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15. THE MECHANICAL DESIGN OF AN IMAGING PHOTOPOLARIMETER FOR THE JUPITER MISSIONS

(PIONEER 10 AND 11)

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SUMMARY

This paper discusses the mechanical design and fabrication of the Imaging Photopolarimeter (IPP), a multifunction space-qualified instrument used on the Jupiter Pioneer Missions. The extreme environmental requirements for the structural design, optical system, and mechanisms are described with detailed discussion of some of the design and fabrication problems encountered.

INTRODUCTION

An Imaging Photopolarimeter (IPP) was launched aboard Pioneer 10 in March of 1972 and, after 21 months of travel through space, passed by the planet Jupiter in December of 1973. During this time, the instrument passed through the asteroid belt and the intense radiation and magnetic fields of Jupiter to successfully fulfill its mission. The interplanetary portion of the mission was utilized to generate sky maps of brightness and polarization of the zodiacal light. During the Jovian encounter, the IPP produced two-color images of Jupiter with resolution and at viewing angles unobtainable from earth. In addition, it measured the brightness and polarization of light reflected from the planet from which, for example, details regarding the size and shape of the particles composing the atmosphere can be deduced.

A second IPP launched aboard Pioneer 11 in April of 1973 will pass by Jupiter in December of 1974 to accumulate additional data at viewing and approach angles different from those of Pioneer 10. Since Pioneer 10 fulfilled its main objectives and successfully survived the Jovian radiation belts, Pioneer 11 has been retargeted so as to pass by Saturn nearly five years after the December 1974 encounter with Jupiter. This will provide significant bonuses with only relatively minor compromises, e.g., somewhat less favorable imaging geometry at Jupiter.

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The IPP is a multifunction instrument designed to: 1) map the zodiacal light (faint light measurement); 2) measure the brightness and polarization of light in two spectral bands (colors) reflected from the planet Jupiter; and 3) produce two-color images of Jupiter. The instrument (see Figure 1) consists of an electronics module and a scanning electro-optics assembly. The instrument is mounted aboard a spinning spacecraft (see Figure 2) and utilizes the 4.9-rpm spin of the spacecraft to scan a narrow strip across the planet (or across the sky in the case of the zodiacal light mode) during each revolution. The electro-optics assembly may also be positioned in 0.5-mrad steps in the direction of flight from 29° from the earthward direction to 170° from the earthward direction. This stepping allows scanning of contiguous strips which can be recombined during ground data processing. The various optical modes are achieved by inserting various field-defining apertures, polarization-analyzing optics, and calibration sources into the optical path at the focal plane. The optical system is a complex combination of mirrors, lenses, prisms, multilayer coatings, and filters that separate the viewed scene into four beams, two red and two blue, with each colored pair orthogonally polarized. The four beams are then individually imaged onto individual cathodes of two dual-channel detectors. The red and blue light is quantized into 64 intensity levels (imaging mode) and 1024 levels (photopolarimeter and zodiacal light modes) and then transmitted to earth as coded numbers. The signals are reconstructed and enhanced by computer to provide two-dimensional displays of the data (spectacular color images and brightness and polarization maps).

ENVIRONMENTAL AND INTERFACE REQUIREMENTS

The IPP was designed to withstand the normal launch environment of most spaceborne instruments and to survive the almost two-year journey through space and passage through the Jovian radiation belts. In addition, the presence of a magnetometer aboard the spacecraft made it necessary to produce a virtually nonmagnetic instrument.

The instrument is located on the spacecraft to take advantage of the 4.9-rpm spin and to provide as optically clear a field of view as possible. The IPP is mounted in the spacecraft instrument compartment with the electro-optics assembly extending through the side of the compartment wall. As a result, the electronics are maintained at close to ambient temperature and the electro-optics assembly is exposed to the sub-zero temperatures of deep space. This mounting configuration caused some concern among the experimenters involved because the exposed telescope could readily collect dust and debris during launch. Dust would create extensive light scattering and could jeopardize the faint light experiment. Maintaining cleanliness of the optics was mandatory during fabrication, assembly, and launch as well as in flight to Jupiter.

