THE VOYAGER MAGNETOMETER BOOM*

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ABSTRACT

The Voyager spacecraft magnetometer experiment utilizes two sensors on a deployable boom. The boom is an Astromast (Ref. 1), which has been described in the literature. This paper describes the implementation of the Astromast into the Voyager design. The hardware used to hold, latch and deploy the mast is described. The tests to demonstrate damping, deployment and alignments are described. Several problems encountered are discussed and their solutions are given. Flight deployment and preliminary alignment results are presented. Finally, the design is evaluated in retrospect.

HARDWARE DESCRIPTION

The magnetometer boom provides the attachment for the two magnetometer sensors to the spacecraft. One sensor is mounted seven meters from the boom base; the other is thirteen meters. The sensors are to be nominally aligned with the spacecraft axes. Alignment knowledge is to be ±1° relative to the spacecraft and ±0.4° relative to each other. Boom and spacecraft combined must produce a magnetic field no greater than 0.2 nT at the outboard sensor. All surfaces of the boom assembly must be electrically conductive.

The magnetometer boom and canister assembly is a part of the Voyager spacecraft as shown in Figure 1. It is made up of the following major elements: (a) the deployable structure itself is a 9" dia by 512" long (13m) Astromast (Refs. 2, 3, 4, 5), which is shown in Figure 2; (b) two deployable magnetometer sensors are attached, one near the middle of the boom and one at the end of the boom as shown in Figure 3; (c) the magnetometer sensor electrical cables are attached to the boom as shown in Figure 4, as is the canister which supports the boom during launch; (d) the baseplate and damper location are shown in Figure 5, which also shows the installation on the spacecraft; (e) the latch for the end plate is shown in Figure 6 and for the mid-sensor in Figure 7; (f) the retracting supports are shown in Figures 8 and 9. The fixed supports are shown in Figure 8; (g) the rate limiter is shown in Figure 13.

During launch, the boom is not completely stowed, but is in the configuration shown in the lower portion of Figure 2. The fully stowed portion or "stack" is 12 inches long and the transition region from the stack to the base is 14 inches long. The outboard end of the stack is supported by the boom end plate, whose latch and release is described below. The inboard end of the

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stack is supported by three retracting supports equally spaced (Figs. 8, 9). Torsion springs pivot them out of the way to provide an unobstructed canister ID as soon as the stack moves outboard, permitting the transition longeron to pass. The transition longeron is supported in its curved shape by the fixed supports (Fig. 8) to prevent the "stack" from rotating during vibration, thus tightening the transition longeron and causing it to bend sharply over its retracting support.

The outboard end plate carries the boom loads and the magnetometer loads to the canister. The three latch pins which do this are held into holes (elongated holes) in the corners of the end plate by two wire ropes (Fig. 6) which are in turn restrained by a pinpuller. The same pinpuller holds a third wire rope which keeps a latch pin in a clevis and holds the mid-sensor support snug against two conical pins (Fig. 7). All these latch pins are spring loaded to release the latched items. Operation of the pinpuller releases the wire ropes which release the latch pins and allow the boom and instruments to deploy. The deployment force is provided by its mast itself, which tends to self-deploy with a constant force of 8.5 lb. Achievement of this force is the reason the base of the mast is erected during launch. The mast is capable of stowing completely, but then the extension force goes to nearly zero. Without restraint, the boom would deploy with ever increasing speed, possibly damaging itself or the sensors when they stop abruptly at full deployment. Therefore, the rate of deployment is controlled by a rate limiter. This is a reel which contains a nylon lanyard that is attached to the boom structure at the outboard end. Connected to the reel shaft is a rotor that rotates in a silicone fluid filled housing. Once extended in flight, the boom is never retracted.

The mast assembly is unidirection S-glass epoxy composite with 6061-T6 aluminum fittings bonded to it with EA 934 A/B epoxy adhesive. The supports for the boom-mounted sensors are epoxy-glass layups. The sensor cables are wrapped with conductive black teflon ribbon. The end plate and sensor support brackets are painted white for thermal reasons over conductive black for static charge bleed reasons. The longerons have a 34-gauge beryllium-copper wire taped to them every few inches by means of copper foil tape. The lanyard has conductive ribbon sewn to it. All these are required to insure that no portion of the boom can accumulate a static charge large enough to arc to ground and damage the spacecraft electronics. All these items are non-magnetic to very low levels.

