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The *Radio Astronomy Explorer* 1500-ft-Long Antenna Array*

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The mechanical components of the Radio Astronomy Explorer spacecraft main antenna array are described. Key components, such as the extendible antenna element and dispenser mechanism, are described in detail. System test techniques, development problems, and solutions are also presented.

I. Introduction

The science of radio astronomy is a relatively new tool for increasing man's knowledge of the universe. Until very recently, all observations had to be made from ground-based arrays. Such observations are severely limited by the ionosphere, the troposphere, and man-made radio noise. Much of the data obtained below 20 MHz is unreliable. With the advent of the space age, the possibility of placing a radio telescope in space was realized. The spacecraft should be able to compensate for its own influence on the incoming antenna signals and to monitor the strength of earth-generated noise. To fulfill these needs, the *Radio Astronomy Explorer* (RAE) spacecraft was developed.

The first RAE spacecraft is presently scheduled for launch in mid-year 1968 and has an expected life of one year. The main antenna array is X-shaped (Fig. 1) and is diagonally 1500 ft long. This extreme length produces an inertia of over 200,000 slug-ft^2 and provides gravity-gradient capture. The array consists of four separate interlocked-seam tubular extendible elements (TEEs), each 750 ft long. Each V portion of the X configuration is electrically coupled, forming one antenna. The earth-oriented V antenna will be utilized to measure earth-generated noise. Solar and planetary emissions will be measured by the space-oriented V antenna. Prior to erection, each antenna element is stored in a 5.0 × 8.0 × 14.0-in. dispenser mechanism. The entire array, including dispensers, weighs 72 lb and can be erected in 25 min with 24 W of electrical power.

II. The Antenna Element

The basic material used in the antenna elements is precision-rolled beryllium copper. The elements are made from 0.002 × 2.00-in. continuous strip which is heat treated to form a 0.570-in.-diameter tube. This technique allows the tube to be wound flat on a spool for maximum compactness.

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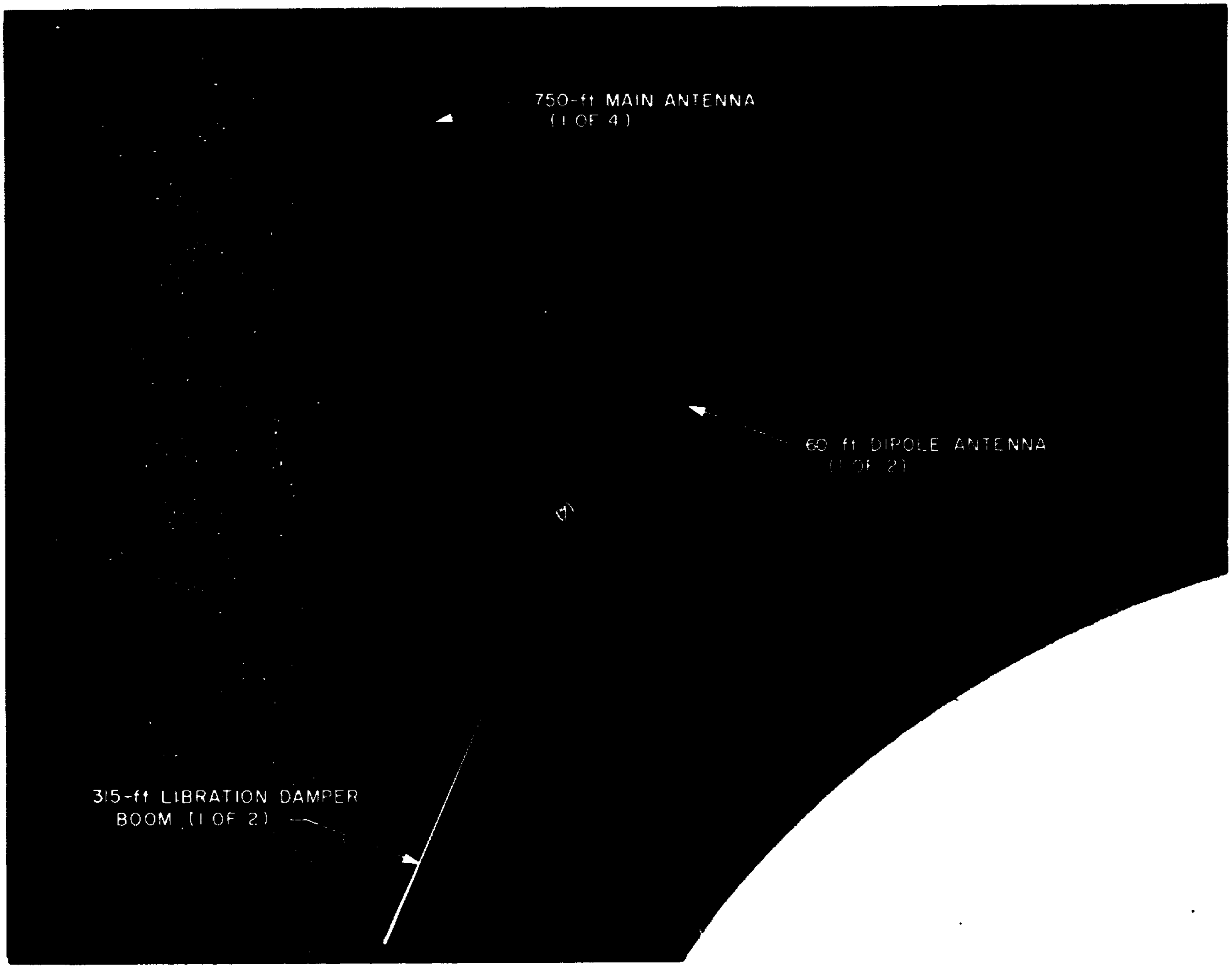