The total weight of the IPP is less than 10 pounds and the power requirement is approximately 2 watts.

MATERIAL CONSIDERATIONS

The IPP was designed to be constructed almost entirely of beryllium. This material was selected primarily to minimize weight. All materials used were considered for their radiation resistance and nonmagnetic characteristics. Materials considered suspect were exposed to specific doses of radiation and evaluated for damage. Radiation problems had their most significant impact in the electronics and optics areas. The most serious problem in the optics area was discoloration or phosphorescence. In the initial design concept, the detectors were mounted with the electronics, close to the high-voltage supply, and the optical beams were relayed to the detectors through fiber optics. However, all the fiber optics materials that were flexible enough to allow the telescope scanning would discolor when exposed to the levels of radiation anticipated during the Jovian encounter. As a result, the fiber optics were eliminated and the detectors mounted directly on the electro-optics assembly. The high voltage was then routed from the electronics module through a specially fabricated flat cable to the detectors on the electro-optics assembly.

Another problem was encountered with the calcite material selected for the three-segment Wollaston prism. Because of its large size, artificially grown calcite was not available and material had to be obtained from naturally occurring crystals. Natural crystals generally contain impurity ions which discolor or phosphoresce when exposed to high energy radiation. As a result, it was necessary to irradiate various small samples cut from large crystals to find a sufficient quantity of material unaffected by the radiation.

Most mechanical materials are not affected significantly by radiation. However, the use of organic materials was potentially a problem. While most epoxies tend to harden a minor amount, teflon and nylon, for example, are severely affected. All materials and components utilized were checked for magnetic characteristics to ensure that some magnetic item was not inadvertently assembled. One magnetic screw or washer could make the system so "hot" that disassembly would be necessary. The glass feedthroughs on the detectors and other electronic components were another problem. These feedthroughs were fabricated of low nickel alloys so that their thermal expansion coefficients closely matched that of glass. It was necessary to clip the magnetic leads off as close to the glass as possible and weld nonmagnetic wire in place of them.

Gimbal bearings were fabricated of Composition 125 and Berylco 25. Small instrument bearings did not cause any significant problems and were therefore screened and used as is.

INSTRUMENT CONFIGURATION

The instrument (see Figure 1) has two major components, the electronics module and the scanning electro-optics assembly. An integral mounting platform was configured to provide a direct thermal path from the electronics and from the scanning optical telescope to the spacecraft without interference from other components or one another. Spacecraft thermal control therefore exerts a direct effect in controlling the environment of these assemblies. The mounting platform was fabricated of black anodized beryllium. Critical interfaces were gold-plated to enhance thermal and electrical transfer. The mounting platform was fabricated of four separate structures and screwed and bonded together to form an assembly. The bonded joints were located such that they do not interrupt the thermal path nor are they solely relied on to carry the structural loading. This four-piece assembly was designed to allow fabrication of the structure from small sections of beryllium plate in lieu of the less available and more costly large beryllium block.

The electro-optics assembly (see Figure 3) is supported from the mounting platform by two gimbal bearings specially fabricated of nonmagnetic materials and dry lubricated with molybdenum disulfide. One gimbal bearing is installed directly between the optics assembly and the mounting platform and the other is installed in the platform-mounted telescope drive assembly which positions the optics along its 160° scan. A flexible braided thermal strap was connected between the optics assembly and the mounting platform to enhance thermal balance between the cold optics assembly and internally heated electronics housing. Thermal conductivity of the braid is considerably greater than that of the bearing assembly.

The electro-optics assembly consists of a Maksutov telescope, a six-position focal plane aperture actuator, a Wollaston prism, various optical elements, and two dual-channel Channeltron detectors (see Figure 4).

