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THE GALILEO SPACECRAFT MAGNETOMETER BOOM

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ABSTRACT

The Galileo spacecraft utilizes a deployable lattice boom to position three science instruments at remote distances from the spacecraft body. An improved structure and mechanism to precisely control deployment of the boom, and the unique deployment of an outer protective cover are described.

INTRODUCTION

The Galileo spacecraft contains an 8.2-meter deployable magnetometer boom as shown in Figure 1. The boom consists of two deployable masts, three instrument mounts, and a launch canister. These mechanisms were developed jointly by the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California and ACE-Able Engineering of Goleta, California.

MAST DESIGN

The masts are coilable, longeron-type, deployable structures. The main structural elements are three continuous (single-piece) longerons which are shear-stiffened when erected. The longerons are elastically deformed (coiled) and the battens buckled in order to stow the boom. They and the shear-stiffening diagonals are made of unidirectional, S-glass epoxy material, and are therefore highly elastic. In effect, the structure is made up of spring members which must be forcibly distorted during initial stowage into the canister. This distortion stores strain energy, which is released to effect deployment. Without some means for controlling the deployment, however, substantial, undesirable accelerations would be imparted to the spacecraft, and the boom itself could be damaged.

The stowed boom is contained in a 0.6-meter-long canister during Galileo launch into earth orbit. The boom then deploys to its full length.

The coilable, longeron-type, deployable structure has been used on previous spacecraft applications, including Voyager, Solar-Max, USAF S-3, and OAST-1. However, the Galileo application is unique with regard to five features:

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- The Galileo boom consists of two independent, deployable sections, an inboard mast and an outboard mast, as shown in Figure 2.

- As it deploys, the boom is attached to a highly maneuverable, spinning spacecraft, and thus experiences loading due to vehicle spin dynamics such as nutation, wobble, and translational accelerations.

- Achievement of a stable, spinning-spacecraft attitude requires predictable boom deployment in order to minimize the amount of undesired acceleration to the spacecraft and boom structure during deployment.

- The Jovian environment requires that the mast structure and electrical cables be protected from electrostatic build-up and micrometeoroids. Protection is provided by the use of a stowable, pop-out cover which totally encloses each mast and provides "first surface" micrometeoroid protection.

- The protective cover over the masts requires that the launch/stowage canister be mounted around the masts after the masts are stowed.

DEPLOYMENT SEQUENCE CONTROL

The Galileo magnetometer boom contains a deployment-control system which provides a precisely controlled deployment rate and sequence without the use of active or commandable elements. Once released from its canister, the boom automatically deploys in a controlled manner with the erecting sequence proceeding as described below.

The deployment rate is controlled by a rotary, viscous damper located at the base of the inboard mast, as indicated in Figures 2 and 4. A metallic lanyard connects the storage reel to the deployable structure. This arrangement is similar to that of previous applications. However, the method used to attach the end of the lanyard to the deployable structure is unique. The lanyard passes through the center of the mast, from the base of the inboard mast to the outer end of the outboard mast. On previous applications, the lanyard was attached at the outboard support plate, but in this application the lanyard is looped over a pulley at the outboard end and routed back upon itself to the midsection structure, where it is secured. This arrangement produces a mechanical advantage between the lanyard forces produced by the inboard mast on the outboard mast.

As the inboard mast deploys, the elastic energy stored in the erection springs and the masts produces a force of 89 newtons (20 pounds) on the lanyard. That force is transmitted to the rotary damper (rate limiter) as the lanyard pays out in a controlled manner. The 89-newton lanyard force acts around the outboard pulley and back to the midsection structure, thereby producing a force of 178 newtons (40 pounds) across the coiled outboard mast. The 178-newton load holds the outboard mast closed even though it has an 89-newton deployment force of its own.

Once deployed, the inboard mast can no longer tension the lanyard. At this time the 89-newton force of the outboard mast and outboard erection springs tensions the lanyard to 44.5 newtons (10 pounds). Now, the outboard mast deploys at a much slower rate than the inboard mast. The rate is slower because the tension in the lanyard is now only half of what it was during inboard-mast deployment, and twice as much lanyard must be deployed for each unit length of mast deployed.

Figure 3 shows that the inboard mast first erects into a rigid structure at its base, and then continues to deploy outward. This controlled erecting sequence minimizes the dynamic loading produced by Coriolis and other forces during deployment.

The inboard end of each mast is caused to erect first by means of a base erecting spring (see Figure 4) at the inboard end of each of the mast longerons. The springs produce a relatively uniform torque through the first 45° of longerons rotation and guarantee that the erecting sequence will begin as shown in Figure 3.

Full deployment of the base of the mast is guaranteed by using batten members with 14% smaller diameters in the first and second batten frames on the inboard end of each mast. This assures that the base of the mast will lock-up into a fully erect structure before the remaining stowed portions of that mast begin to deploy.

Completion of the deployment of a coilable, longeron-type mast results in a large transient load condition resulting from the final release of stored energy as the longerons rapidly rotate into their fully deployed state. This peak load is as much as 20 times greater than the 89-newton deployment force. It is necessary to provide a method for relieving the peak load in order to prevent failure of the lanyard.

Figure 5 shows the method employed for this purpose. The body of the rate limiter is spring-loaded with a negator spring to the base plate of the canister. When the spring preload is exceeded by the peak deployment force, the body of the rate limiter rotates, allowing sufficient additional lanyard to pay out, thereby reducing peak lanyard loads. By using this method, the peak lanyard loads are limited to approximately 200 newtons (45 pounds).

DEPLOYMENT RATE CONTROL

The mechanism to control the magnetometer deployment rate is a "shear-type" rotary damper. The damping force is produced by the fluidshearing action across a gap between the stationary damper housing and the rotor contained within the housing. Figure 5 shows the construction details of that unit.

A similar damper configuration was previously used for boom deployment control on the 3-axis-stabilized Voyager spacecraft (Ref. 1). However, the Voyager boom was smaller in cross section, and the required damping was correspondingly less. Also, deployment from a 3-axis-stabilized platform eliminated much of the need for precise control of the deployment rate.

Three specific characteristics of the Voyager damper were unacceptable for the Galileo application:

- The Voyager deployment force was 38 newtons (8.5 pounds) versus 89 newtons (20 pounds) for Galileo. Therefore, more damping was required.

- The ambient temperature deployment rate for the Voyager boom varied from 0.26 m/s (10.2 in/s) at the start of deployment to 0.006 m/s (0.25 in/s) at completion of deployment. This large variation in the deployment rate was not acceptable for Galileo applications.

- Because of the high fluid-shear rate associated with the 0.26-m/s Voyager deployment, a thixotropic loop (See Figure 6) occasionally formed in the damping fluid and this occurrence caused less than expected damping.

DAMPER PERFORMANCE

The performance of the shear-type damper is given by the approximate (but acceptably accurate) equation

$$T = \frac{hD^3}{cC_1}$$

T = Torque

h = Rotor width

= Dynamic viscosity

= Rotor speed

D = Mean diameter of the fluid gap

c = Fluid gap width

C_1 = Numerical constant depending on system of units used

This equation can be simplified using the following factors:

h = 1.11 cm (same as Voyager)

= Kinematic viscosity = 32.11 $(V/C)^{0.5}$ lb·s/ft^2 (measured value for 500,000 cSt fluid; see Ref. 2)

c = 0.128 mm (same as Voyager)

V = Velocity across the fluid gap

V_D = Deployment velocity

R = Pulley radius

C_2 = Numerical constant depending on system of units used

The damping equation then simplifies to the form:

$$V_D = \frac{F_D^2 R^3}{C_2 D^5}$$

This equation identifies the sensitivities of the controlling damping parameters, and shows that D and R greatly affect performance.