Fig. 1. Artist's conception of the RAE satellite, with antennas deployed

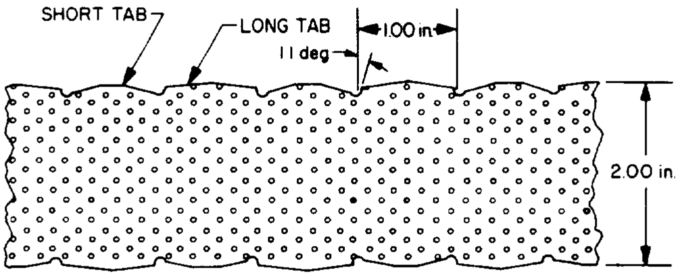

Fig. 2. Unformed antenna element

Figure 2 illustrates the antenna element prior to heat treating. The locked seam is made possible by punching a series of tabs on the edges of the flat element. Every other tab has its apex flattened, i.e., the distance from the centerline of the element to the edge of the tabs alternates between long and short. When the flattened element springs into a tube, a short tab is presented to a long tab. The seam is "zippered" by tucking short tabs under long tabs. The "zipper" (Fig. 3) consists of a narrow-crowned roller mounted inside the half-formed tube on the centerline of the seam at a point just before the tabs to be mated touch each other. The pair of tabs move across the roller together as the element is dispensed but are restrained momentarily by the roller from curling into a tubular shape. The shorter tab springs clear of the roller first and curls into its normal position on the centerline of the seam. The longer tab clears the roller last so that when it springs down, it overlaps the

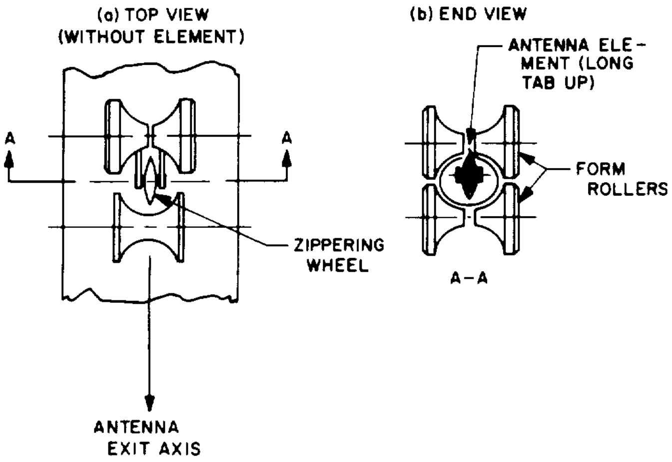

Fig. 3. Antenna element edge lock zipper

shorter tab already on the centerline. The process is reversed on the next pair of tabs. The end result is a row of interlocked tabs. Each tab is 1 in. long in the axial direction. To avoid play between adjacent tabs, an interference fit was achieved through the incorporation of an 11-deg wedge angle.