The canister is 7075-T73 aluminum, .016 inches thick. The rings riveted to it are also 7075-T73. The spacecraft attachment is made through three quadrupod trusses. Each of these is made up of 6061-T6 aluminum tubes riveted to 6061-T6 aluminum fittings. The base support truss is made of epoxy glass tubes (thermal isolation) bonded to 6061-T6 aluminum fittings. The baseplate is a 6061-T6 aluminum machining. The dampers (Fig. 10) which bridge between the baseplate and the base support truss fittings (Fig. 5) are a polyurethane elastomer ("Dyad 606", Ref. 6) bonded to 6061-T6 aluminum bushings.

DAMPING TESTS

So that oscillations during picture-taking sequences won't cause image smear, 4% damping of the boom was required. Boom tests showed less than 1%

inherent damping, so it was clear that dampers were required. A detailed structural analysis of the spacecraft showed that the critical vibration mode for the boom was equivalent to a 12 lb simple pendulum on a 375-inch arm pivoted at the boom base.

In order to test one damper rather than a set of three, it is necessary to determine the appropriate inertia. For the flight condition, the inertia is $12 \text{ lb} \times (375 \text{ in})^2 = 1.69 \times 10^6 \text{ lb-in.}^2$. This is damped by three dampers equally spaced on a 5 in radius. The appropriate inertia for one damper is $I = 1.69 \times 10^6 \div [1 + \sin^2 (30) + \sin^2 (30)] = 1.12 \times 10^6 \text{ lb-in}^2$, also acting on a 5 inch arm. This was provided by a damper test fixture (Fig. 11) consisting of a beam pivoted in the center with 200-lb weights at 50 in from the pivot: $I = 2 \text{ ml}^2 = 2 \times 200 \times (50)^2 = 1.0 \times 10^6$. (The 12% discrepancy was due to a geometry error - the original calculation erroneously arrived at 353 inches instead of 375.)

The test was set up as shown in Figure 12. The U-shaped spring was adjusted to provide .30 Hz with the damper replaced by a rigid block. This motion simulates the undamped boom attached to a rigid base. When the rigid block is replaced by the damper, the motion properly simulates the flight design condition. Amplitude is measured by a proximity sensor and recorded on a strip chart at the end of the beam. The beam tip amplitude is started at .025 in., which gives the damper arm a .0025 in. displacement. Some of this absorbed by the adjustable spring, which simulates the flexing of the boom; the remainder is absorbed by the damper, and matches the flight displacement.

The damper design is shown in Figure 10. To size the washer, a dummy damper was made with a large area damping washer. It was installed in the fixture and tested. The dummy was removed and machined to a smaller size and the test was repeated. This was continued until the size providing optimum performance was obtained. The flight dampers were made to this size, and were all tested in the fixture to verify they performed as required. Tests were conducted over temperature-the white box is a foam insulating box in Figure 11.

DEPLOYMENT TESTS

Two types of deployment tests were conducted. A full-length test at low temperature was done one time only as a design verification test. A two-foot deployment test was conducted on each assembly at low and high temperatures as a flight qualification test to verify proper unlatching and exiting from the canister.

The two-foot deployment test was done vertically upward, with a counterweight. The stack was tied together except for the six feet nearest the base. This permitted only a few feet of deployment, but it was adequate to demonstrate proper unlatching and exiting of the canister. Typically, the force margin was 5 or 6 pounds, indicating the drag against the canister was about 3 pounds (compares to the deploy force of 8.5 pounds).

There was concern that the electrical cables might prevent boom deployment, especially because they could be as cold as -20°C at deployment. A test was conducted in which the boom assembly was attached to a stand so the mast could deploy full length downward. A chain counterweight whose weight per foot matched the boom (and cabling) was wrapped up on a drum during mast extension, as shown in Figure 13. This simulated zero-g by counterweighting the stack. The entire assembly was precooled in foam box, the bottom of the box was removed, and the latches were released with a pneumatically powered pinpuller. The test was successful. Note than an upward deployment with the chain allowed to collapse into the floor will not work because this will pull the boom out of the canister tip end first (much as fish line spools off a spinning reel) instead of whole stack coming out.

ALIGNMENT TESTS

To obtain the alignment of the Magnetometer sensor mounting surfaces in zero-g, the following system was devised. The boom was initially deployed down putting it in tension (+1 g). The boom was then deployed upward placing it in compression (-1 g). The boom was also counterweighted in both modes to obtain fractions of g's in both tension and compression. The angles obtained were then plotted (g's vs misalignment angle), and a zero-g value was obtained by interpolation. Misalignment angles were obtained, before and after assembly level vibration at each sensor location relative to the mounting points of the canister to the spacecraft. A worst case tolerance build-up from this interface to the spacecraft axes was then calculated and introduced into the results as part of the uncertainty. Measurements were obtained using mirrors at each sensor location and at the canister for bending and a porro prism for twist. A laser mounted on a three axis rotating head was used to find the angles by autocollimation.

