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DESIGN OF AN ATMOSPHERIC SOUNDING RADIOMETER FOR THE GOES METEOROLOGICAL SATELLITE SYSTEM*

Robert G. Jensen

Santa Barbara Research Center
Goleta, California

ABSTRACT

Each of the U. S. Geostationary Operational Environmental Satellites (GOES) has as the principal on-board sensor a spin-scan radiometer called a "VISSR" (Visible Infrared Spin Scan Radiometer). An advanced version of the VISSR will add a vertical dimension to the instrument's infrared atmospheric images through the addition of a rotating filter wheel and an oscillating calibration shutter. The following presentation gives an overview of the radiometer design with a close look at the filter wheel and calibration shutter mechanisms and their pre-flight test performance.

INTRODUCTION

Six VISSR's have been placed in synchronous orbits at various locations around the world. From their geostationary orbital positions, the VISSR instruments sense energy radiated from earth in the broad-band visible and infrared spectrums, thus enabling ground-based operational terminals to produce day and night pictures of the earth's cloud cover.

An advanced version of the VISSR called a VAS (VISSR Atmospheric Sounder) is now under development and will be flown on future GOES spacecraft. With the addition of twelve selectable narrow-band filters and more precise in-flight calibration of the infrared detectors, the VAS will provide increased data to help determine the earth's atmospheric temperature and water vapor distribution.

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VAS SYSTEM DESCRIPTION

The completed VAS Scanner is shown in Figures 1 and 2, while a cross section of the scanner is shown in Figure 3. For purposes of discussion, the instrument can be divided into three major subassemblies:

- Telescope (Three-Mirror System and Scanner Housing)
- Aft Optics Assembly (Visible Light Sensing Devices)
- Radiative Cooler (Infrared Sensing Detectors)

The VAS Telescope Assembly is a lightweight, all beryllium structure consisting of a scan mirror, primary mirror and secondary mirror mounted in a cylindrical housing. The plane scan mirror is mounted at 45° to the scanner spin axis and is elliptically shaped so as to reflect collected energy into the 40 cm diameter entrance aperture of the Ritchey-Chretien primary and secondary mirrors. In scanning the earth from North to South, the scan mirror is servo-positioned through 1820 steps (0.192 mr/step) by the twin torque-motor drives which support it. East-West scanning is provided by the 100 rpm spacecraft spin.

Mounted just behind the telescope is the Aft Optics Assembly. Energy collected in the visible spectral region is focused on a fiber optics array and transmitted from the telescope focal plane to eight photomultiplier tubes mounted radially on the Aft Optics Plate. The Aft Optics assembly contains a lens system which relays the infrared spectral energy from the telescope focal plane through the optical bandpass filters and on to the infrared detectors located in the Radiative Cooler at the rear of the instrument. The calibration shutter and a blackbody reference source are also contained in the Aft Optics Assembly as well as focusing gear-motor mechanisms which can be stepped to reposition the Visible and IR optical elements axially.

A passive radiative cooler is used to cool the long-wavelength detectors of the infrared channels to a controlled temperature of 95°K for optimum detector performance. The Cooler Assembly consists of an external sunshield, first stage cooler and a second stage cooler with the latter supporting the evacuated infrared detector package. Each stage of the cooler is thermally isolated from its surroundings and is cooled by a honeycomb high-emissivity radiator which views space. The satellite subpoint resolution varies from 0.9 km in the visible channels to 6.9 km in the infrared.

FILTER WHEEL ASSEMBLY

Filter Wheel Design Requirements

As mentioned earlier, the expanded infrared data acquisition capabilities of the VAS system are made possible mainly by the addition of twelve optical filters within the Aft Optics Assembly. When operated in the infrared atmospheric "sounding" mode, the instrument scans the earth scene from West to East with one of the twelve filters in the optical beam. The same scan line is then retraced on the next spacecraft spin with the second filter in the optical beam and so on for all twelve filters. The scan mirror is then stepped from North to South to the next scan line and the filter sequencing is repeated.

In keeping time with the 100 rpm spacecraft spin rate and to allow some time for detector calibration, any one of the filters must be inserted in the optical beam and settled within a 350 milli-second allotted time period for each spacecraft spin. Power consumption must be less than 5 watts. The flat filters must be parallel to each other within 0.5 mrad. Additionally, the mechanism which holds and positions the filters must withstand the environmental requirements of launch vibration induced by the Thor Delta 3914 booster vehicle and then operational temperature extremes of -15°C to +45°C in space vacuum. All functional elements must be dual redundant so as to have high reliability over the five year operational design life of the instrument.