The antenna element also incorporates a system of thermal control coatings which are intended to minimize thermally induced deflections that could occur as a result of large diametral thermal gradients. (A ΔT of 2°C is considered prohibitive.) The outer surface has a coating of silver (0.0001 in.) which is polished to produce an absorptivity of less than 8%. To counteract the 8% thermal input that is being absorbed, the antenna is perforated to allow 8% of the solar energy to pass through the antenna and strike the back side. The inside of the element is coated with a film of highly absorptive black paint. Thus, 8% of the thermal input is absorbed on the front side of the antenna and 8% is absorbed on the back side, resulting in a theoretical zero gradient. Silver degradation and perforation passthrough is expected to occur because of extended operation in space. However, this combination of coatings and perforations is expected to maintain a diametral thermal gradient of 0.75°C.

III. The Antenna Dispenser Mechanism

The mechanism that is utilized to dispense each of the four RAE 750-ft-long antenna elements is illustrated in Fig. 4. It consists of a storage reel, drive train, element

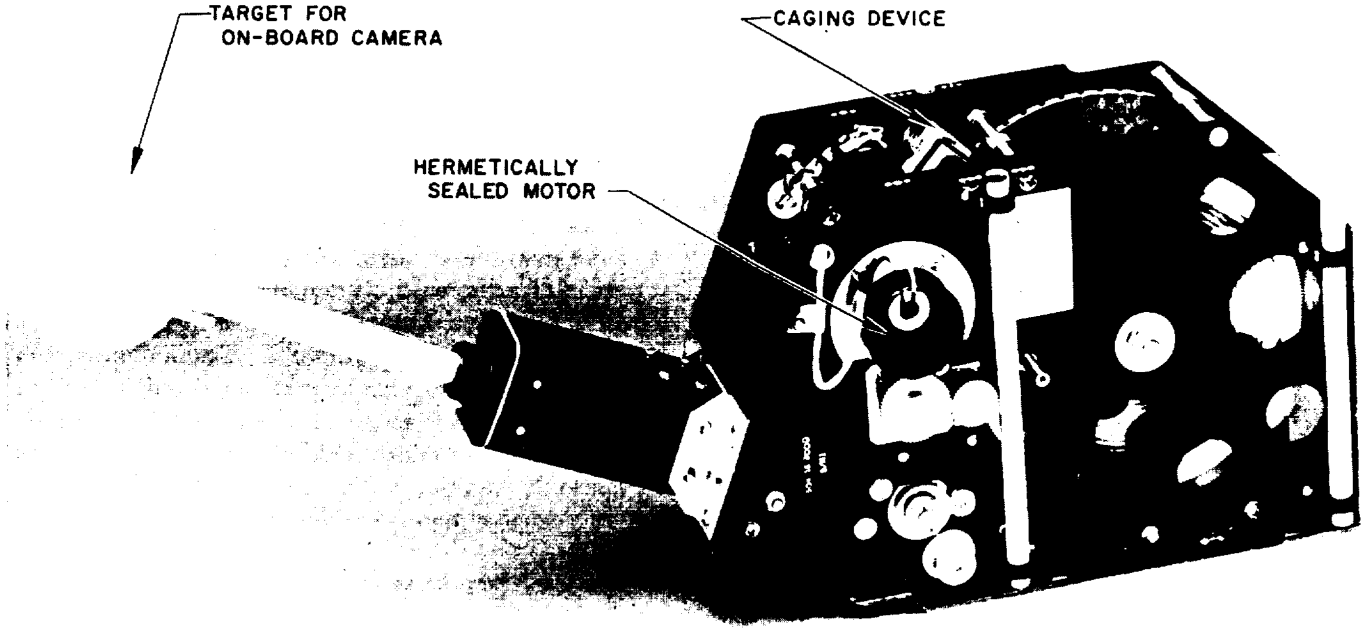

Fig. 4. Antenna dispenser mechanism

guide supports, antenna element edge locking device, launch caging mechanism, and analog instrumentation, mounted in a lightweight magnesium support structure. The mechanism is enclosed by an aluminum-foil-lined plastic cover that minimizes tarnishing of the silver-plated antenna element and provides the required RF shielding.