The Maksutov telescope consists of a primary mirror, secondary mirror, and spacer installed between the mirrors. The spacer is fabricated of the same fused silica material as the mirrors to minimize focal plane shift as a result of thermal expansion. The entrance aperture is 2.5 cm in diameter and is located at the primary mirror. Contact pressure is maintained between these components by a Viton O-ring installed on the outside of the secondary mirror (corrector). The entire telescope is housed in a machined black anodized beryllium tube which contains integral "knife-edge" baffles for stray light suppression.

The six-position aperture actuator is driven by a stepper motor specially designed to minimize static and dynamic magnetic fields. The actuator design integrates the aperture carrier into the basic structure and provides a receptacle for bonding in place the aperture plate and the focal plane optics.

The aperture plate contains the **field-defining** apertures which vary in size from a 0.5-mrad square (0.038-mm square) to a 40-mrad square. The aperture is fabricated of beryllium copper, plated with black chrome and photoetched. Because of the design change that required that the detectors be mounted on the moving optics, the space allocated for the aperture actuator was limited and resulted in an actuator configuration with a limited bidirectional rotation (±50°). As a result, the damping and calibration required to achieve desired detenting within the specified response times and voltage range, and over the required temperature range, were extremely difficult. It is felt that this type of design should be discarded on future designs in favor of unidirectional continuous rotation configurations where space permits.

The Wollaston prism (see Figure 5) is constructed of three segments of calcite. Calcite is a material possessing an anisotropic thermal expansion coefficient, $25 \times 10^{-6}/°C$ parallel to its optical axis and $-6 \times 10^{-6}/°C$ perpendicular to its optical axis. It is necessarily (optically) configured such that the thermal expansion coefficient of each segment differs from other adjacent segments along the same axis. The three segments of the prisms are bonded to each other and suspended in an aluminum housing by an elastomeric encapsulant. Aluminum was selected for the housing because the combined thermal expansion coefficients of the calcite and the elastomer closely match the expansion coefficient of aluminum when used in the subject configuration. As a result, the prism remains essentially stress free. Calcite is a very fragile material and must be handled with special precautions. Care must be exercised to shroud the material when thermal cycling, as even mild thermal shocks were shown to produce fractures in the raw material.

Two dual-channel detectors were mounted on the optics assembly in an aluminum housing with a semi-flexible adhesive. Aluminum was selected for this housing as it provided more radiation protection for the detectors than beryllium.

The various mirrors and lenses in the optics assembly were fabricated of radiation-resistant glass and bonded to the beryllium housings by a semi-flexible adhesive. All mirror and lens positions were individually adjustable by replacement of premachined shims to allow optimum positioning of the optical images on each detector.

The completed optics assembly is shrouded by a low emissivity polished aluminum drum which eliminates the excessive heat loss that would result from direct exposure to deep space. It is gimballed between the platform-mounted telescope drive motor and platform-mounted bearing assembly.

The telescope drive actuator (see Figure 6) which produces the 160° scan is a special sealed drive system designed to transmit rotational motion through a welded hermetic seal. Thus, suitable lubricants were completely contained within the active mechanical portion of the drive to assure reliable operation over the lengthy Jupiter mission.

The gear configuration is divided into two stages such that it converts 15° steps at the rotor to 0.5-mrad steps at the output. The first-stage gear reduction of 7.3:1 is accomplished in two passes of conventional gearing. The second-stage gear reduction of 72:1 is accomplished through a harmonic drive.* The harmonic drive consists of three basic parts: the wave generator, flexspline, and rigid spline. The wave generator is an elliptical cam which deforms the flexspline into an ellipse causing it to engage with the circular rigid spline at two points of contact. The flexspline is fixed and the wave generator is rotated by the first-stage gearing. As the wave generator rotates, tooth engagement between the flex and rigid spline follows the rotation of the wave generator. The number of teeth in the flexspline differs from the number of teeth in the rigid spline by two. As the wave generator makes one rotation, the flex and rigid spline are displaced with respect to each other by two teeth. With a 144-tooth flexspline, this produces a 144:2 reduction.