Filter Wheel Design Description

An 11.2 cm diameter magnesium wheel provides accurately machined cells for the circular filters with a minimal moment of inertia(2.8 x 10^{-4} newton-meter-sec^2 total including filters).

The wheel is mounted on a shaft which is suspended between two preloaded duplex bearing pairs mounted in series such that if either bearing set fails, the other set will still turn freely. The bearings are dry-lubricated by a molydisulfide film on all contacting surfaces and teflon-impregnated retainers. Wheel positioning is accomplished using a direct drive six-pole brushless torque motor together with a 5-bit optical position encoder.

A second similar motor(mounted in tandem with first) is normally used as a tachometer to assist in the control loop for settling the wheel in any given filter position. This second motor can be driven together with the first, thereby doubling the available torque should this failsafe measure ever become necessary to move a particular filter into the optical beam.

The mechanism arrangement can be seen in the cross section and photograph shown in Figures 4 and 5. Since the different-mass filters are arranged around the wheel for best mechanical balance, the electronic drive logic must step the wheel back and forth in a complicated sequence which depends on filter wavelength. However, the maximum single-step rotation is never more than 180°. The filter wheel acceleration and deceleration rate is then approximately 1000 rad/sec^2 with a peak velocity of 20 rad/sec. The wheel and housing external surfaces are finish-coated with high emittance flat black and low emittance gold for purposes of filter thermal control.

Filter Wheel Problem Areas

During testing of an engineering model filter wheel assembly, two problems arose, one in the motor design and one in the position encoder.

The tandem redundant motor concept led to the development of a torque motor which could be used for both the primary drive and the tachometer. Ease of production and simplicity of electronic drive circuitry were both reasons for pursuing a single interchangeable motor design. The 6-pole, 2-phase torquer provided 12 magnetic detents for holding the wheel in any position without power. In order for the drive motor to step the wheel, it needed to have a torque sensitivity high enough and with the proper angular distribution to overcome the unpowered detent torque of both motor rotors. Although the motor performance was specified in order to achieve tandem operation, the motor manufacturer was unable to meet the specified torque sensitivity curves and as a result, the engineering model motors would not drive the wheel reliably between certain filter positions. A new motor was built which had the twelve stator pole pieces skewed at an angle to the motor axis but with the rotor pole pieces still aligned axially (Figure 6). By skewing the stator pole pieces, the magnetic flux from each rotor pole piece is spread among several stator pole pieces and the unpowered magnetic detent is reduced to nearly zero with a negligible reduction in powered torque sensitivity. The combination of a primary drive motor with skewed stator poles and a tachometer motor with straight stator poles (original design) resulted in a tandem pair with a total magnetic detent torque that was half of what it was originally yet still retaining the double total powered torque required for failsafe operation.

The position encoder problem arose during radiation testing intended to simulate radiation exposure in space. The encoder consists of 12 light-emitting-diode / phototransistor pairs and a thin intervening metal disc with cutouts in 5 tracks. When exposed to a $1x10^5$ rad dose of Cobalt 60 radiation, the output of the LED's was reduced to a level which rendered the encoder inoperable. Correction of the problem was achieved by adding a radiation shield made of tantalum around the entire encoder area. There were no failures of this kind after subsequent radiation tests.

Filter Wheel Testing

Once the drive motor problems were solved using the engineering model, a second filter wheel assembly was built using all new parts. Testing on this "reliability model" started with qualification vibration exposure followed by a functional check-out and then long-term operation in a vacuum chamber. An operational extreme was simulated wherein the filter wheel was automatically stepped back and forth 180° rather than in the normal filter sequence. Continual 24 hour operation accelerated the duty cycle to about 4 times that which would ever be experienced in space. This test was allowed to continue for a simulated space lifetime of eleven years. Periodic measurements of the time required for each step were used together with measurements of rolling and static bearing torque to evaluate bearing life expectancy. Bearing torque increased with time for both the inner and outer bearing sets as shown in Figure 7. Interestingly, the static torque required to turn each bearing separately did not equalize with time but rather exhibited a leapfrog increase at first and then a large difference for the duration (Figure 7). After approximately 7 million cycles of the filter wheel, the stiction in the larger outer bearings rose substantially so that the inner bearings were turning nearly all of the time.