This analysis also clearly indicates that the increased deployment force associated with the Galileo boom would result in excessively rapid deployment unless the Voyager damper were redesigned to provide increased damping control. This was accomplished by increasing the mean rotor diameter (D) from the 3.20-cm diameter for Voyager to 7.62 cm for the Galileo damper. Also, the Voyager lanyard pulley allowed a pulley-radium decrease, as the lanyard paid out, from 3.56 cm at deployment initiation to 1.02 cm at deployment completion. This difference of radius (R) allowed the excessive deployment rate variation as previously discussed. For Galileo, the variation of R is minimized by using a larger pulley and a thinner, metallic lanyard with R varying from 3.81 cm at the start of deployment to 3.30 cm at the completion of deployment.

These damper modifications result in the performance indicated in Figures 7 and 8. A fluid viscosity of 50,000 cSt was selected for the Galileo damper, and this resulted in deployment characteristics as shown in Figure 9. The maximum fluid-shear rate which occurred in the Voyager damper was 411/s. But, for Galileo, this maximum value was reduced to 178/s, and, can be seen from the slopes of the damping curves in Figures 7 and 8, the possibility of the formation of a significant thixotropic loop is eliminated.

PROTECTIVE COVER

The magnetometer boom cover provides: (1) a black, nonspecular surface to minimize reflections from the spinning boom back to the science instruments located on the despun section of the spacecraft; (2) a conductive outer surface to prevent build-up of electrostatic charges; and (3) a "first surface" against micrometeoroids in the Jovian environment for protection of the mast structure and the instrument's electrical cables.

The "pop-out" covers (Figure 10) are fabricated from a graphite-coated, Kapton thermal-blanket material. Each cover is spaced from the coilable structures by fiberglass, lenticular-shaped springs (standoffs) (Figure 11) which are attached to the mast at each batten frame. The cover and lattice masts are folded together by manually collapsing all standoffs (Figure 12), and then folding the collapsed cover into the stowed masts (Figure 13).

Figures 3B, 10, and 13 show the cover as being loosely formed and not in the triangular shape shown in Figure 11. The extra material in the cover is to allow for differential thermal shrinkage between the boom and cover. It is desired that the cover be untensioned when cold (approximately -223°C) to prevent it from affecting the mast shape and thus changing the alignment of the instruments.

LAUNCH CANISTER AND RELEASE MECHANISM

The magnetometer outboard support plate and canister are shown in Figure 14. The canister consists of three curved, honeycomb panels joined at three longitudinal joints along the panel edges, and attached to the magnetometer boom base plate by a circumferential bolt pattern on the inboard end of the canister. This structural arrangement is necessary to allow access to the sides of the mast while it is being stowed. Access is required to align the protective cover's "pop-out" brackets and to fold in the deployable protective cover. Once the masts are fully stowed, the canister segments are assembled around them and secured to each other and to the base plate.

Spring-loaded latch pins are located at six places on the canister. These pins engage a set of three slots in the magnetometer boom outer plate and three additional slots in the magnetometer boom midsection structure. Three wire-rope cables (Figure 14) are tensioned to push the spring-loaded pins into the appropriate slots in the magnetometer boom. A single pyrotechnic pin-puller mounted to the side of the canister (Figure 14) releases all of the cables and allows deployment to start.

SUMMARY

The Galileo magnetometer boom development program began in late 1978 and the flight boom was delivered to the Galileo spacecraft in May 1984. Magnetometer boom formal testing included: sine and random vibration, hot and cold deployments, magnetic cleanliness checks, and electrical bonding/grounding checks.

The Galileo magnetometer boom design relied heavily upon the experience gained during the earlier Voyager program. Many potential problems were avoided and the Galileo development effort was mainly problem-free.

For the Galileo magnetometer boom, the use of a larger, less delicate, coilable-mast structure than the one used for Voyager greatly reduced the handling damage which was a continuing problem during the Voyager program. The only significant, unresolved Galileo magnetometer boom problem relates to the complexity of the boom-cover design. Each cycle of operation (deployment/stowage) causes some damage to the cover surface. This damage is repairable after each deployment; however, the cover is definitely life-limited. A total of six deployments is considered to be a reasonable life limit. With the exception of the cover design, and given the same set of design requirements, no design change would be recommended for similar boom applications.

REFERENCES

(1) "The Voyager Magnetometer Boom," David C. Miller, 12th Aerospace Mechanisms Symposium, April 27-28, 1978, Moffett Field, California.

(2) "Mariner-IV Structural Dampers," Peter T. Lyman, 1st Aerospace Mechanisms Symposium, May 19-20, 1966, Santa Clara, California, pp. 37-50.

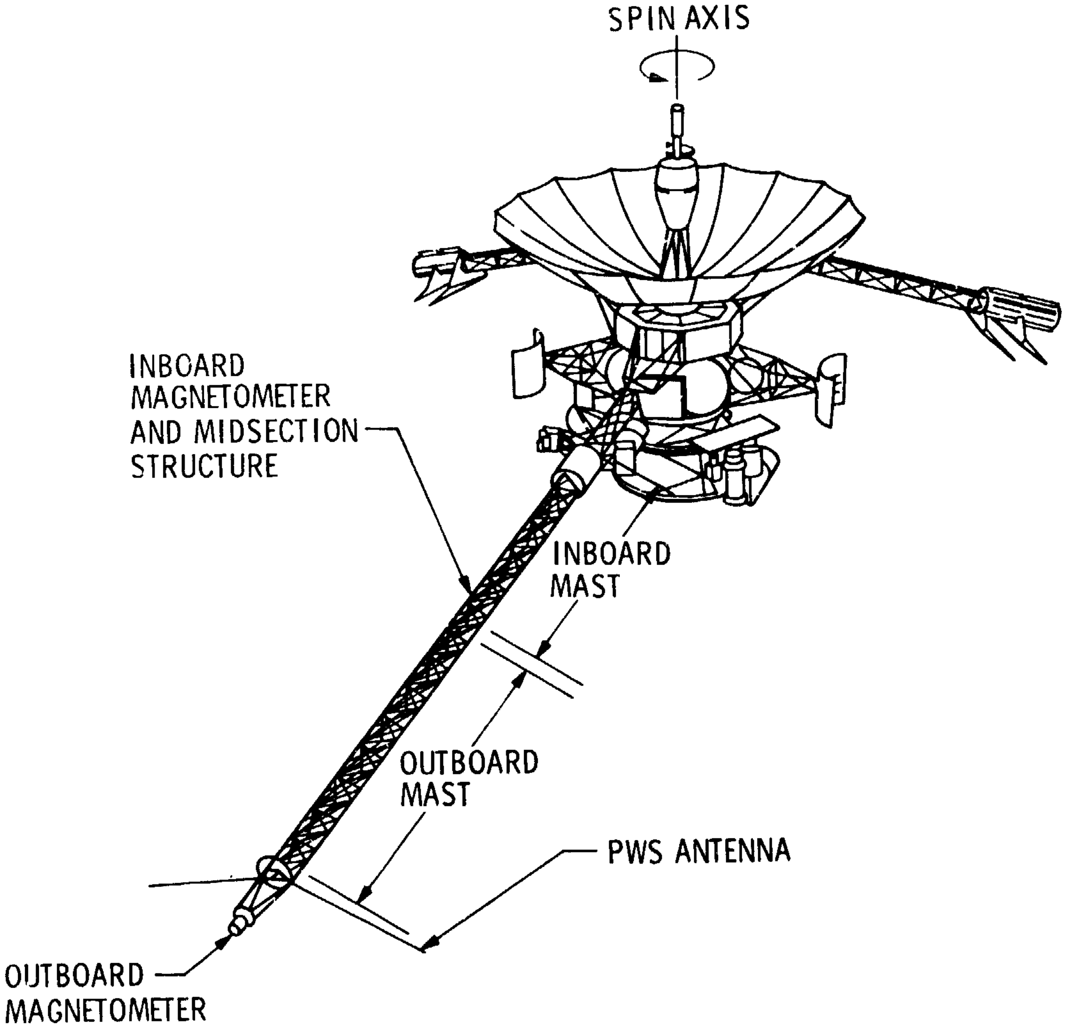
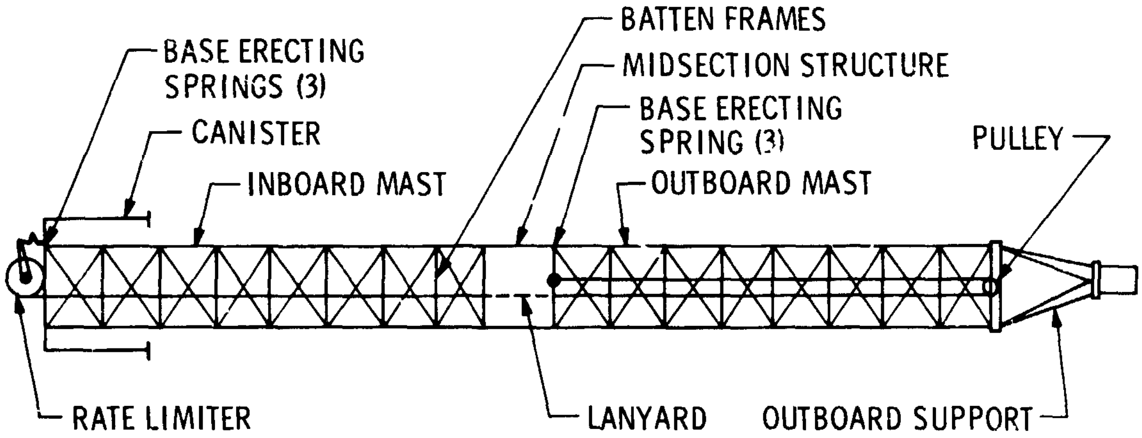