The stepping accuracy (0.5 ± 0.1 mrad) required was pushing the state of the art for this size actuator. The windup in the flexible spline (variation in resisting torque as a result of discontinuities in the deflection member) resulted in somewhat worse accuracy than required in the initial unit. This problem was minimized by matching flexsplines to wave generators and by the ultimate addition of a torsional spring to the output shaft of the actuator. This spring loading put a higher torque on the drive and made the variation in torque caused by flexspline windup less significant.

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*Gear Systems Division, United Shoe Machinery Corporation, Beverly, Massachusetts.

An input encoder was built into the motor to indicate stepper motor rotor position; this is used in conjunction with an output shaft encoder to indicate telescope position. The input encoder thus acts as a vernier position readout. An output (brush type) position encoder is mounted directly on the motor output shaft and is indexed to the main mounting platform and the telescope. This encoder provides the coarse positional readout.

An important actuator design consideration was that of magnetic field suppression so as not to interfere with the extremely sensitive spacecraft magnetometer. This was accomplished by special design of tightly coupled flux paths and the use of magnetic materials of very low remanence characteristics.* Both motor-driven actuators in the IPP exhibit magnetic cleanliness characteristics of approximately 10% of the allowable Pioneer specified values, thus confirming the validity of these techniques. For example, the aperture actuator which contains no shielding measured less than 0.1 gamma at 0.9 meter (3 feet) static and 0.2 gamma in the worst axis while stepping at maximum rate. The telescope drive assembly with a mu-metal shield measured 0.3 gamma at 0.9 meter (3 feet) depermed, 1.2 gamma at 0.9 meter (3 feet) after 25 gauss exposure and 0.06 gamma depermed and operating at maximum rate.

ACKNOWLEDGMENTS

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*Designed under subcontract by Schaeffer Magnetics, Inc., Chatsworth, California.