The bearing torque increases were attributed to the formation of small bumps in the raceway lubricants as the teflon retainer material became unevenly distributed on contacting surfaces. Once the large bearing set became stuck in a particular spot, the repeated vibration created by operation of the small bearings caused the large bearings to become increasingly mired in that spot. Although the step time increased with the bearing stiction, it never exceeded 250 milliseconds, and since the test lasted more than double the design lifetime, no redesign was necessary and the subsequent flight model assemblies were built exactly like the reliability model.

CALIBRATION SHUTTER ASSEMBLY

Shutter Design Requirements

In-flight radiometric calibration of the scanner's infrared detectors is required for each spacecraft spin. A heated conical blackbody mounted within the Aft Optics Assembly serves as a constant-temperature IR reference source when viewed by the detectors through a 45° reflective mirror. Since 100% field-of-view coverage is required for calibration, the 2 x 3.5 cm rectangular mirror must be completely inserted into the optical beam within 50 msec, maintain blockage for 33.3 msec, and then be completely removed in 50 msec prior to earth view. After surviving the launch vibration mentioned earlier, the shutter mirror mechanism must operate continuously in the same environment as the filter wheel with minimal power consumption and must not block the optical beam whenever power is removed.

Shutter Design Description

Since shutter power consumption was to be minimized, the design concept evolved around mounting the mirror on a torsional spring so that it would oscillate at a natural frequency in time with the spacecraft spin. Then only a slight amount of input power would be required from a drive motor to maintain the amplitude and to occasionally correct frequency for spacecraft spin rate variations.

As shown in the photographs and cross section in Figures 8, 9 and 10, two flex pivot devices are mounted in series to provide the proper spring rate at sufficiently small deflection amplitude to insure nearly infinite spring life. The rotor of a two-pole brushless torque motor is coupled to the oscillating mirror portion of the mechanism. Attached to the same arm as the mirror is a chopper flag which actuates a 2-bit optical encoder for amplitude and frequency control. The shutter was designed to oscillate at twice the satellite rotation frequency to meet the insertion timing requirement without increasing the oscillation amplitude or swing radius beyond those allowed by the available space within the VAS Aft Optics area. Shutter mirror motion is then expressed as

$$\theta_m = 18°\sin 2\ (\theta_s - 5.17°)$$

where θ_m is mirror position and θ_s is satellite angular position relative to earth nadir. Static balancing of the rotating mass is accomplished by simply changing the thickness of a counterbalance weight.

Precise adjustment of the shutter natural frequency is then accomplished by adding thin rings to the shutter hub, thereby increasing the moment of inertia of the oscillating portion in accordance with the torsional pendulum relationship:

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{J}}$$

where f = frequency
K = total spring rate
J = polar moment of inertia

The rings are mounted so as to have no effect on the static balance of the shutter arm.

Shutter Problem Areas and Testing

A major oversight was made in the mathematical analysis of the dynamic forces acting on the shutter during operation in the spinning scanner. The shutter assembly is mounted in the scanner about 7 centimeters off the scanner spin axis. Since the Scanner's optical axis is nearly coincident with the spin axis, the shutter mirror moves on and off the spin axis in a plane that is tilted 45° to the spin axis. When the scanner is spinning, three types of dynamic forces affect the sinusoidal shutter arm motion:

1. Centrifugal force on the shutter arm CG resulting from static imbalance.
2. Forces resulting from Coriolis acceleration of the shutter mass as it moves in a rotating inertial reference frame.
3. Forces that are the result of any inertial imbalance in the shutter arm.

Static balancing of the shutter arm reduces the effects of the centrifugal force to negligible levels. The analysis also showed that since the shutter oscillates in one plane, the Coriolis forces always act on the arm in a direction intersecting the shutter rotation axis, thereby producing no torque about the shutter axis. The analysis stopped at that point, and consequently the first shutter assembly was built with a 6:1 imbalance ratio between the principle non-polar moments of inertia of the shutter arm. The unit worked fine until the scanner was spun, and then shutter motion was uncontrollable at spin rates over 30 rpm due to the inertial imbalance.

Corrective action was accomplished by redistributing the mass along the shutter arm by material density changes and the addition of two inertial balance weights at 90° to the axis of the shutter arm. Inertial balance between the two principle axes was thereby achieved, and a retrofitted unit operated flawlessly throughout the maximum electronic control range with scanner spin rates ranging from 80-120 RPM.