Figure 1. Galileo Spacecraft



THE BOOM DEPLOYMENT CONTROL SYSTEM CONSISTS OF THREE FUNCTIONAL ELEMENTS:

1. THE DEPLOYMENT LANYARD.
2. THE DEPLOYMENT RATE LIMITER.
3. THE BASE ERECTING SPRINGS.

Figure 2. Galileo Magnetometer Boom

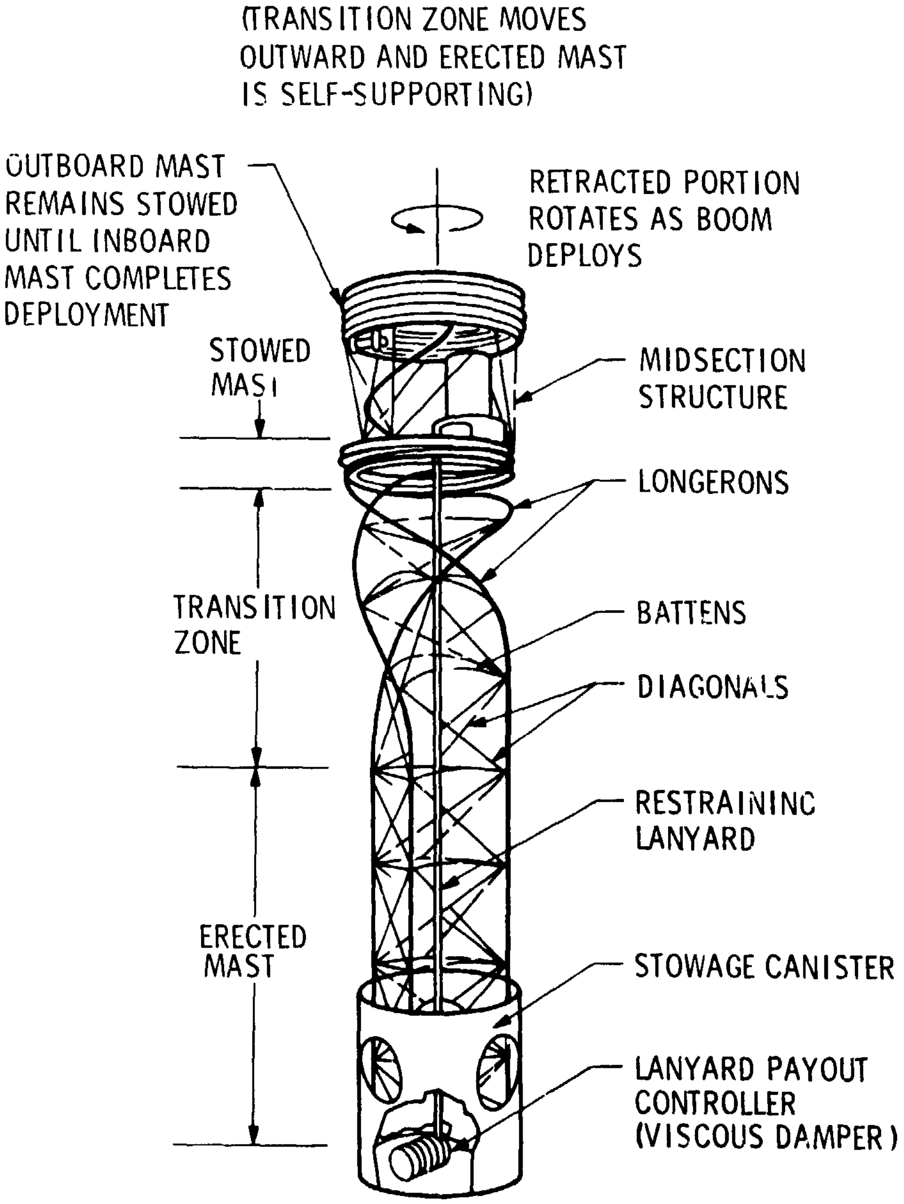


Figure 3A. Erecting Sequence

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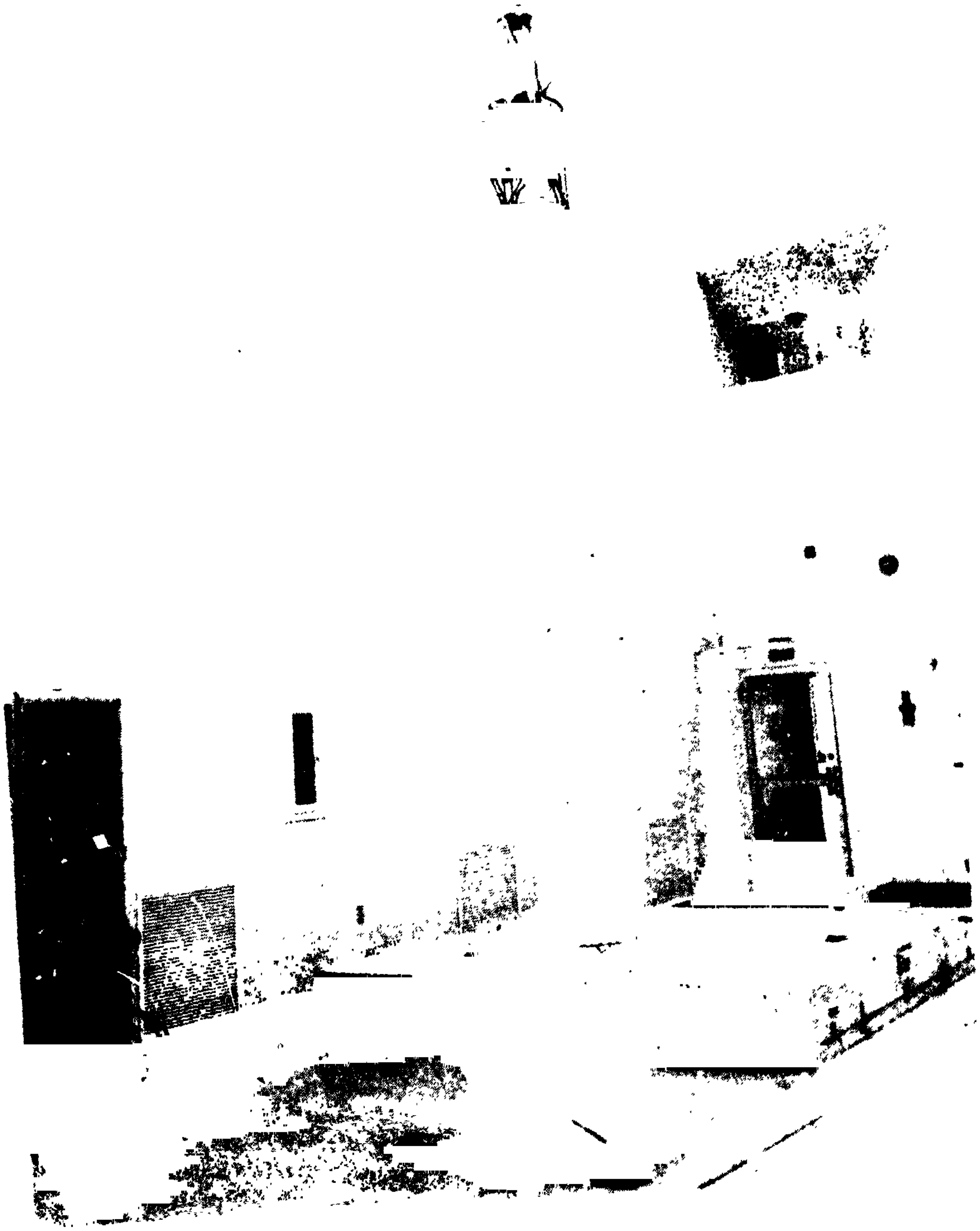

Figure 3B. Galileo Magnetometer Boom at Deployment Midpoint

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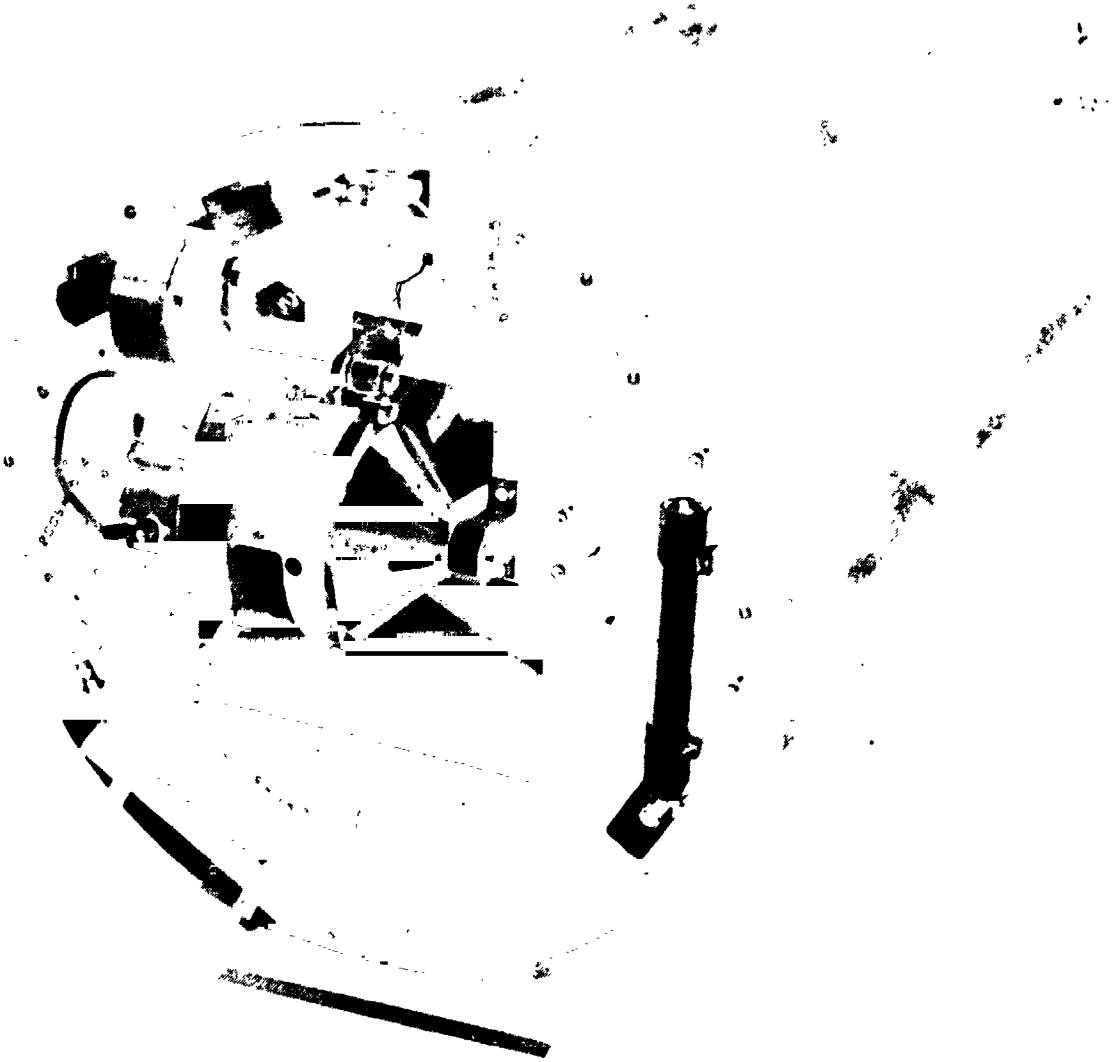

