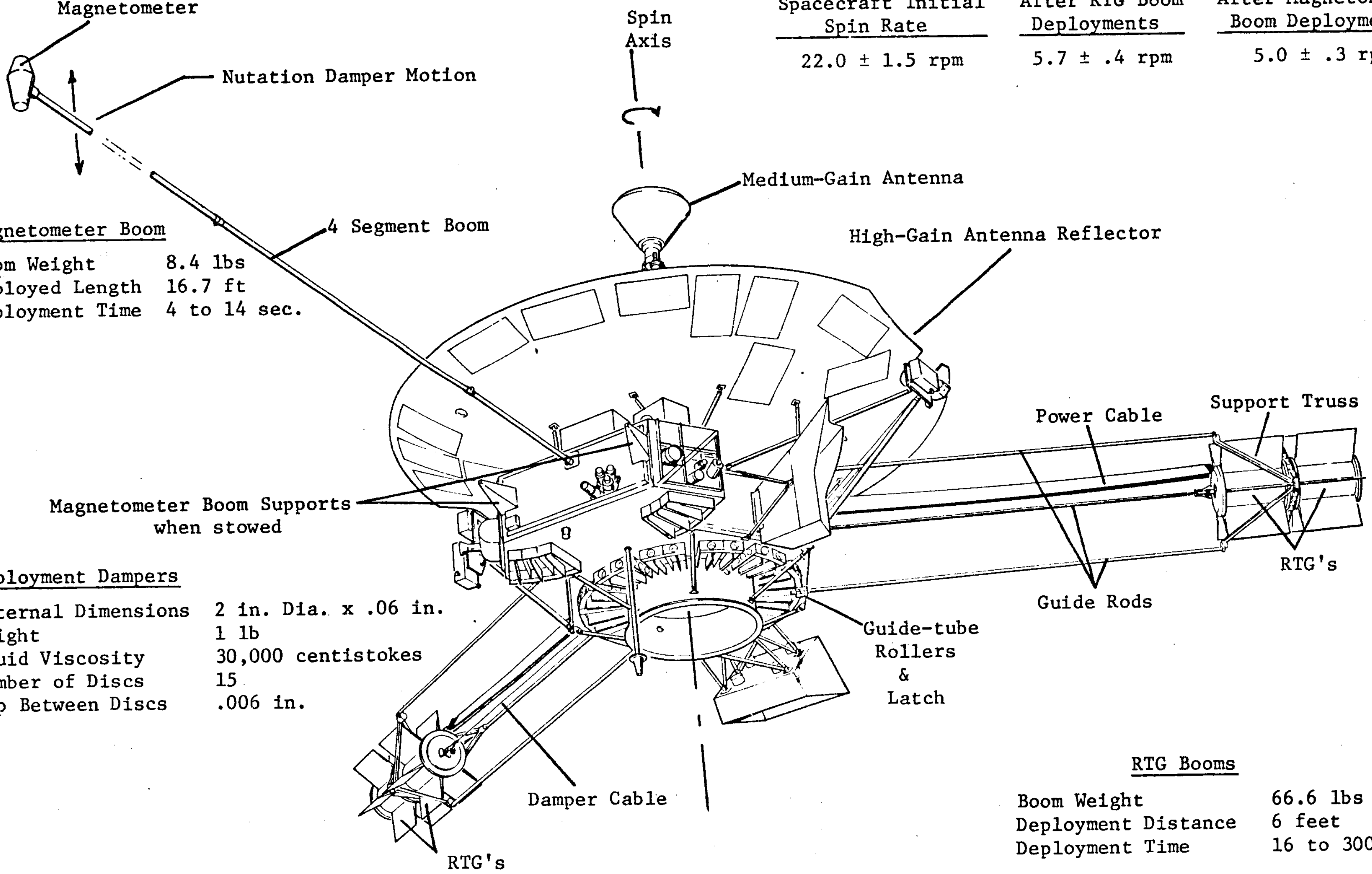
The combined analysis and test program used to verify in-orbit deployment capability of Pioneer F/G appendages is believed to be a reliable and cost effective technique. The approach circumvented deficiencies inherent in attempting to rely solely on either testing or analysis to provide deployment verification. The program successfully incorporated:

- Tests of a zero-g system in a one-g environment.
- Non-spinning tests of spinning deployment systems.
- Tests that verified the analyses as well as hardware functionality.
- Analysis to project final in-flight deployment systems performance over the range of hardware and environmental extremes.

Spacecraft Inertial Properties - Deployed

Weight = 550 lbs $I_x = 280$ $I_y = 190$ $I_z = 440$ slug/ft$^2$

| Spacecraft Initial Spin Rate | After RTG Boom Deployments | After Magnetometer Boom Deployment |
|---|---|---|
| 22.0 ± 1.5 rpm | 5.7 ± .4 rpm | 5.0 ± .3 rpm |



Magnetometer Boom

| | |
|---|---|
| Boom Weight | 8.4 lbs |
| Deployed Length | 16.7 ft |
| Deployment Time | 4 to 14 sec. |

Deployment Dampers

| | |
|---|---|
| External Dimensions | 2 in. Dia. x .06 in. |
| Weight | 1 lb |
| Fluid Viscosity | 30,000 centistokes |
| Number of Discs | 15 |
| Gap Between Discs | .006 in. |