Just as with the Filter Wheel Assembly, a "reliability model" of the shutter assembly was built and tested in the laboratory. After being subjected to the launch vibration environment, the shutter was placed in a vacuum chamber and allowed to operate on a real-time basis for a period of 3 years. Periodic measurements of spring rate and natural frequency showed no change. Since the shutter assembly is a resonant-frequency device, no acceleration of the test is possible and it will therefore continue until five years of operation have been accumulated.

CONCLUDING REMARKS

In retrospect, the basic design approach was sound for both the Filter Wheel and Calibration Shutter assemblies. If requirements arise in the future for longer mechanism lifetime, some changes will have to be made to improve the Filter Wheel bearing lubrication. Research has already been performed on the bearing lubrication scheme in the scan mirror drives where the partial rotation creates a bearing "bump" problem much more rapidly than in the Filter Wheel Assembly. Perhaps a thinner RF sputter coating of molydisulfide would reduce the teflon transfer rate and thereby improve Filter Wheel bearing longevity as it did in the scan mirror drives.

The Calibration Shutter design concept was adopted for use in two shutter assemblies in the Thematic Mapper instruments now under development for the Landsat program. An improvement to the VAS design was made in the Thematic Mapper Shutters by supporting the oscillating mass between two side-mounted flex pivots rather than in a cantilever arrangement as in VAS. This prevents bending loads from being exerted on the pivots by the drive motor and affords better control of the rotor-stator air gap. Although this design was considered for VAS, the VISSR retrofit requirement left insufficient space for the bulkier side-mount flex pivots.

Three VAS Systems are currently being built. The first of these has successfully completed all of the scanner-level acceptance tests and is now being installed on the GOES 'D' spacecraft. Launch of the GOES 'D' is scheduled for August of 1980 with GOES 'E' and GOES 'F' following at six-month intervals.

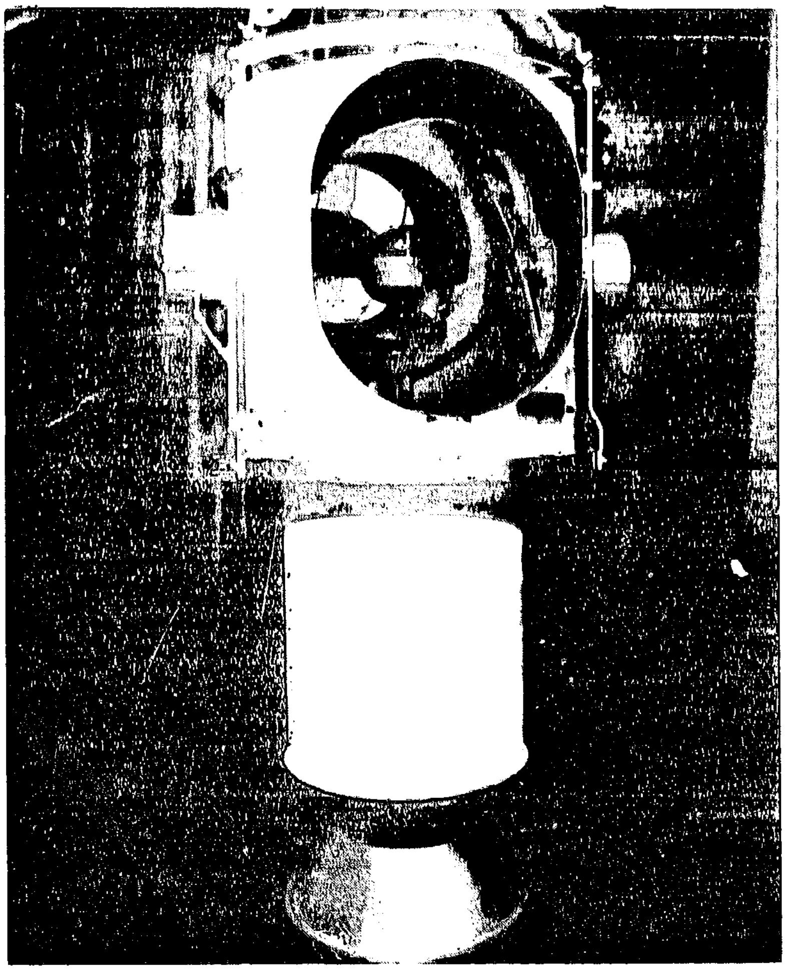

Figure 1.- VAS Scanner.