A basic problem was discovered in the test. With the boom in tension the angles measured at a sensor location for each counterweight value were plotted and found to be nearly linear, as expected. This was also true in the compression mode. When the two curves were extrapolated to zero-g, however, a significant offset occurred between the tension and compression curves as shown in Figure 14 (approximately two degrees in twist and less than one degree in bending). This anomaly was never resolved.

The predictions of the sensor mounting surfaces in zero-g with respect to spacecraft X, Y, and Z axes and each other for each boom are given in Table 1, along with a total uncertainty comprised of the boom repeatability (from deployment to deployment), boom thermal distortion, sensor removal and reinstallation, allowable sensor bracket thermal distortion, S/C bus and RTG outrigger worse case tolerance build-up, boom dampers, and alignment test measurement error. Because of these large uncertainties, a magnetometer calibration coil was constructed around the high-gain antenna reflector. This permitted an in-flight measurement of two axes of sensor alignment.

PROBLEMS

There were many problems with the development of this hardware. Those judged to be of interest to a future use of this type of boom are given here.

Canister Diameter. The canister diameter is a compromise between a snug fit around the boom to provide good support in launch vibration and a loose fit to provide low drag on the boom during deployment. The geometry is illustrated in Figure 15. The problem was that the tie-strap locks did not nest between the cables as intended, resulting in their rubbing against the canister. In addition, one deployment was stopped by a lock which became caught in one of the retracting support cut-outs. The solution was to replace the tie-straps with string ties. This was a much more tedious installation, but the knots in the string ties were significantly smaller and they caused no significant problems.

Inboard Sensor Slot. As the boom deploys, a point on the stack traces a helix. However, the helix is not uniform because of end effects. The actual path traced by a point on a longeron is shown qualitatively in Figure 16. The first motion of a fully stowed mast is axial; once the base is fully deployed (approximately 30 inches for this mast), the helix angle is 45°; there is a smooth transition between them. This curve, from the 14-inch point outward (our mast is 14 inches from fully stowed) is the curve that should be cut in the canister to allow for deployment of the inboard sensor. (An adjustment has to be made because the canister diameter is greater than the mast.) The design, however, failed to take this into account, and the slot was at the angle appropriate for 30 inches and beyond. The result was that the inboard sensor support moved more nearly axial than the slot and hit the edge of the slot. This was sufficient to stop deployment, under some test conditions. Two changes were made. First, a low-friction pad (teflon) was attached to the inboard sensor support to rub on the canister. Second, the edge of the canister was cut away to provide more clearance.

Handling. A problem which persisted throughout the program was handling damage. This was largely because the mast is a new item and is delicate due to the many slender members. About a dozen diagonals were kinked or significantly nicked such that they were replaced. A handling procedure was generated and revised twice as more handling information became available.

Inspection. The mast is an inspector's nightmare. The boom assembly is made up of 91 bays, each with approximately 20 visual inspections for nicks, splits, chips, etc. in longeron, diagonal and batten elements, tears in the conductive ribbon on the sensor cables, tears or unwrapping of the copper tabs, and ground wire out of place or broken. The electrical checks are simple continuity tests with a multimeter on each pivot fitting and each foil tab. The visual checks are not quickies, especially scanning the diagonals for damage, which requires good lighting and a view from two directions. Initially, these inspection points and methods were not known. Damage was discovered, especially to the diagonals, and when it occurred could not be pinpointed because the inspections made earlier were not in enough detail to have detected them. All this came to light only during rework of the booms for late changes. From that point on, good inspections were performed and in fact verified that vibration and deployment operations were not the cause of these diagonal damage incidents. It takes two people approximately 6 hours to inspect a boom properly.

FLIGHT PERFORMANCE

Final mast stowage and installation on the spacecraft for launch occurred after many problems had been resolved and tests developed to give us confidence that the mast would deploy properly. Nevertheless, the signal confirming full extension of the mast was a most welcome event. The magnetometer sensors were recording data during mast deployment, and the output from each axis was a sinusoid as it rotated in the earth's magnetic field. Figure 17 shows the data from one axis of the sensor at the end of the Voyager 2 boom.

A 12 foot diameter 20 amp-turn coil is attached to the spacecraft antenna for the purpose of making certain alignment measurements in flight. However, two such coils perpendicular to each other would be needed for a complete verification. The experimenter is using the one coil and the interplanetary field to make such measurements as are possible. The work involves developing some new techniques and is not complete at this time. However, we have the preliminary results shown in Table 2. The discrepancies between predicts and actuals are not resolved, and are most disappointing. However, the use of two independent measurements (tension and compression) was most important. Their disagreement identified the problem so that an alignment coil could be implemented to make an in-flight measurement.