Figure 4. Magnetometer Boom Base Plate

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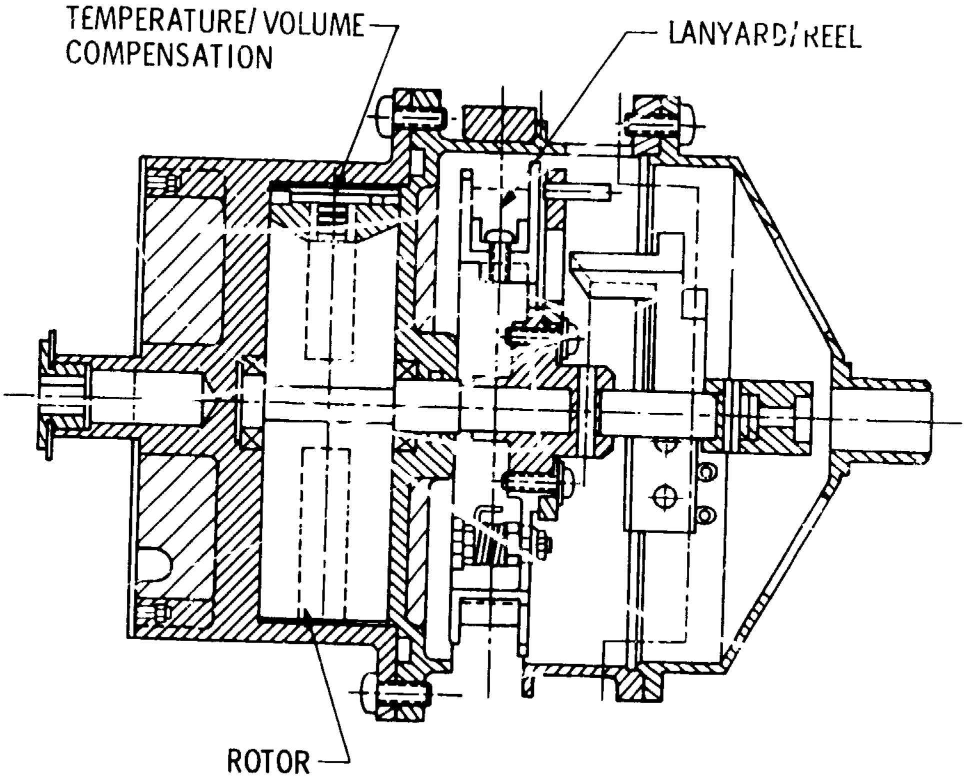