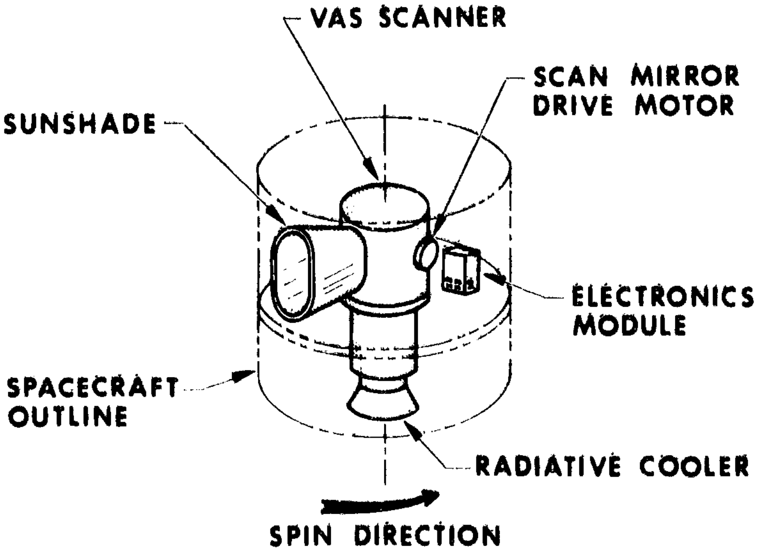

Figure 2.- VAS mounting in GOES spacecraft.

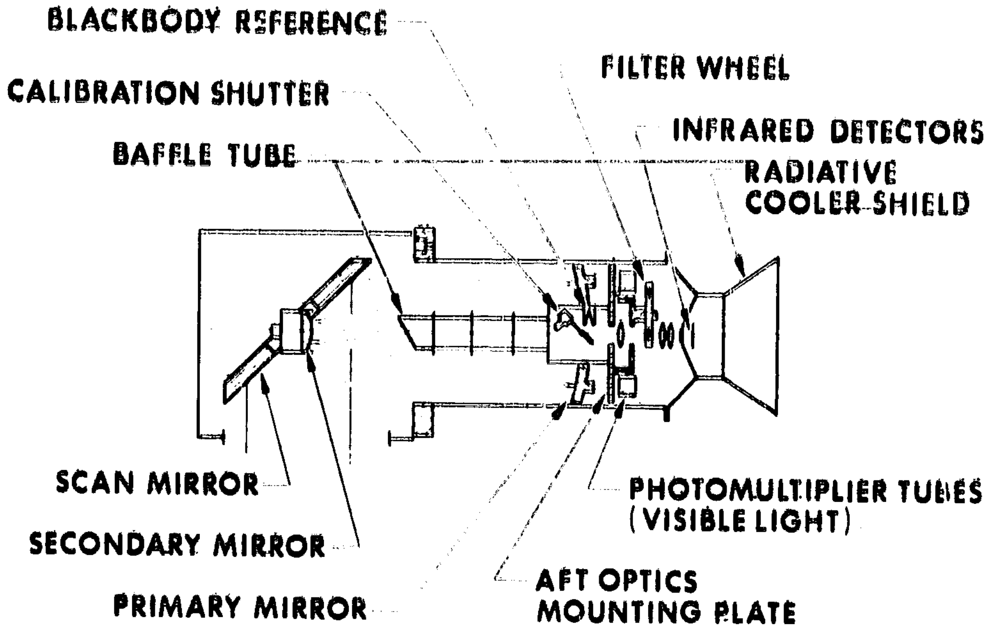

Figure 3.- VAS schematic cross section.