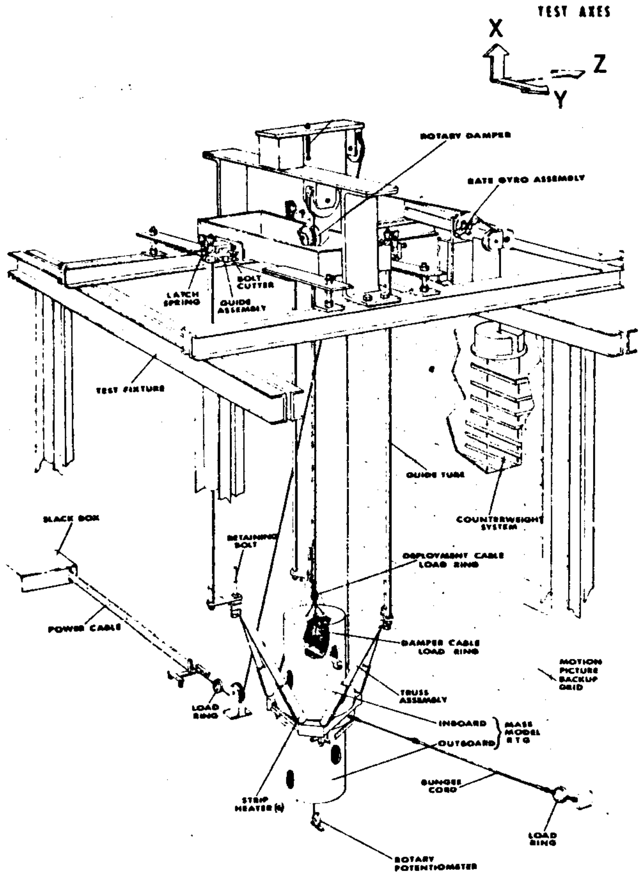
RTG Booms

| | |
|---|---|
| Boom Weight | 66.6 lbs |
| Deployment Distance | 6 feet |
| Deployment Time | 16 to 300 sec |

FIGURE 1

PIONEER F/G SPACECRAFT IN DEPLOYED CONFIGURATION

Fig. 2A RTG Boom Test Setup



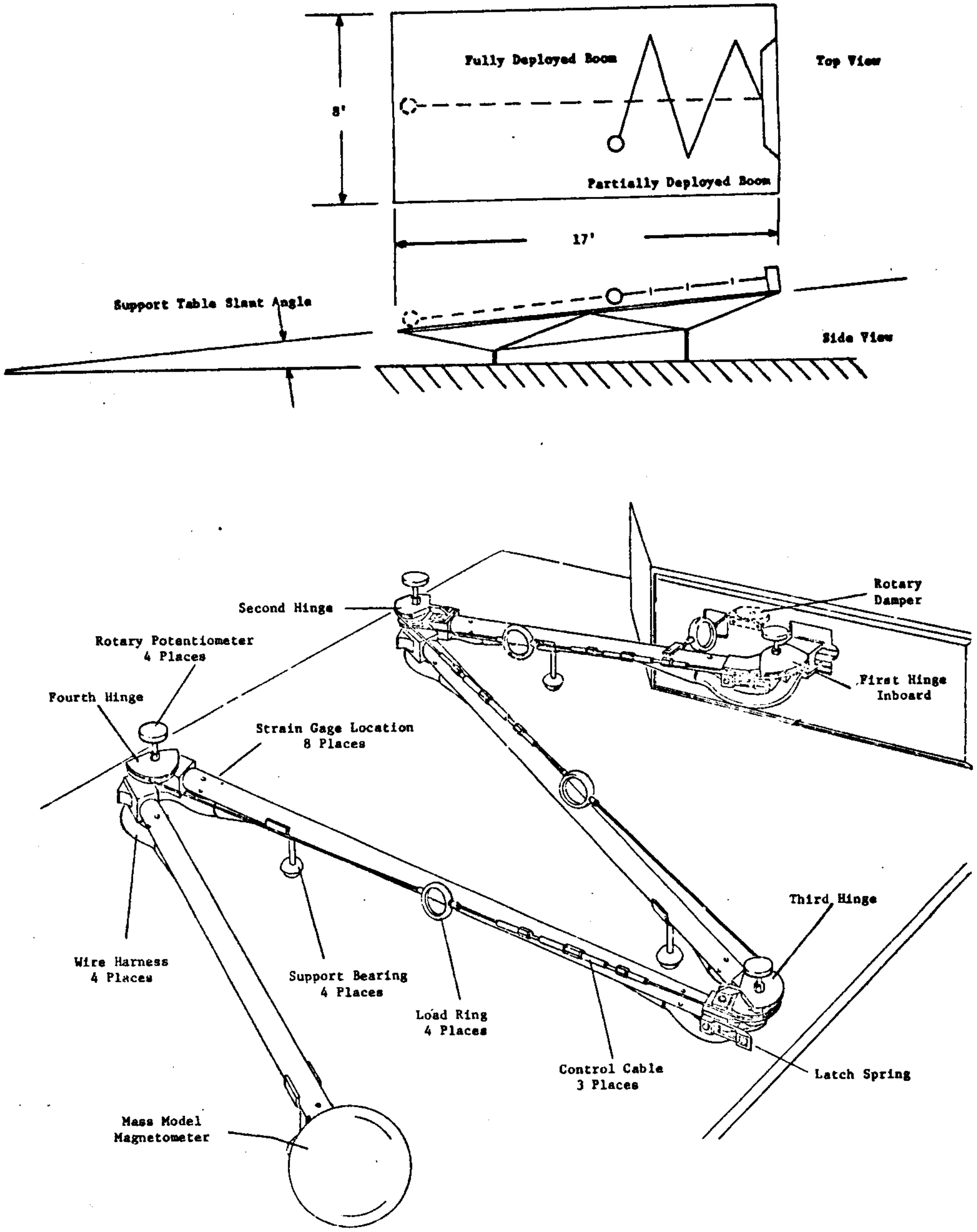


Fig. 2B Magnetometer Boom Test Setup