In the extend mode of operation, the element is pulled from the storage reel by a pinch drive roller while a small retarding force is applied to the storage reel through a friction clutch. This feature precludes buckling of the element, because it is in tension instead of compression. In addition, the pinch roller drive system maintains an essentially constant deployment speed without the complexity of a servo control system to compensate for the changing diameter of the spool-stored element. Furthermore, this unique drive feature eliminates the need for a translating main reel shaft because axial alignment of the extending element is achieved at the pinch drive roller.

Essentially the same drive principle is employed in the retraction mode. The basic difference in this mode is that the storage reel is driven with drive coupling derived through an electrically operated crown tooth clutch. During the retract mode, a slight retarding force is applied by a slip clutch at the pinch drive roller, which maintains element tension between it and the storage reel. This feature ensures a repeatably tight element storage wrap.

Ball-bearing-mounted rotating guide rollers are used exclusively to assist the antenna element in making the transition from flat to round. These rotating guides are contoured so as to achieve a smooth transition of the antenna element with no deformations after a minimum of 25 cycles. The contoured rollers also provide element bending root fixity. The output end of the guide system contains an adjustable pylon which has the edge-locking roller at its tip.

A redundant system is provided for electrical connection to the antenna. A spring-loaded, gold-plated, rotating wheel makes one RF contact directly on the antenna element at the pinch drive roller. The second RF contact is made through a spring-loaded clip that is used to attach the antenna root to the storage reel.

The mechanism design incorporates a ball detent, solenoid-actuated, reel-caging device so that the spring-like antenna material will remain tightly wrapped on the storage spool during the launch vibration environment. This caging device consists of a spring-loaded plunger which engages with one of the slots provided on the periphery of the antenna element storage reel. After the desired orbit is achieved, the caging device is actuated. A telemetry switch is provided to verify uncaging of the reel. The switch also opens the solenoid circuit to conserve spacecraft electrical power. Inadvertent reset of the solenoid is precluded, since it requires a manual override.

An analog signal provides a direct readout of the length and speed of the antenna at all times during extension and retraction. The signal is derived from a 10-turn precision potentiometer driven from the pinch drive backup roller shaft. A gearhead speed reducer is interposed between the backup roller and the potentiometer to reduce the number of revolutions of the backup roller to slightly less than 10 turns at the potentiometer shaft for extension of 750 ft of antenna.

The limits of extension and retraction are sensed by a subminiature switch which has a spring-loaded contactor wheel that rides against the silver-plated surface of the element. This contact takes place at the backup roller adjacent to the antenna electrical connection. Switch actuation occurs when a slotted hole punched in the beginning and end of the antenna element passes under the switch roller, allowing the antenna to descend into a cutout in the backup roller, thereby opening the drive motor circuit.

IV. System Tests

Tubular extendible elements, like many other space-applied extensible systems, are unable to support their own weight in the earth's gravitational field. Regardless of this limitation, it was necessary to verify, first, that the antenna elements were straight as manufactured and, second, that the dispenser mechanism could in fact extend and retract the element in a simulated spatial environment with the required edge locking and unlocking. As a result, a unique straightness testing and element take-up device system was designed.

A. Antenna Straightness Testing

To date, straightness testing of tubular extendible elements has been conducted in water troughs several feet wide and up to 150 ft long. The specimen under test is usually supported by a row of saddles, each saddle being mounted on an individual float. The energy in a bowed element is enough to displace the floats across the surface of the water until a two-dimensional reproduction of the curve is produced. Attempts have also been made to measure a three-dimensional displacement by incremental rotation of the element or by suspension on neutrally buoyant balloons. The prospect of scaling up one of these 150-ft facilities to meet the 750-ft RAE requirement presented formidable problems, particularly since the RAE specification permits a total tip deflection of 13 ft.