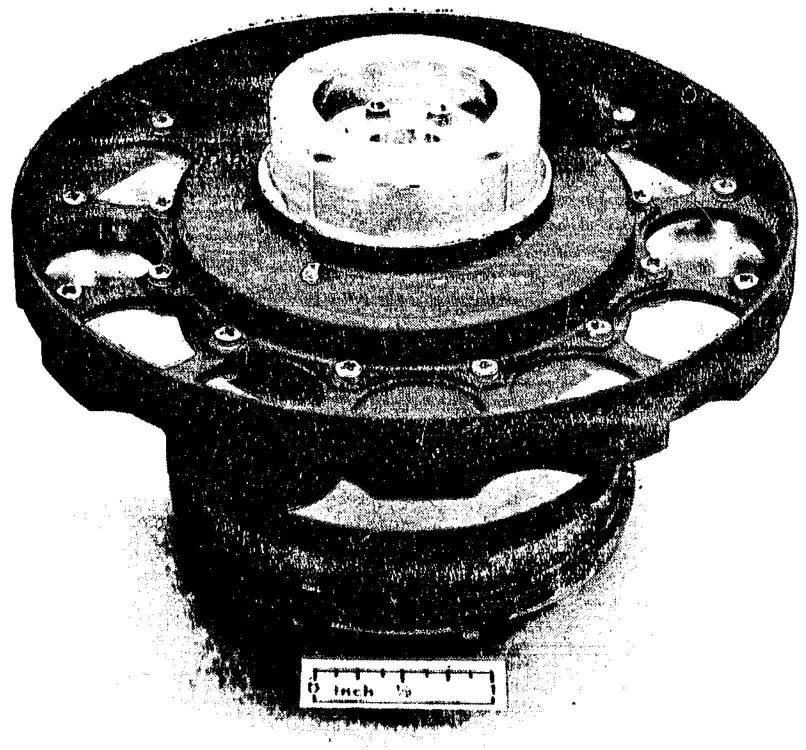

Figure 4.- Filter wheel assembly.

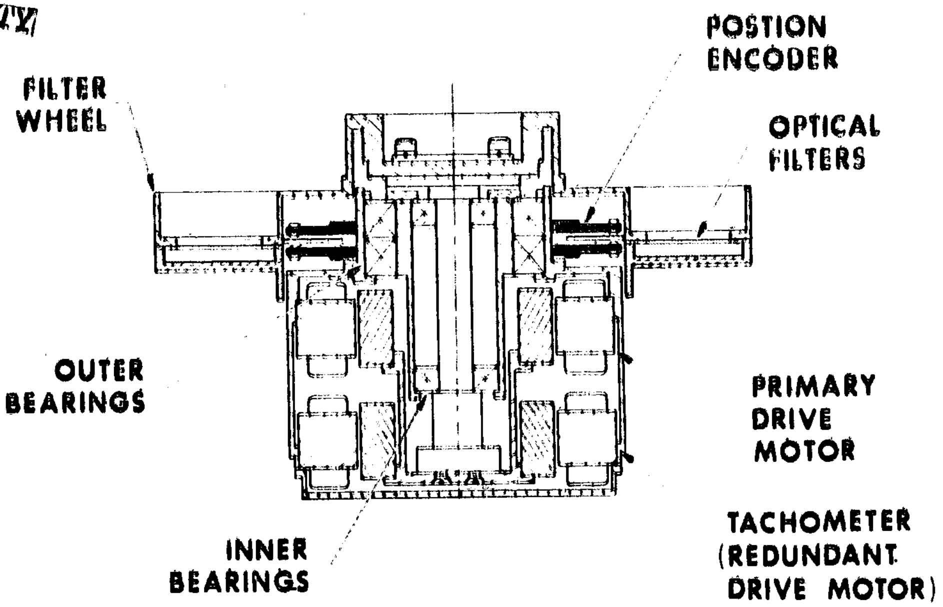

Figure 5.- Filter wheel schematic cross section.