Figure 5. Magnetometer Boom Rate Limiter

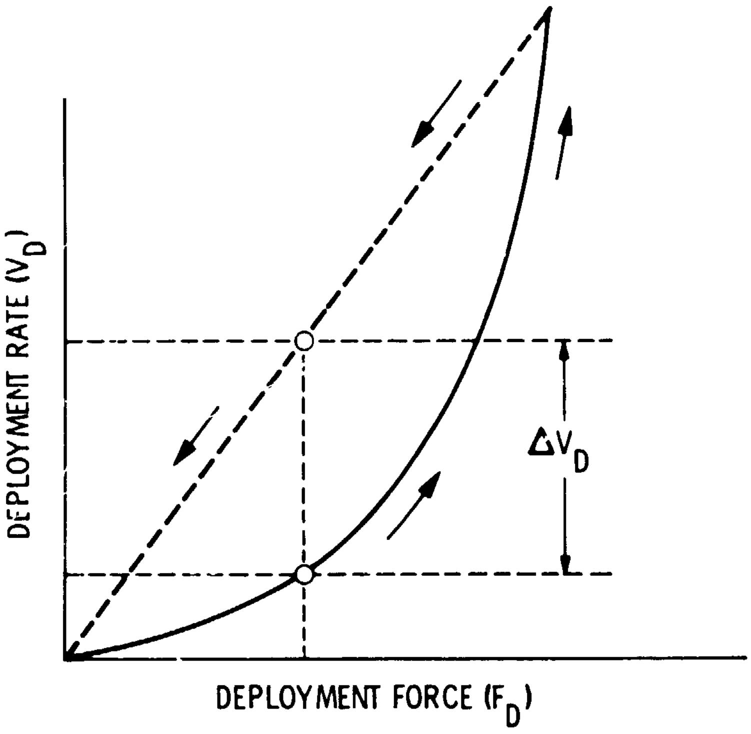

Figure 6. The Thixotropic Loop

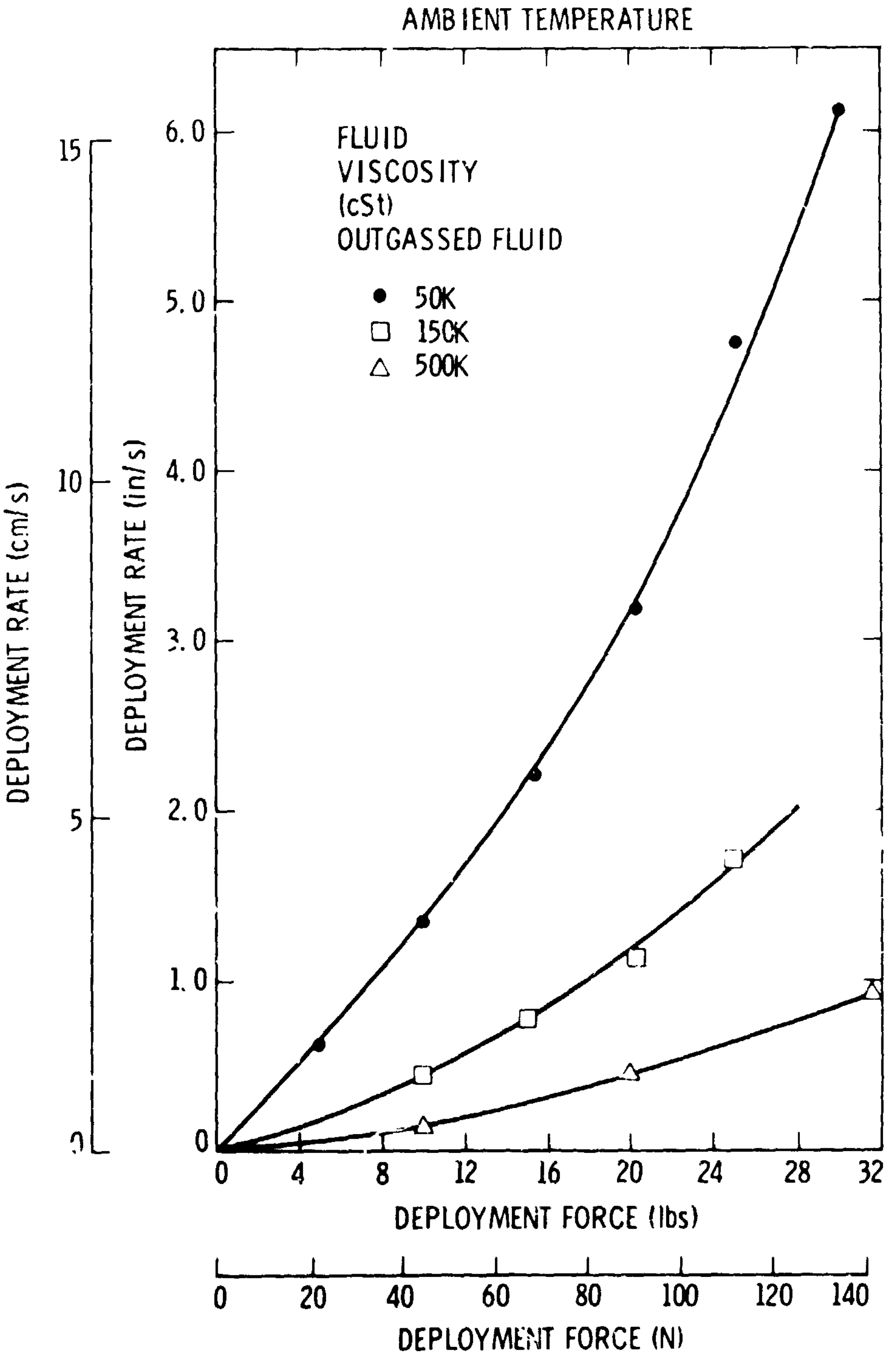

Figure 7. Galileo Magnetometer Boom-Rate-Limiter Damping Characteristics

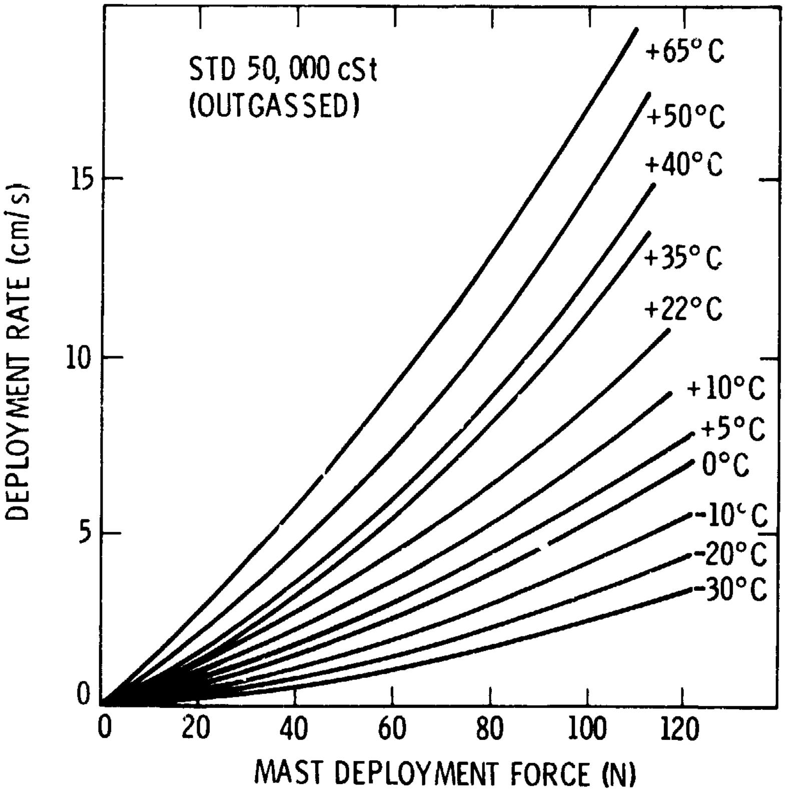