1. Test facility. The ideal test facility was located just 10 miles from the NASA Goddard Space Flight Center, at the Naval Ordnance Laboratory, White Oak, Maryland. The site is an underground ballistic missile range that is 1000 ft long, 10 ft in diameter, humidity controlled, and draft free, with the capability of having the air evacuated. Since the facility is underground, the temperature is stable. Because the range is in active use, its conversion to an RAE antenna straightness facility, together with the running of the test and removal of all gear, had to be accomplished during a weekend.

In order to keep the entire rig portable, it was decided to float the test antenna on small individual pans of water in lieu of one continuous trough. A spacing of 5 ft was selected. Since any bow in the floating element would cause it to strike the side of the pan, the pans had to be movable and were therefore suspended from overhead crossbars. The crossbars were attached to the steel walls of the range tunnel with magnets to avoid the need for any welding or other permanent modifications. Figure 5 illustrates the straightness test facility. Since there were 150 pan suspension systems, the cost of each had to be kept to a minimum. Thus, such things as cake pans, coat hangers, and beaded chains were used effectively throughout.

2. Test procedure. Each test is conducted as follows: First a ruby laser is mounted on the centerline of the tunnel and aimed down the row of suspended pans. To bring the water level in all pans to a uniform height, a target with cross hairs is floated in the first pan so that the laser produces a dot upon it. A technician with a pair of syringes, one empty and one filled with water, then adjusts the water level of that pan to bring the horizontal cross hair to the level of the laser beam. He then advances the target to the next pan and adjusts its water level. Since the target is made from a transparent material with scribed cross hairs, the laser shines through it and can be used simultaneously by other technicians leveling pans farther up the tunnel.

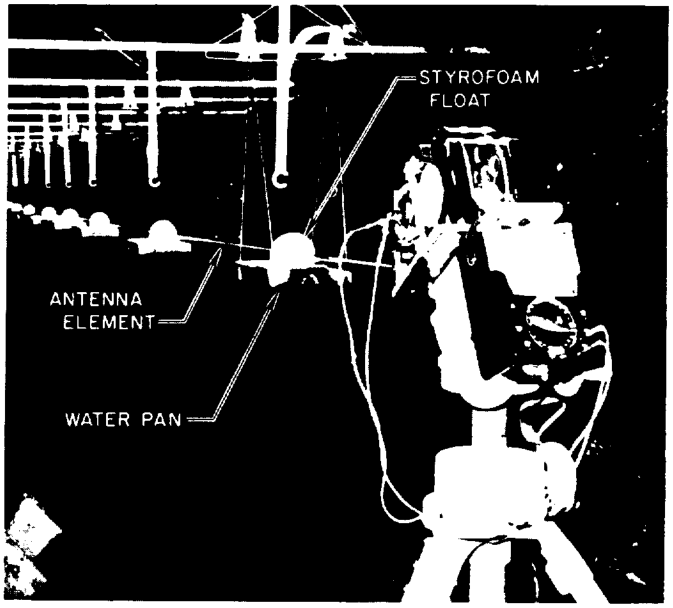

Fig. 5. RAE antenna element straightness testing

Once the pans have been leveled, the next step is to extend the antenna element to its full length and support it by Teflon hooks (prior to supporting it on floats). The antenna element with locked seam up is manually guided through all 150 hooks. The next step is to attach the floats, which are styrofoam cylinders 3 in. in diameter with a 0.570-in. hole on the axis. They are molded in halves and are secured around the antenna with a piece of tape wrapped once around the circumference of the float. The cylindrical design of the float is extremely important because it allows the antenna seam to twist. The antenna element is then removed from each successive hook and the float is placed in the water. Each pan is adjusted laterally as required to keep the float in the center of the pan. The off-axis deviation is then measured along the antenna element. Once these measurements are completed, the antenna element and mechanism are rotated 90 deg. Flotation adjustments are again made, and the off-axis deviations are measured. This technique therefore provides information that verifies that the manufacturing process is not resulting in excessively distorted antenna elements.