DESIGN IN RETROSPECT

The Astromast appears to have been the right choice for the magnetometer boom; it was superior to any of the alternates, including a graphite-epoxy 4-member boom with hinges. Keeping the base erected in the launch configuration was also a good decision. Dampers at baseplate corners worked well. Use of a rigid batten for the mid sensor was good. The pretwisted boom was correct for this application, to preclude thermal twist distortions. The rate limiter works extremely well. Attachment of sensor cabling to the longerons, rather than reeling from a separate spool, worked well but some details should be reexamined. The latch concept of spring-loaded pins held engaged by a cable which is released by a pinpuller was good choice. The outboard sensor latch details were fine but the inboard latch needs reexamination. In fact, the inboard sensor mounting and latching scheme is the only design concept that is really poor, due to operational problems and temperature sensitivity as described below. The alignment concept was most difficult to implement, gave some inconsistent results, and needs to be reexamined. However, alternate approaches appear to have their difficulties also.

The inboard sensor latch has been a source of concern ever since it was designed. The existing hardware meets the requirements, but possesses two troublesome features: temperature changes cause preload on the latch pin, and latch engagement with sensor attached is difficult. The temperature characteristic is resolved by performing an unlatching test over the expected temperature range. The engagement difficulty is largely muddled through with much grunting and groaning of technicians. Another problem with this area is that the boom must be deployed to install the sensor.

The following list of potential changes is offered for consideration. (a) order three lengths of diagonals instead of one to provide twist angle adjustment capability; (b) make the longerons, battens and diagonals electrically conductive inherently instead of as an add-on. (Carbon-filled resin, graphite epoxy, wires imbedded in the material, use titanium instead of fiberglass, etc?); (c) use as large a diameter mast as practical. This minimizes the number of bays, the number of parts (to be reworked perhaps) and the cost. It maximizes the deployment force and accessiblity; (d) the instrument supports (end plate, outboard support bracket, rigid batten) should be redesigned. Present designs are intricate and a little heavy. Consider metal machining with fiberglass insulators. (Voyager eddy current fears resulted in a requirement for nonconductive parts);

(e) pursue a completely stowed boom. If conditions permit full stowage, the result is a shorter package and the elimination of both the retracting and fixed supports.

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2. "Astromasts for Space Applications", available from Astro Research Corporation, P.O. Box 4128, Santa Barbara, California, 93103.
3. "Automatically Deployable Booms", available from ABLE Engineering Company, P.O. Box C, Goleta, California, 93017.
4. "Ball Brothers Research Corp. Design Data for a Coilable Lattice Boom", available from Ball Brothers Research Corporation, P.O. Box 1602, Boulder, Colorado, 80302, Attn: Mr. Nelan Peterson.
5. R. F. Crawford, "Strength and Efficiency of Deployable Booms for Space Applications", AAS/ASAA Variable Geometry and Expandable Structures Conference, Anaheim, California, April 21-23, 1971 (AIAA Paper No. 71-396).
6. Product of the Soundcoat Company, Inc., Brooklyn, N.Y.