Figure 8. Galileo Magnetometer Boom Rate Limiter Performance at Temperature

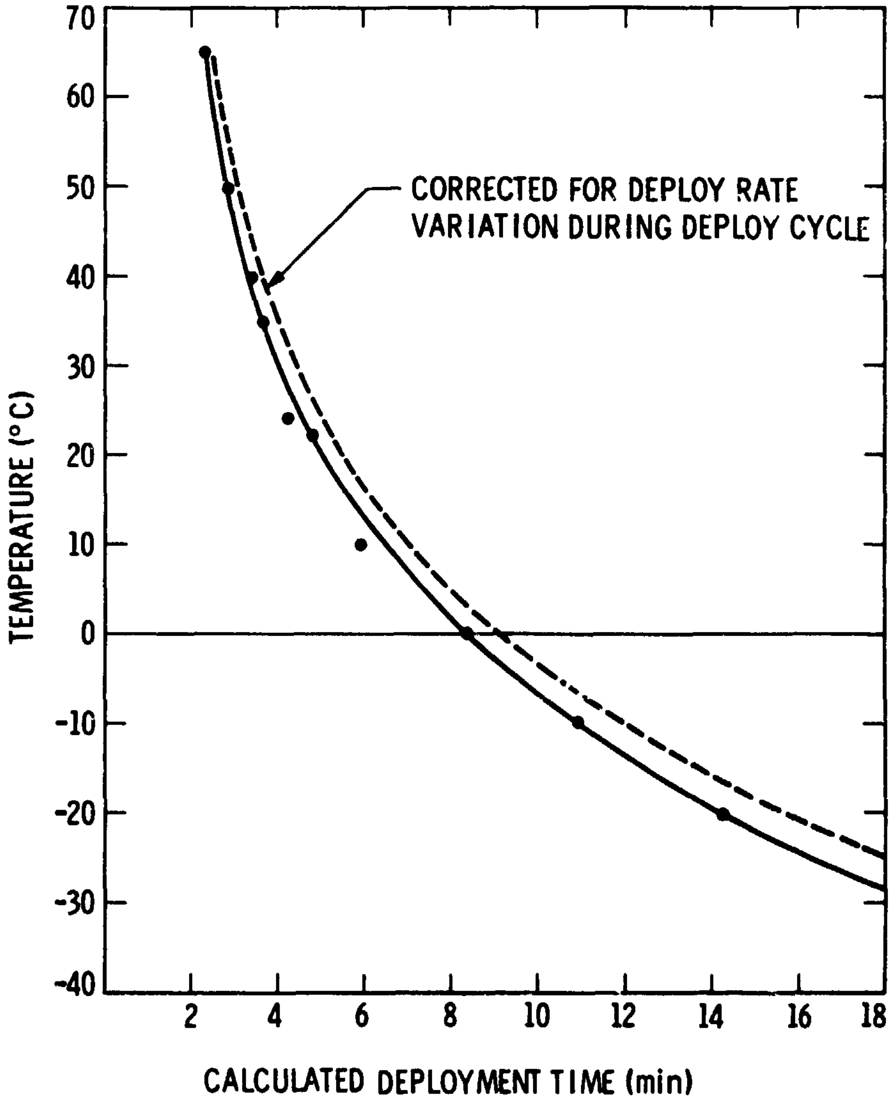

Figure 9. Galileo 7-Meter Deployable Mast Deployment Characteristics

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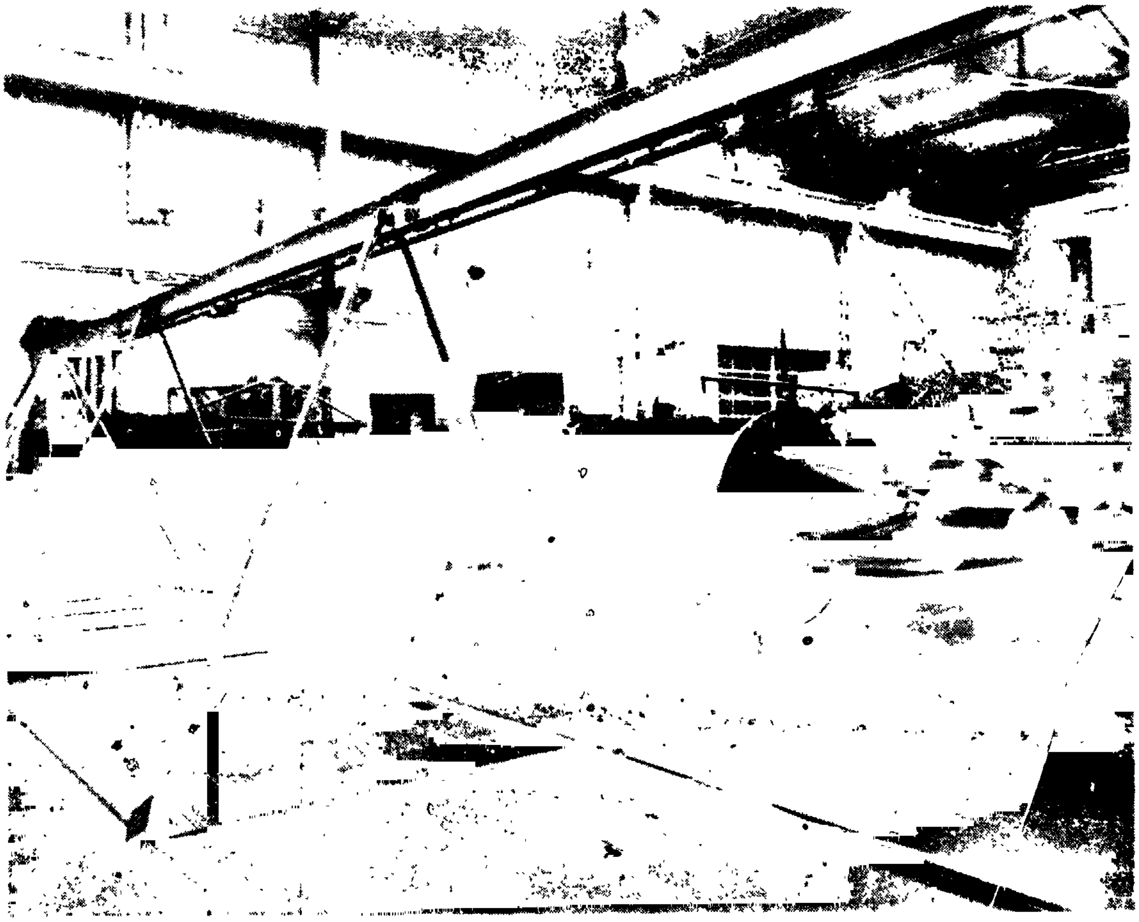