B. Dispenser Mechanism Testing

Verification of dispenser mechanism design integrity requires a device that can accept or release the antenna element without imparting an axial load on it. This was accomplished through the design of a bidirectional servo-controlled take-up mechanism. In effect, the take-up mechanism was designed as a mechanical symmetry of

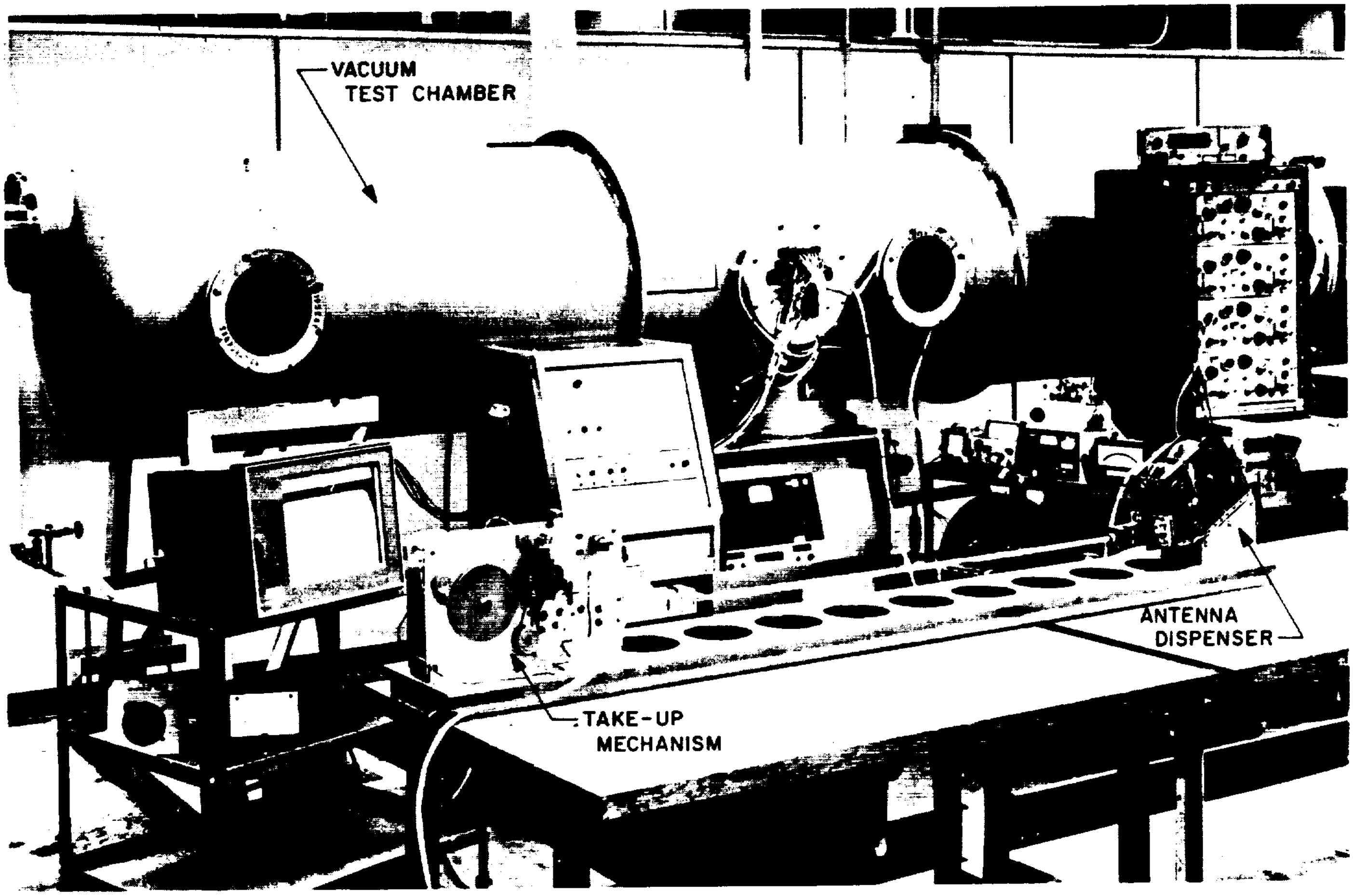

Fig. 6. Antenna dispenser mechanism testing

the flight dispenser. That is, drive principles such as motors, pinch drive rollers, drag clutches, rotating forming guides, etc., were preserved, since they were understood and known to function properly. A bidirectional servo system was designed to satisfy the velocity requirements of the flight units. Operation was simple, in that arming the electronics required only one switch closure. After this operation, the take-up device system simply responded to the flight units. The fixture length required the utilization of the 18-ft-long horizontal thermal vacuum test chamber at the Fairchild Hiller Space Technology Center. Figure 6 illustrates this test setup.