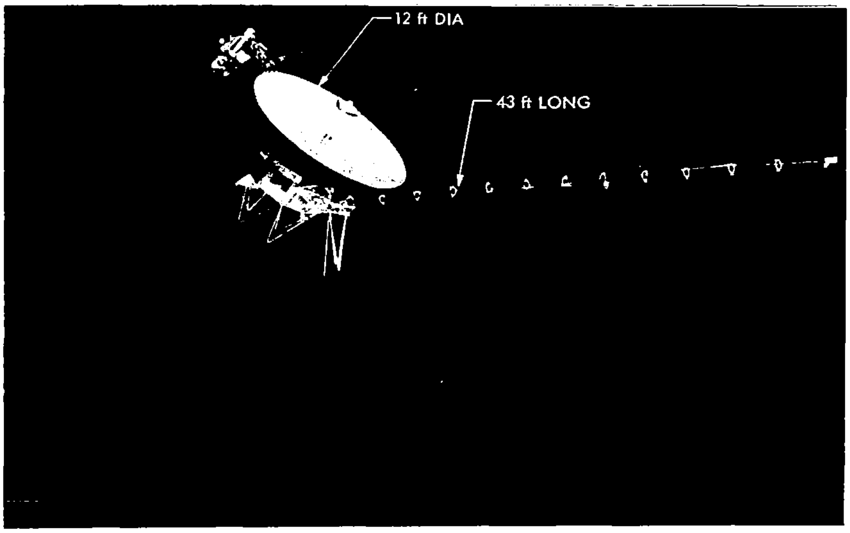
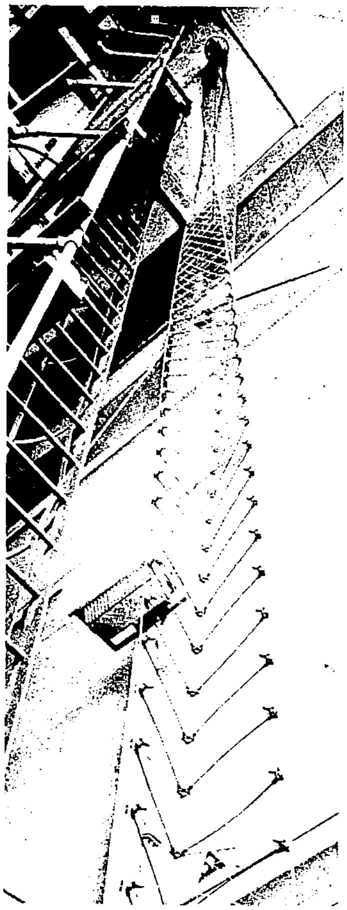
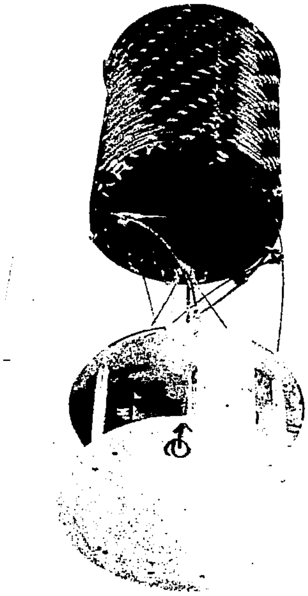