Figure 10. Galileo Magnetometer Boom (Fully Deployed)

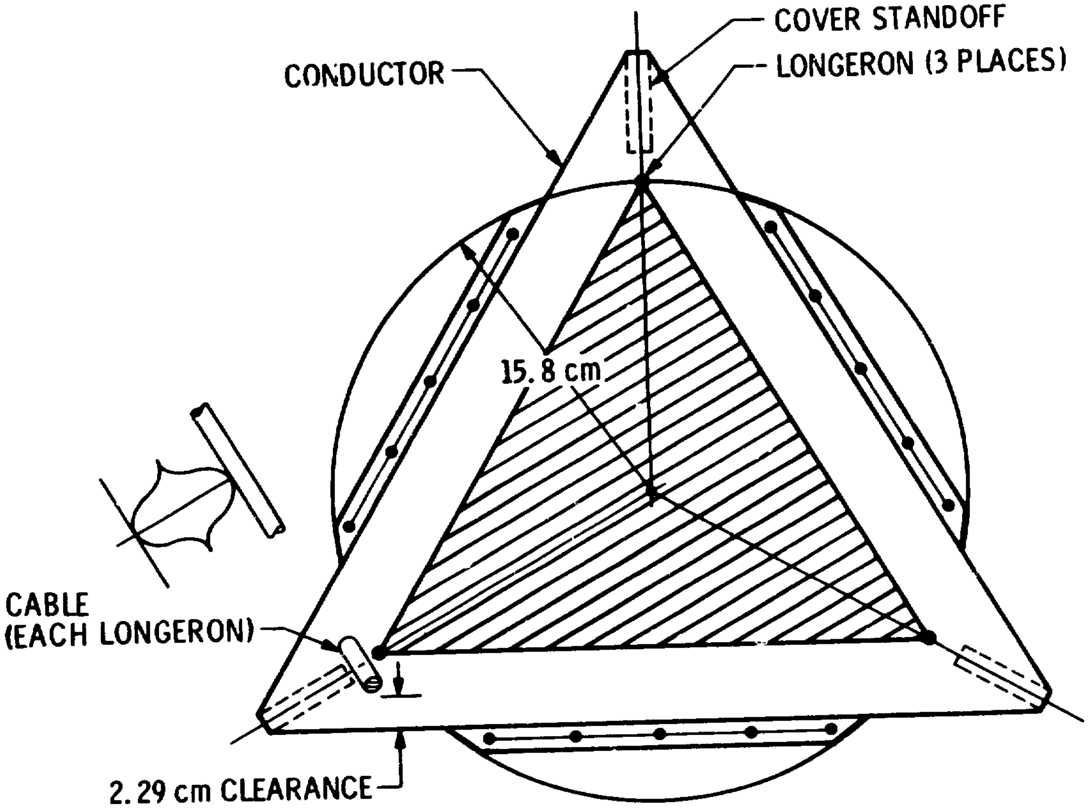

Figure 11. ESD Cover With Cable Clearance

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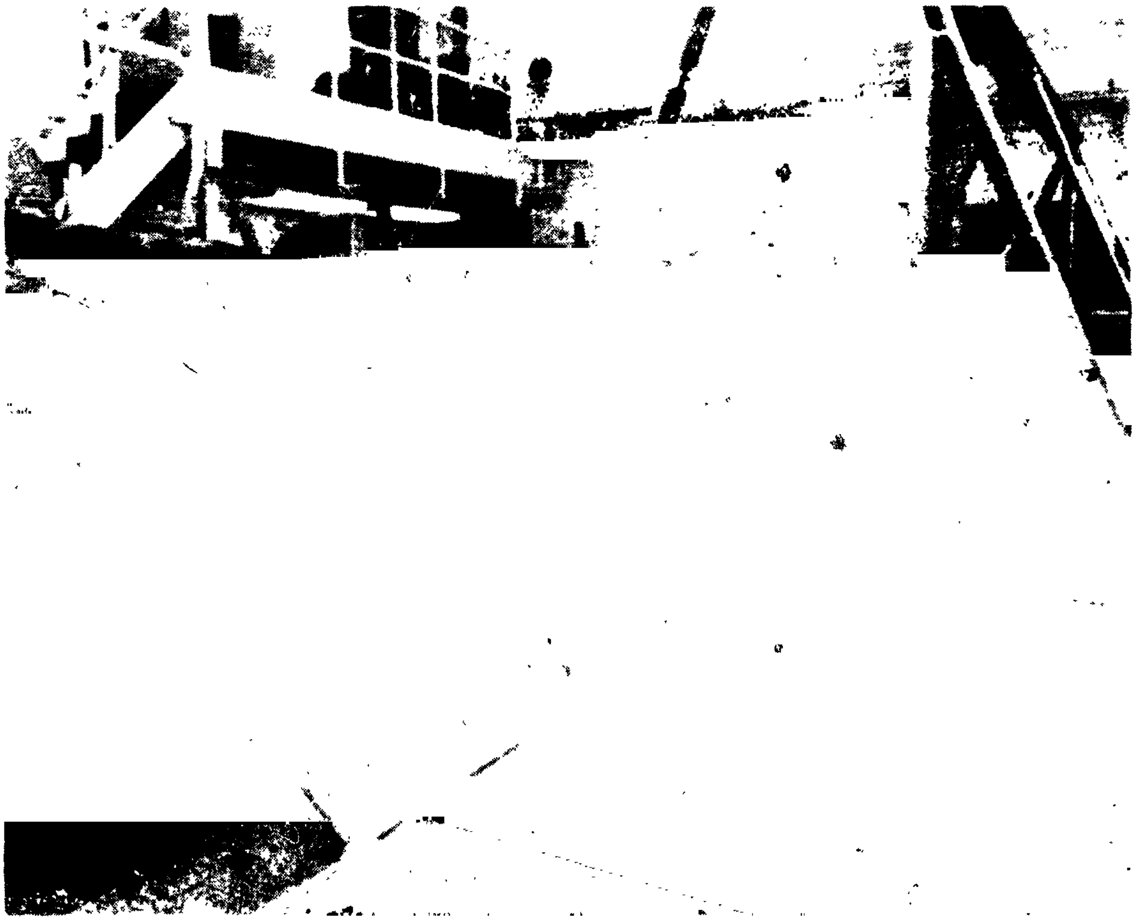