V. The Take-up Mechanism

Figure 7 illustrates the mechanical design concept of the take-up mechanism. The object of the device is to accept and/or release the antenna element without inducing an appreciable axial load in the formed tubular element section. To accomplish this, all forces acting in the element must be nullified. As shown in Fig. 7, force F_1 is caused by the strain energy of the element which occurs as it translates from the flat to the tubular shape. When the flight mechanism is in the extend mode, the element is coming into the take-up mechanism at a constant rate. Drag forces D_1, D_2, and D_3 add to force F_1. The spring must nullify these forces. Since the force-sensing roller is restrained by two strands of tape, only half of F_2 is applicable in calculating the element tension. Likewise, only half of D_3 is applicable. The equation then becomes

$$F_1 + D_1 + D_2 + \frac{D_3}{2} = \frac{F_2}{2} \qquad (1)$$

Equation (1) is the equation that must be satisfied when the calibration system is in the extend mode. Since the tape velocity is constant, the various forces are constant, and the equation can be satisfied. The take-up mechanism motor does not enter into the calculations,

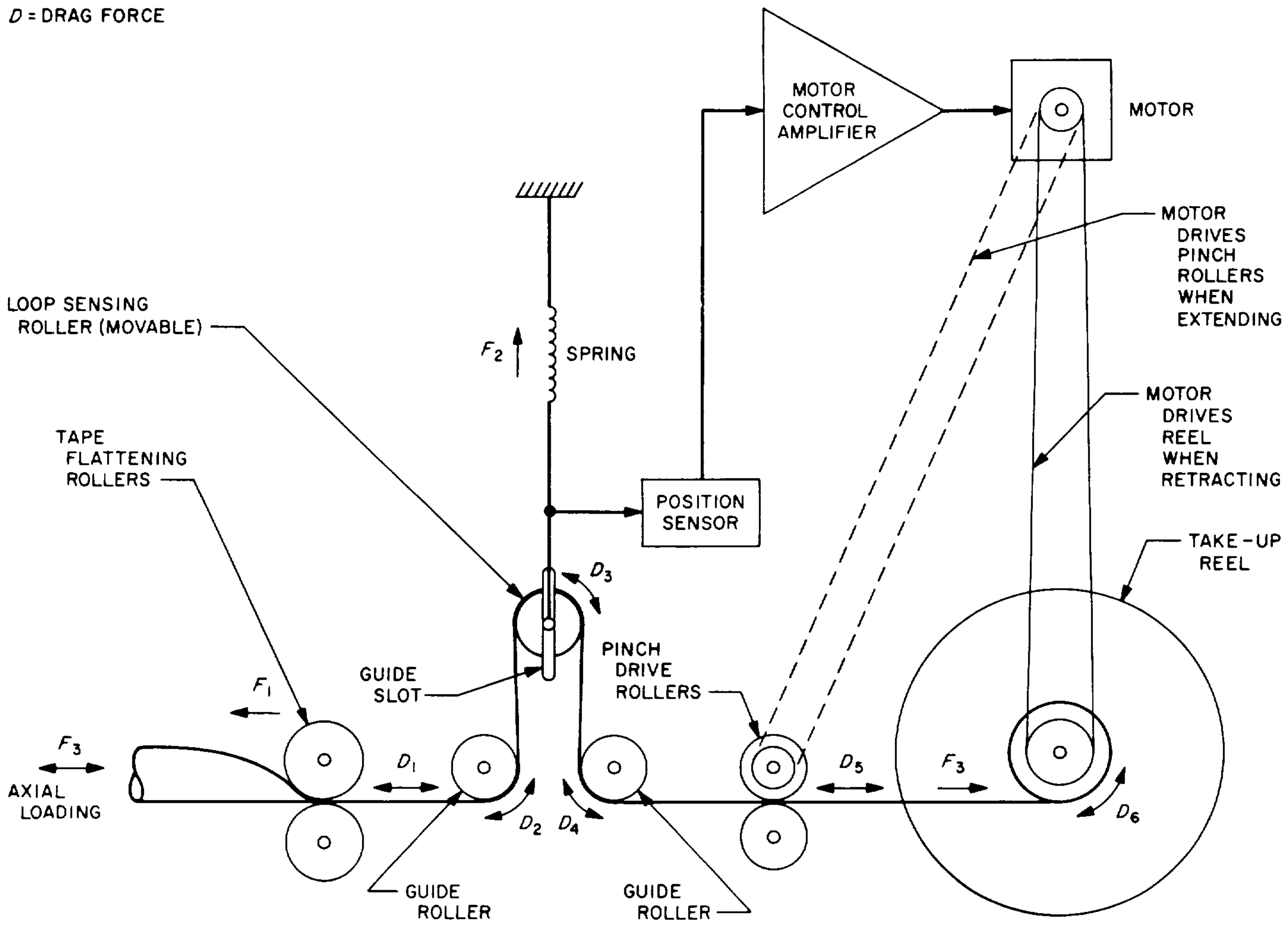

Fig. 7. Schematic diagram of take-up mechanism

since the spring is an effective buffer and tension regulator.

In the calibration system retract mode, the element is being pulled from the take-up mechanism storage reel by a pinch drive roller. The various forces now subtract from force F_1. In addition, the element velocity is variable. Because of the buffer action of the spring, the force equation becomes

$$F_1 - D_1 - D_2 - \frac{D_3}{2} = \frac{F_2}{2} \qquad (2)$$

Since the drag forces D_1, D_2, and D_3 are small and do not vary significantly with velocity, it is not necessary to change the spring force F_2 in order to accommodate Eq. (2).

This automatic calibration system was used extensively throughout the RAE mechanism design qualification and acceptance test program. Five full-length extensions and retractions were performed on each mechanism prior to installation in the spacecraft.

Operational integrity of the calibration system was verified visually by merely observing the position of the element loop sensing roller relative to the bearing slot extremities. As long as the roller shaft is not bottomed against either end of the slot, an axial force is not being transmitted to the translating antenna element.