Figure 1. Voyager Spacecraft





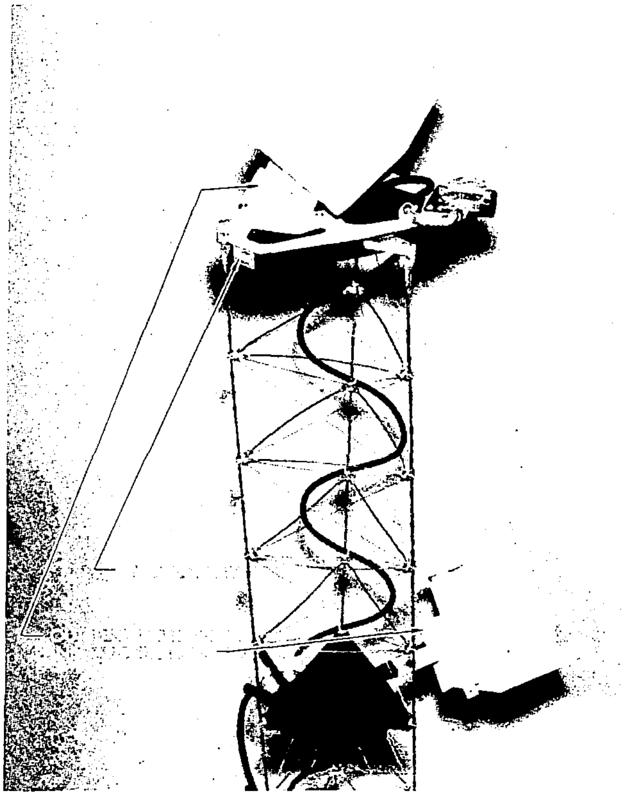


Figure 3. Sensor Attachments

Figure 2. Astromast

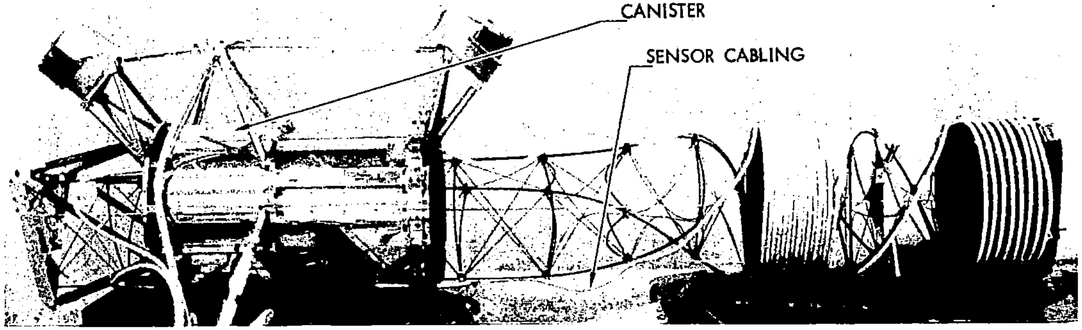


Figure 4. Sensor Cabling Attachment

Figure 5. Spacecraft Installation

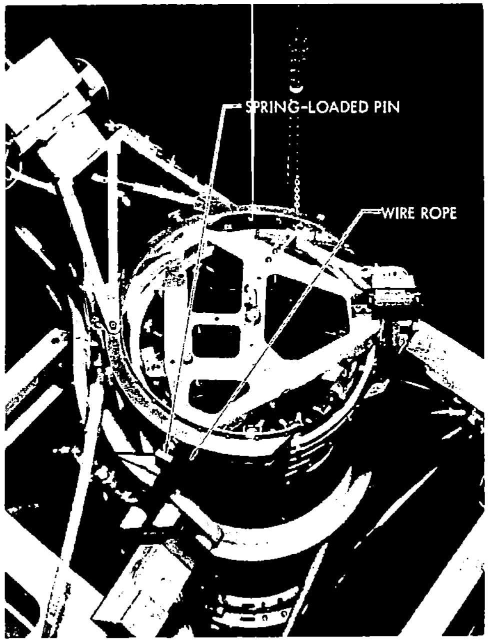


Figure 6. Outboard Latch

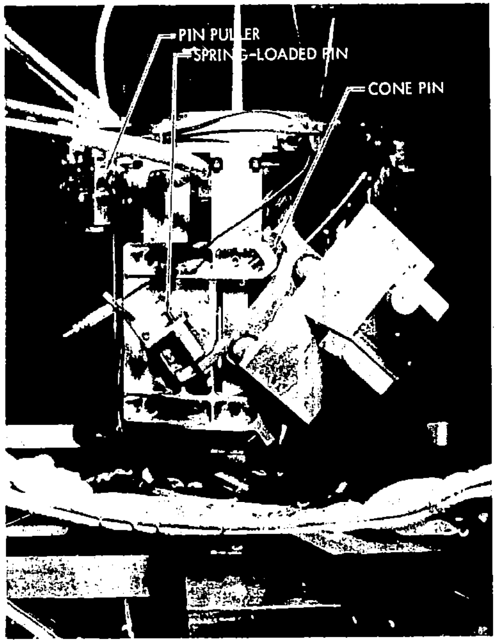


Figure 7. Inboard Latch

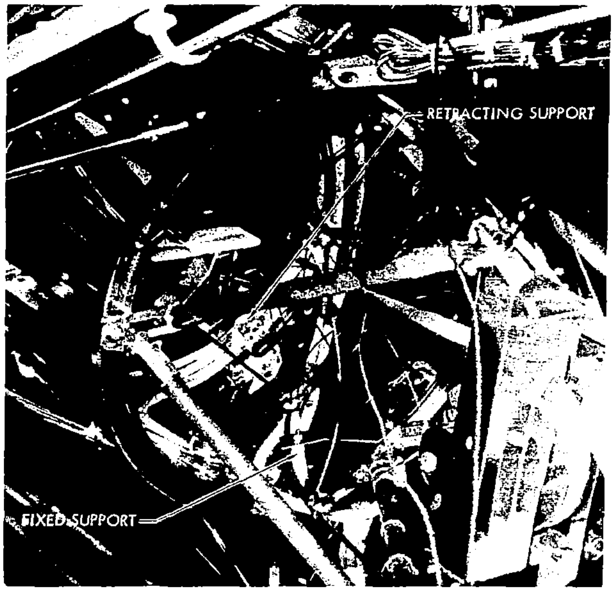


Figure 8. Retracting & Fixed Supports

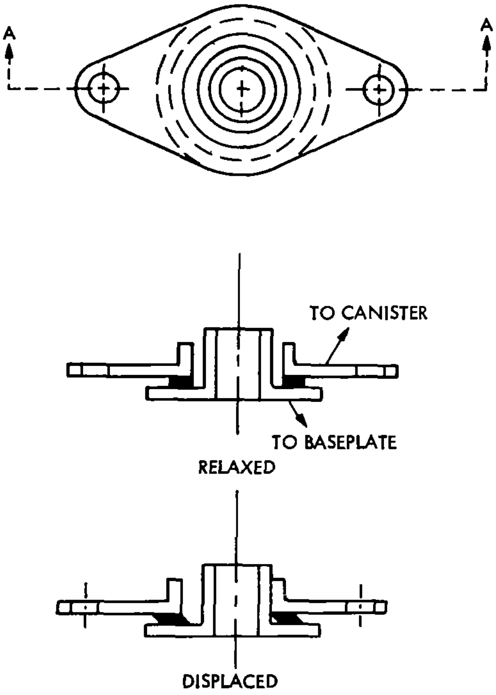


Figure 10. Damper

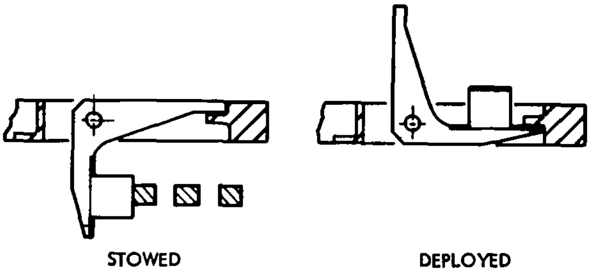


Figure 9. Retracting Support

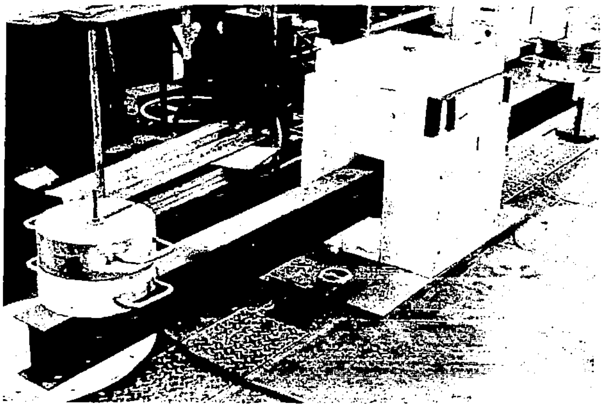


Figure 11. Damper Tester

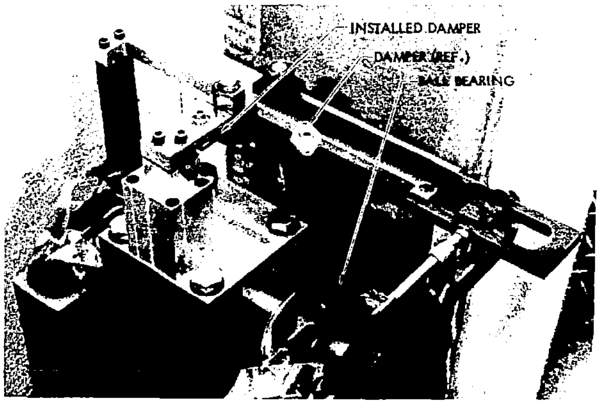