Figure 12. Magnetometer Boom Cover Stowing Procedure

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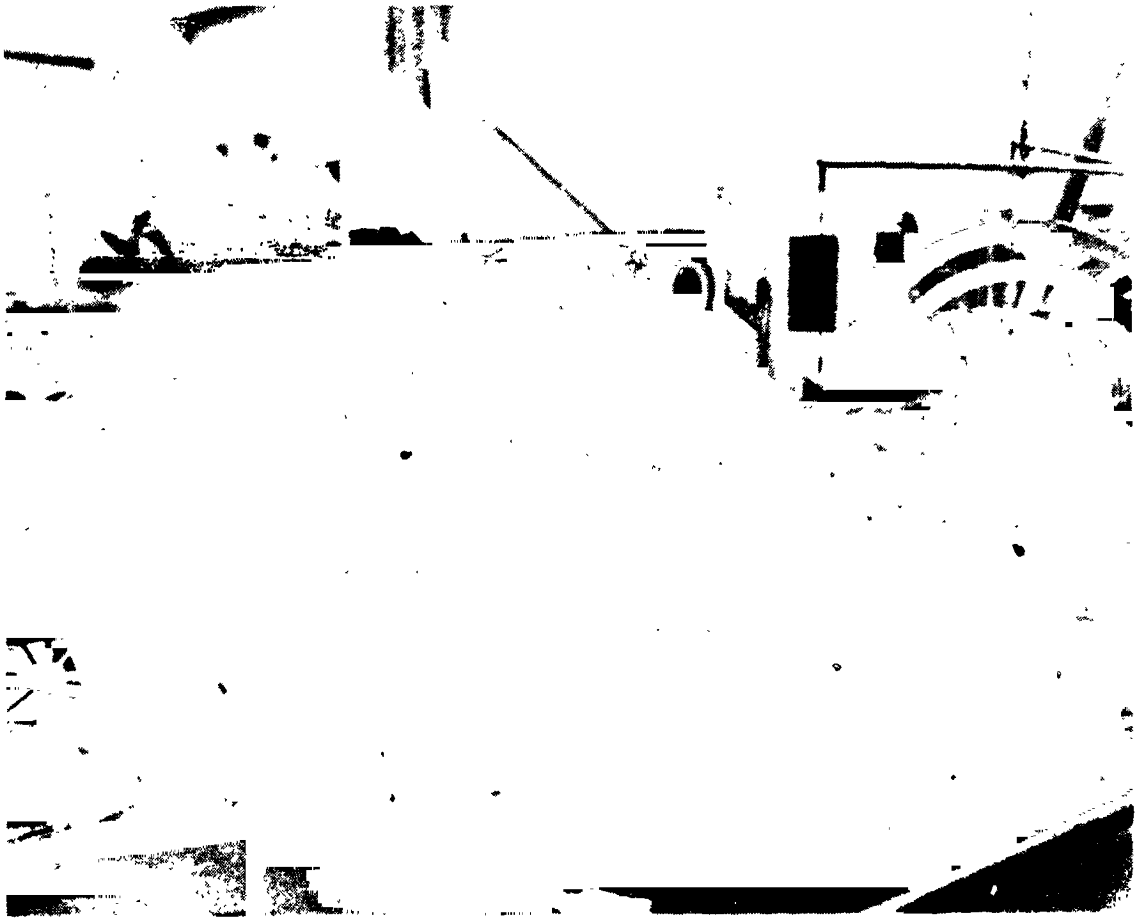

Figure 13. Magnetometer Boom Initial Deployment

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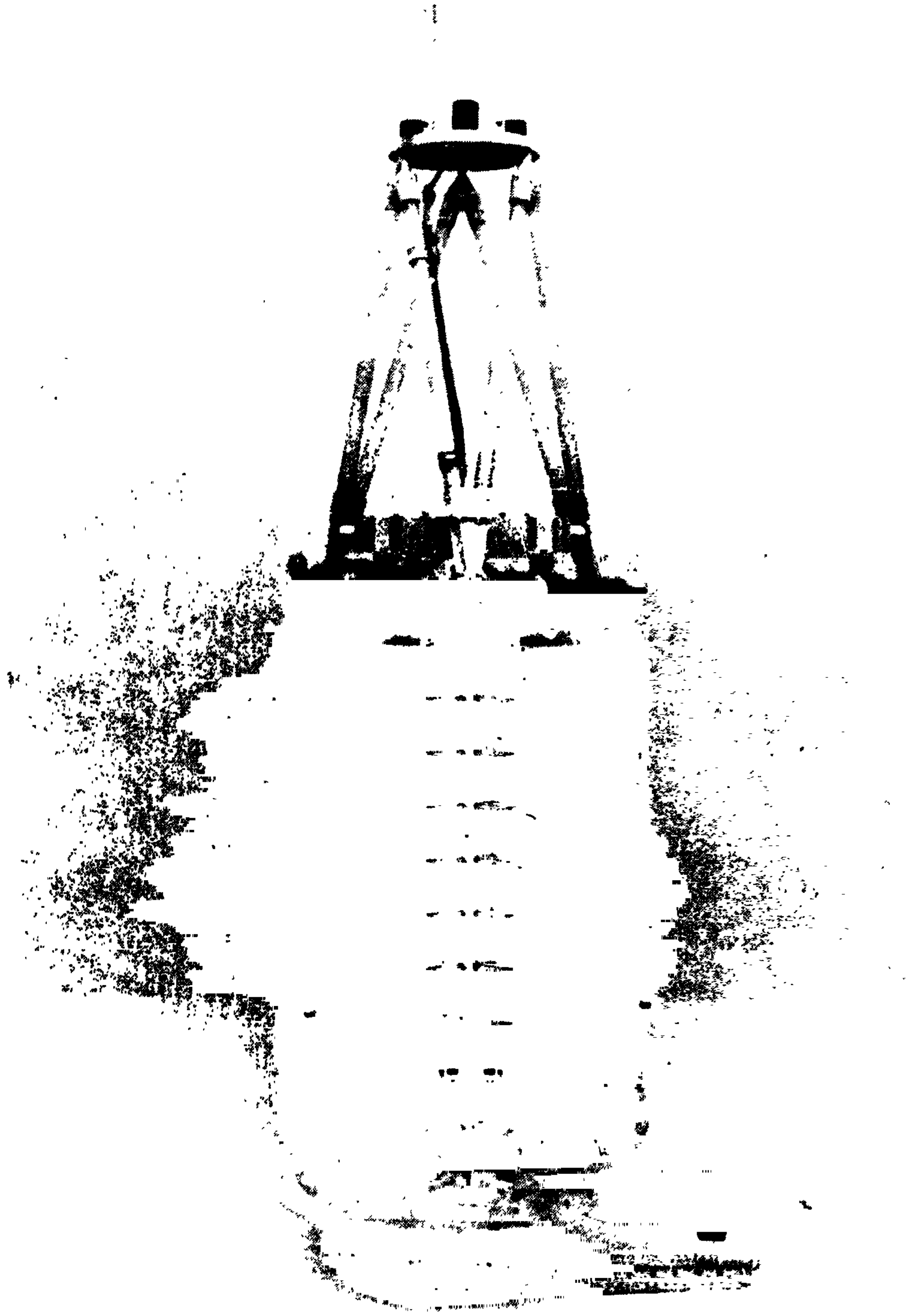

Figure 14. Stowed Magnetometer Boom