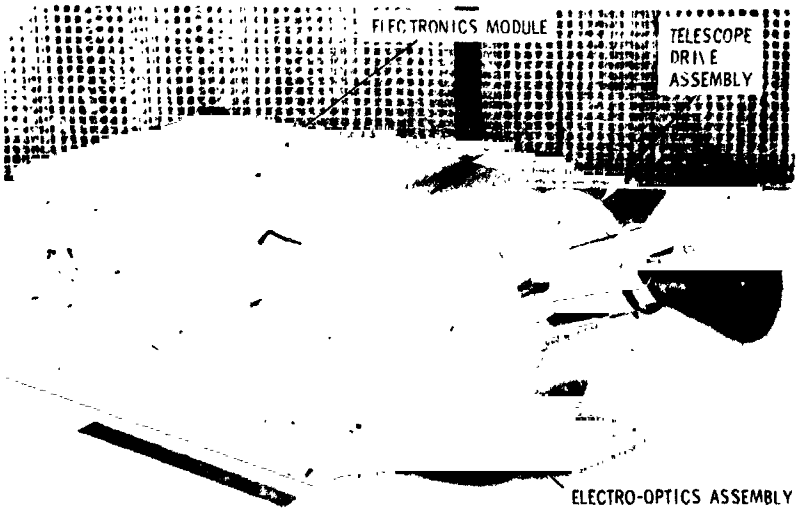

Figure 1. Imaging Photopolarimeter

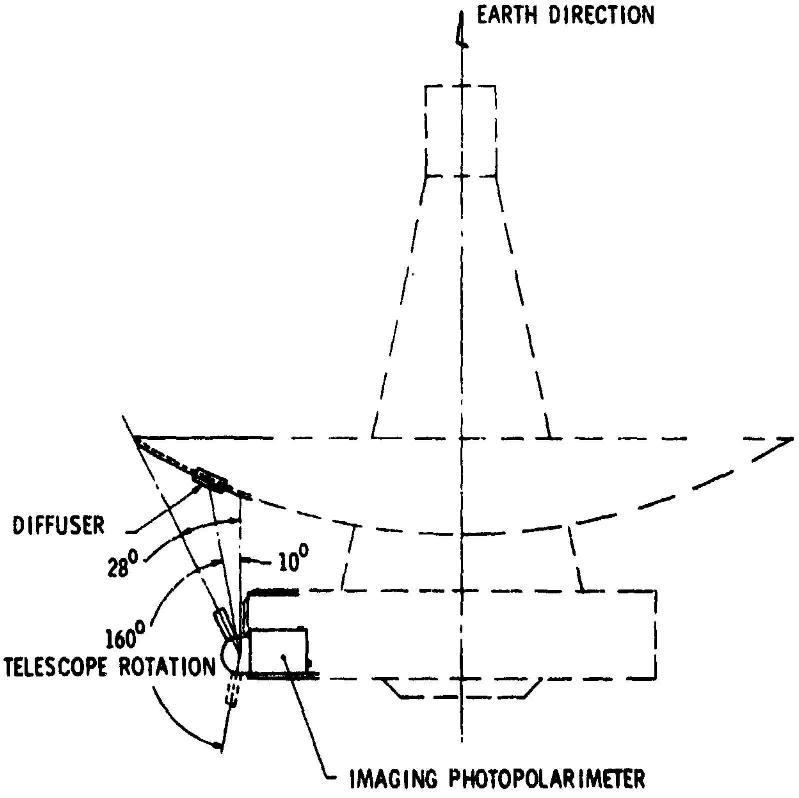

Figure 2. Imaging Photopolarimeter Orientation on Pioneer 10 and 11 Spacecraft

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Figure 3. Electro-Optics Assembly

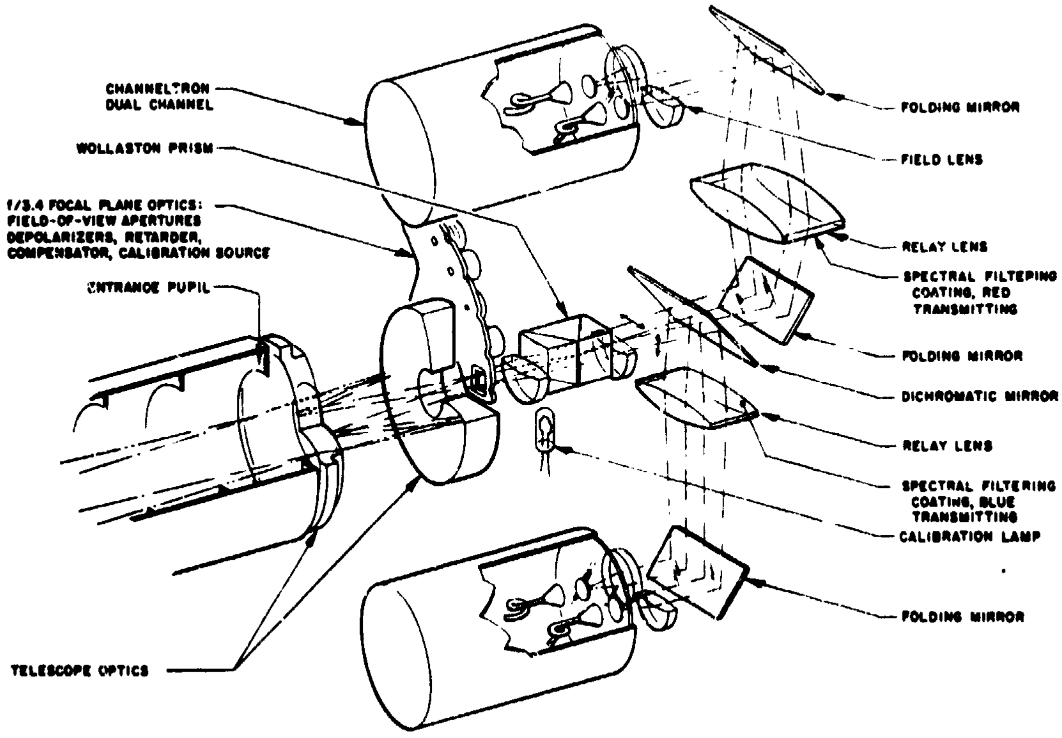

Figure 4. Optical System of the Pioneer Jupiter Imaging Photopolarimeter (Analysis of two orthogonally polarized beams into two colors, red and blue, is shown.)