Figure 12. Damper Tester Details

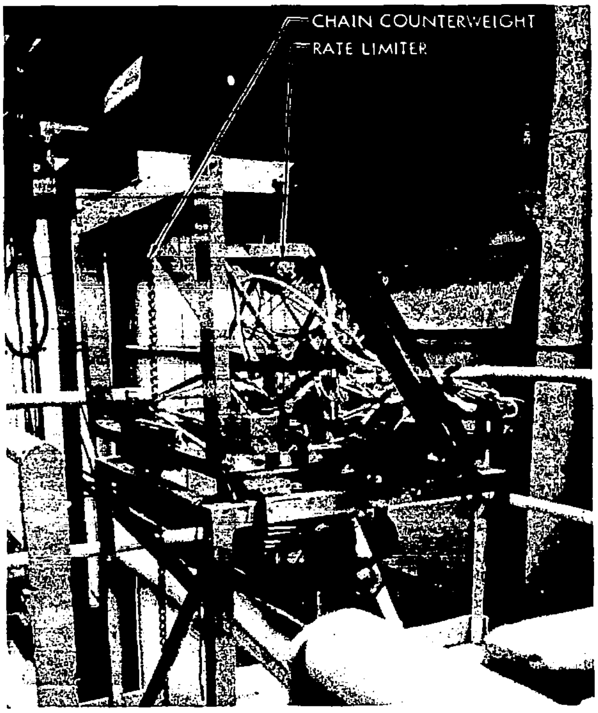


Figure 13. Full Length Deployment Test

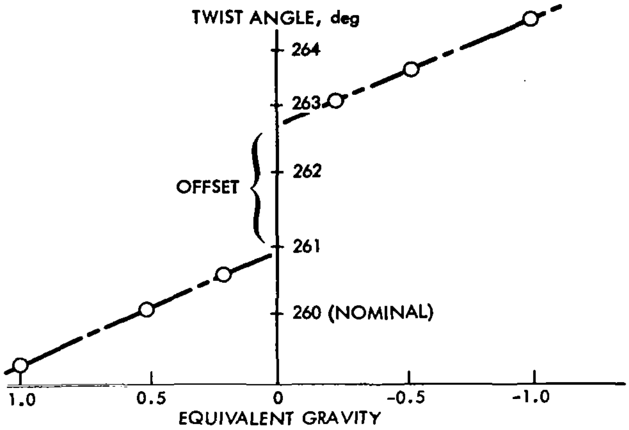


Figure 14. Twist Angle vs Gravity

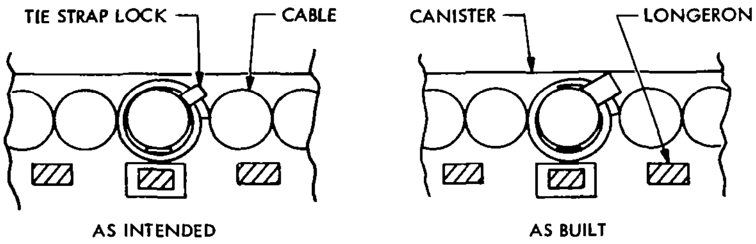


Figure 15. Tie Strap Problem

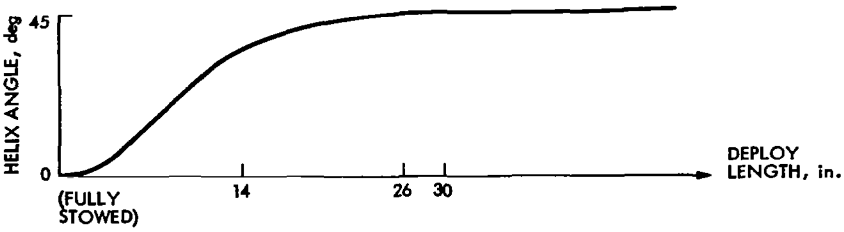


Figure 16. Helix Angle vs Transition Length

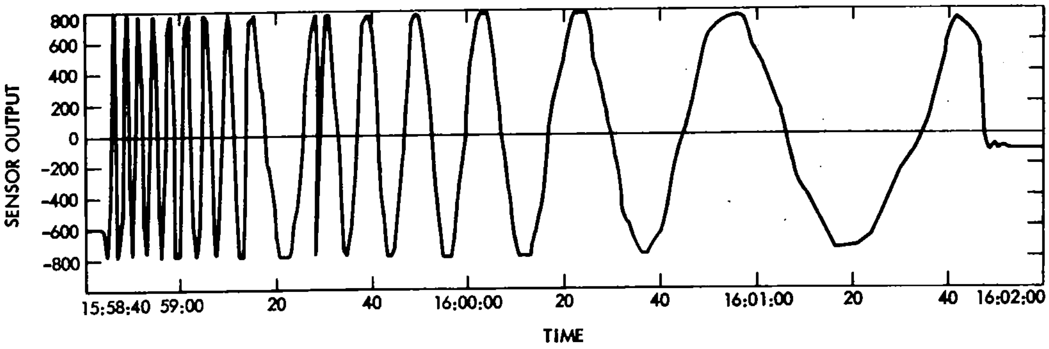


Figure 17. Voyager 2 Flight Deployment

Table 1. Predicted Flight Alignments*

		X-AXIS	Y-AXIS	Z-AXIS
VOYAGER 1	INBOARD SENSOR TO S/C	+1.59 ± 0.39	+1.51 ± 2.21	-1.49 ± 1.95
	OUTBOARD SENSOR TO S/C	-0.20 ± 0.87	+0.17 ± 1.35	-0.17 ± 1.14
	INBOARD TO OUTBOARD SENSOR	+1.40 ± 1.16	+1.37 ± 1.70	-1.35 ± 1.95