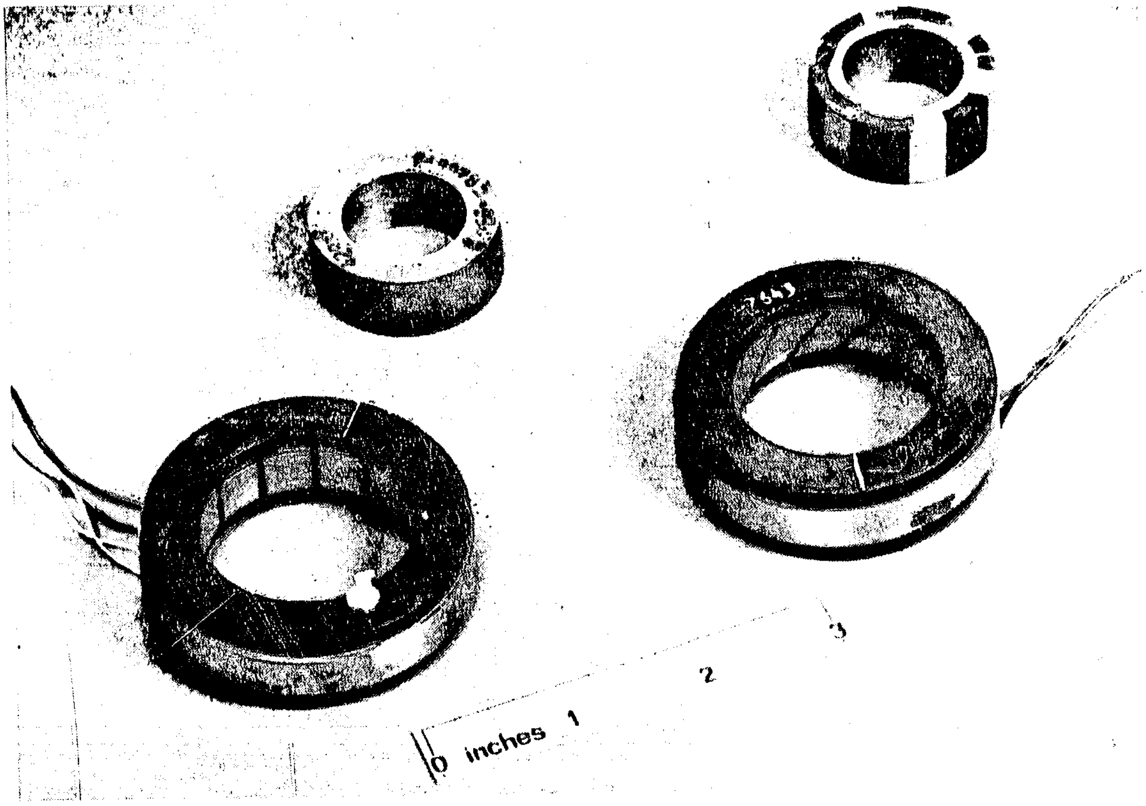

Figure 6.- Filter wheel motors - primary drive on right, tach (redundant drive) on left.

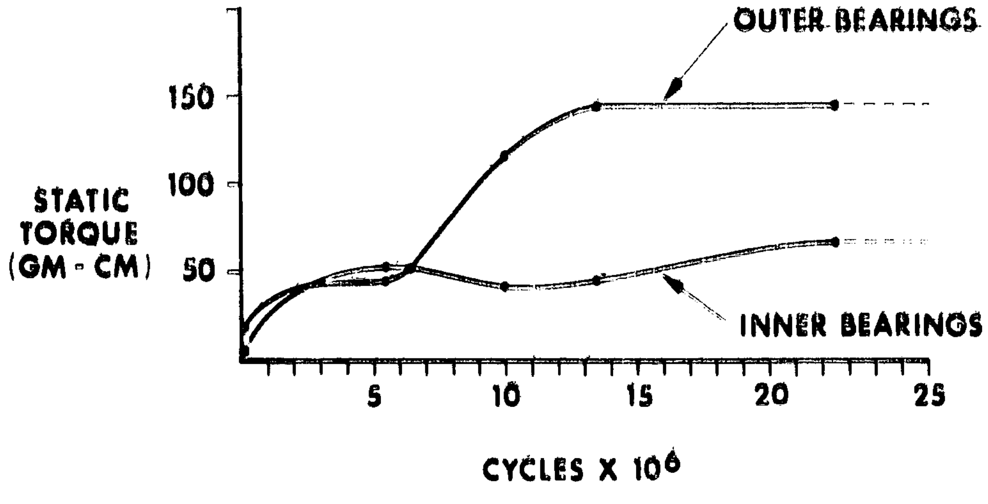

Figure 7.- Filter wheel life test - bearing torque vs. accumulated operation.