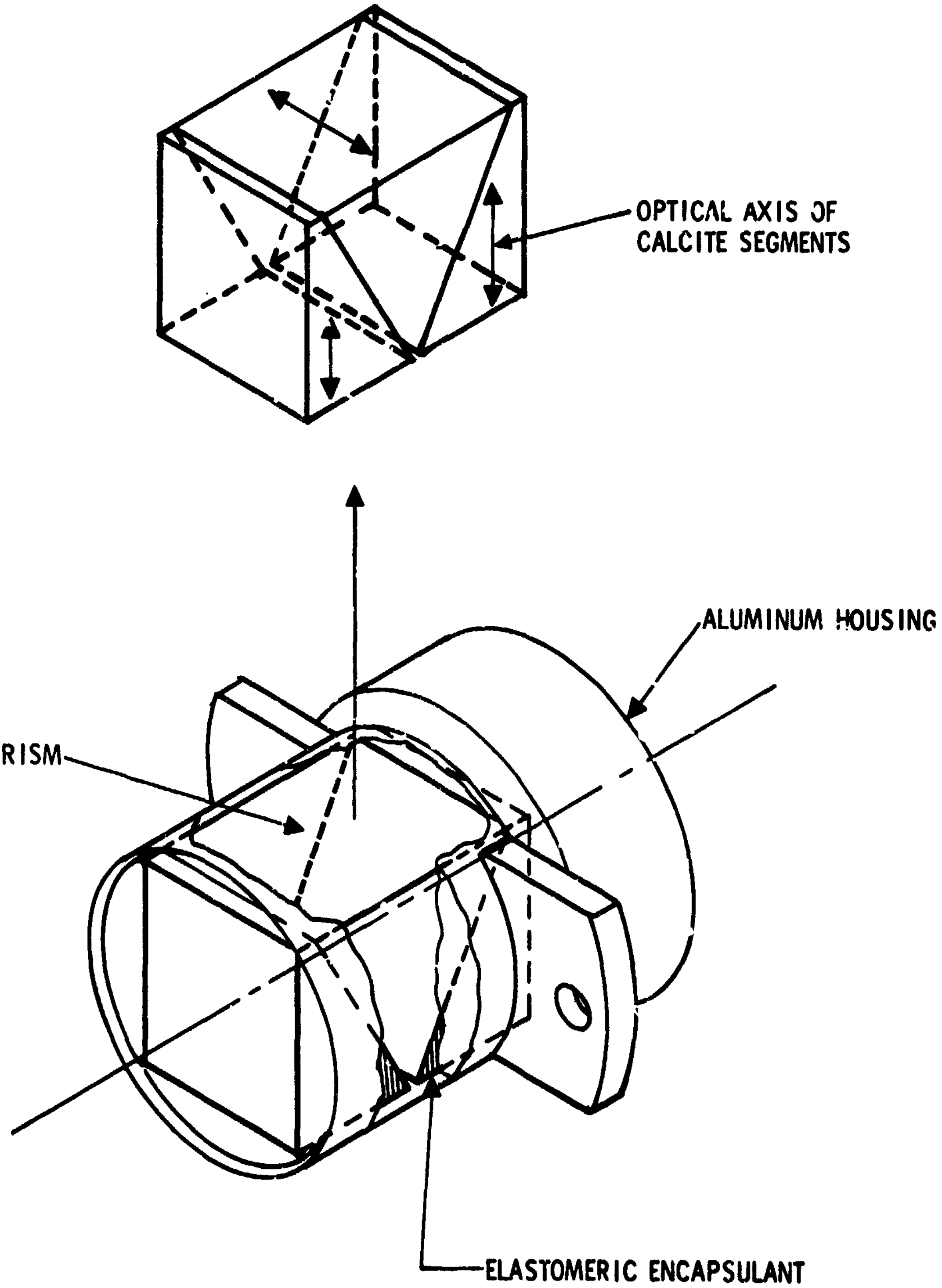

Figure 5. Wollaston Prism Mounting Configuration