VOYAGER 2	INBOARD SENSOR TO S/C	+2.40 ± 0.67	+1.80 ± 2.82	-1.73 ± 2.42
	OUTBOARD SENSOR TO S/C	+0.79 ± 0.71	-0.76 ± 2.26	+0.76 ± 1.94
	INBOARD TO OUTBOARD SENSOR	+1.62 ± 0.67	+2.27 ± 4.06	-2.25 ± 3.45
SPARE	INBOARD SENSOR TO S/C	+1.27 ± 0.67	+1.70 ± 2.17	-1.69 ± 1.90
	OUTBOARD SENSOR TO S/C	+1.09 ± 1.03	+0.96 ± 1.15	-0.95 ± 1.02
	INBOARD TO OUTBOARD SENSOR	-0.45 ± 0.64	+0.68 ± 1.56	-0.68 ± 1.34

Table 2. Actual Flight Alignments
(Preliminary)*

		X-AXIS	Y-AXIS	Z-AXIS
VOYAGER 1	INBOARD SENSOR TO S/C	0	0	+1.9
VOYAGER 2	INBOARD SENSOR TO S/C	-1.6	0	+1.4
	OUTBOARD SENSOR TO S/C	0	0	0

*Values are deviations from nominal (in degrees) about spacecraft axes, with 3-sigma uncertainties given for the predictions.