VI. Conclusions and Recommendations

It can be concluded from the results of this development effort that compact lightweight tubular extendible element systems (TEEs) can be employed for extremely long space antenna arrays. Furthermore, this activity has demonstrated that it is possible to adequately test very long antenna systems in the earth's gravitational field. In order that this segment of the technical community might benefit from this activity, the following development findings are mentioned:

(1) Pinch driving of thin web material such as TEEs requires adequate tension control. Friction drag clutches can be utilized. Delrin friction plates should not be used. Recommended for use are composite bearing materials consisting of a brass backing onto which is sintered a thin porous layer of spherical bronze, which is, in turn, impregnated with a mixture of TFE fluorocarbon resin and lead powder.

(2) The pinch drive roller elastomer should be chosen carefully. Viton should not be used because the durometer changes 90% at +5°F. Instead, we recommend a silicone elastomer per Federal Specification ZZ-R-765a, Class III Type 50.

(3) Magnetically shielded, crown tooth, electrically operated, duplex clutches can be used for mode switching, provided mode coupling is isolated with one-directional mechanical clutches. This will prevent the front wheels from turning when the rear wheels are standing still.

(4) Bidirectional servo-controlled TEE storage systems (take-up mechanisms) with narrow bandwidths can be devised. The designer should not attempt to compensate for inertia-caused jitter electronically. Instead, he can use viscous dampers, which are available for operation in a thermal vacuum environment.

(5) Brush-type permanent magnet direct-current motors can be used for space applications without incorporating baffling schemes, O-rings, or wobble plates. Hermetic sealing can be achieved with bearing-supported eccentric shafting and a bellows. However, the shaft and bellows materials and bearing support system should be chosen with extreme conservatism.

(6) Torsionally rigid, edge-locked TEE systems can be made simple. The designer should evaluate and understand his system geometry before launching into a complicated moving part system, and should provide sufficient adjustment to compensate for assembly and component tolerances. The RAE system uses a simple, fixed-shaft-mounted wheel, which reliably achieves edge-locking of 43,560 tabs per spacecraft.