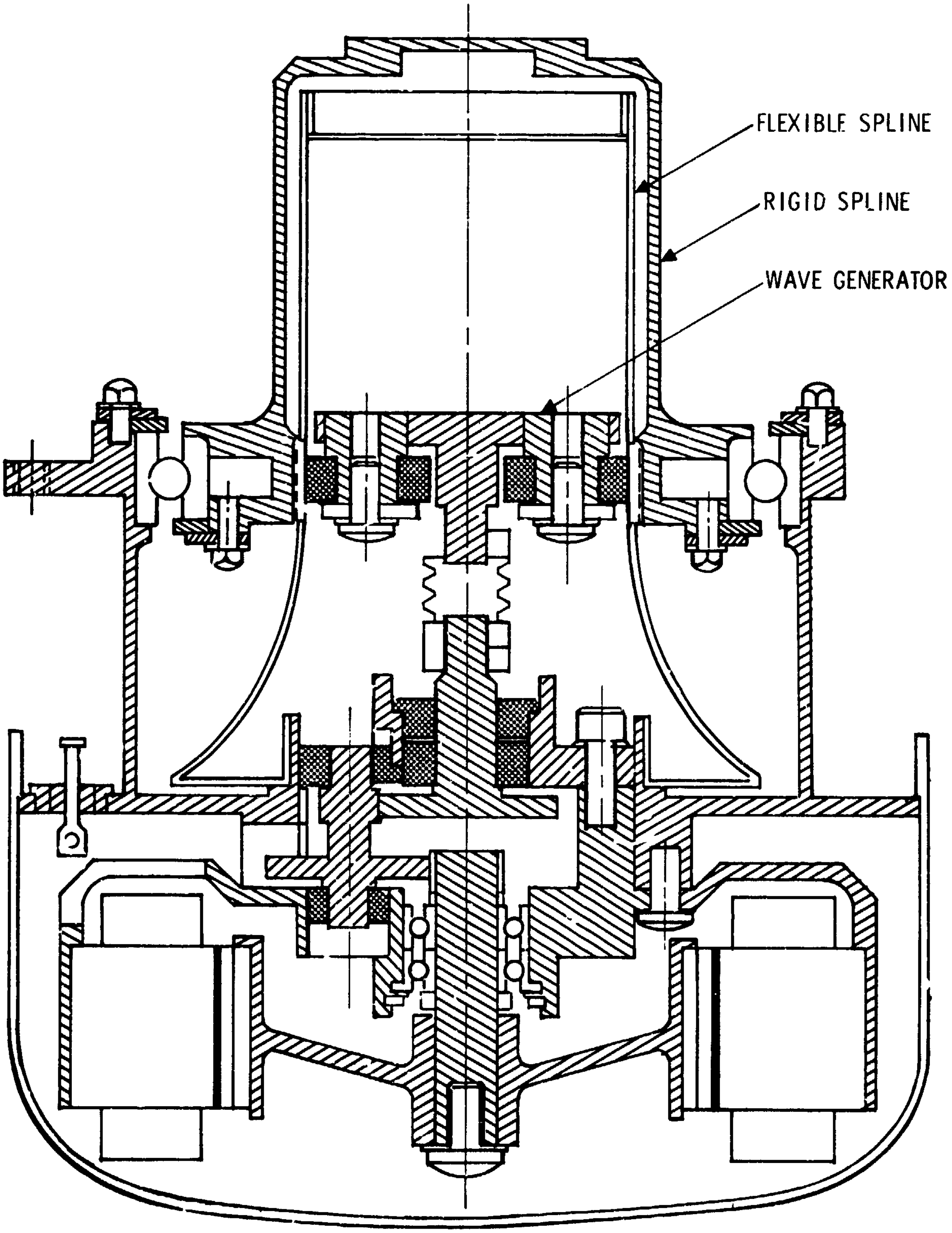

Figure 6. Telescope Drive Actuator