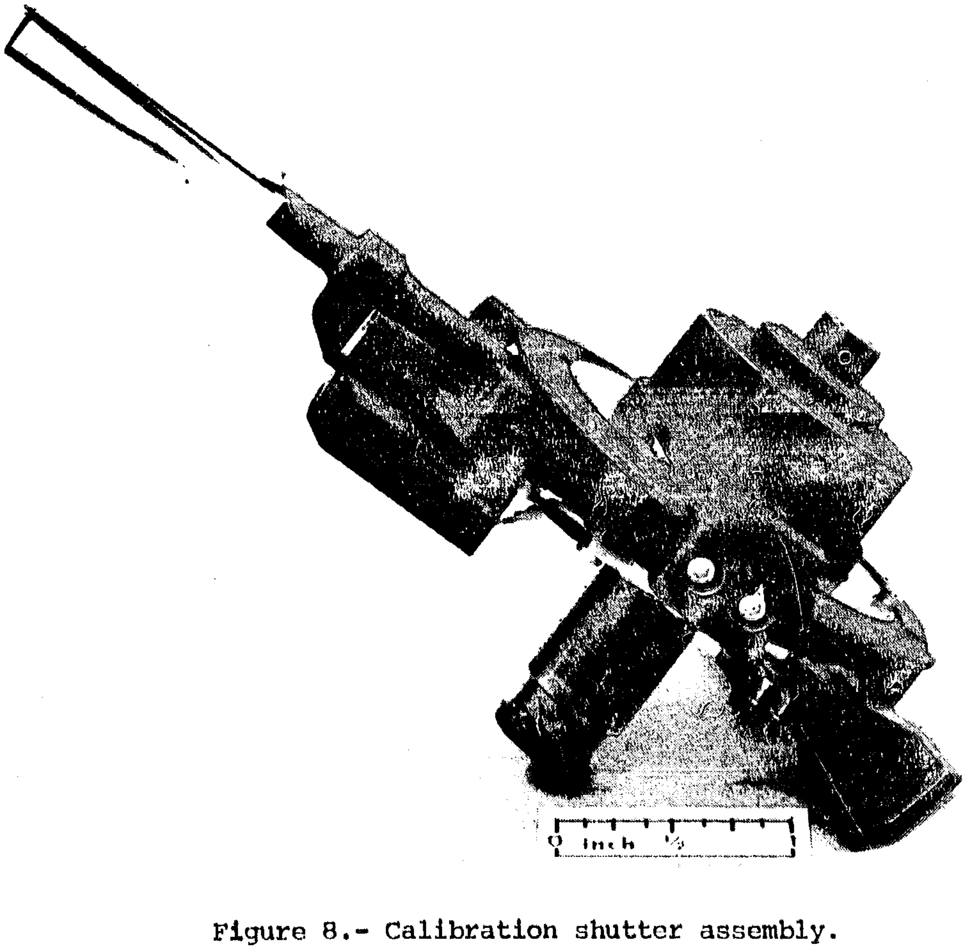

Figure 8.- Calibration shutter assembly.

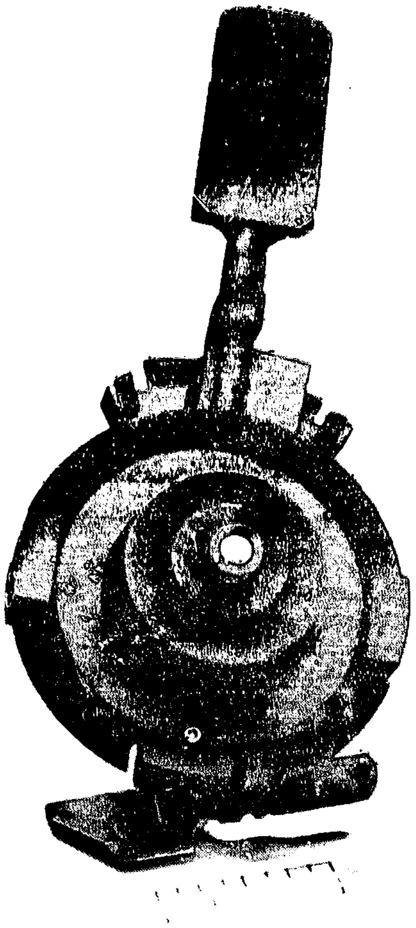

Figure 9.- Calibration shutter assembly.

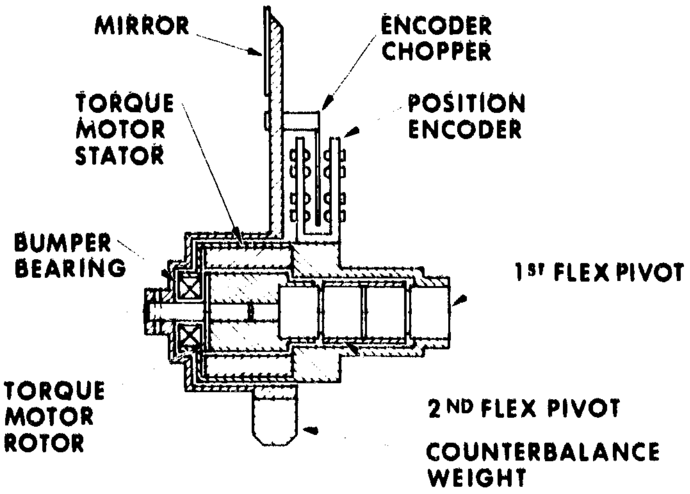

Figure 10.- Calibration shutter schematic cross section.