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DESIGN OF THE GALILEO REMOTE SCIENCE POINTING ACTUATORS

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ABSTRACT

This paper describes the two actuators developed for pointing the remote science instruments from the spinning Galileo spacecraft. Details of the key elements are presented together with their design features and developmental difficulties. Four techniques used for power and signal transfer across the actuators' rotating joints are also discussed.

INTRODUCTION

The Galileo mission to investigate the planet Jupiter and its satellites will use the dual-spin spacecraft shown in Figure 1. A major portion of this spacecraft, the rotor, will spin continuously at 3.15 revolutions per minute to provide gyroscopically stabilized antenna pointing together with a rotating base for the sky-sweeping fields and particles experiments. Instruments which must be pointed for remote sensing, including the imaging system, will be carried on a non-spinning, or stator, portion of the Galileo Orbiter spacecraft. A Spin Bearing Assembly (SBA) will mechanically and electrically couple these spun and despun Orbiter sections to permit instrument pointing around the spacecraft "clock" axis. The Scan Actuator Subassembly (SAS) will couple the remote science scan platform to the despun stator to provide instrument pointing in the "cone" axis.

Since achievement of the mission remote science objectives is very dependent on the reliable operation of these two mechanisms, they contain redundant elements. Total redundancy was not possible, however, so their development required extensive analysis and testing to insure successful mission completion. Both of the actuators, and their associated electronics, were developed by the Space Systems Unit of Sperry Flight Systems, Phoenix, AZ, under a contract with the Jet Propulsion Laboratory.

Although the two actuators are very dissimilar in configuration, their key design elements, described below, are very much alike.

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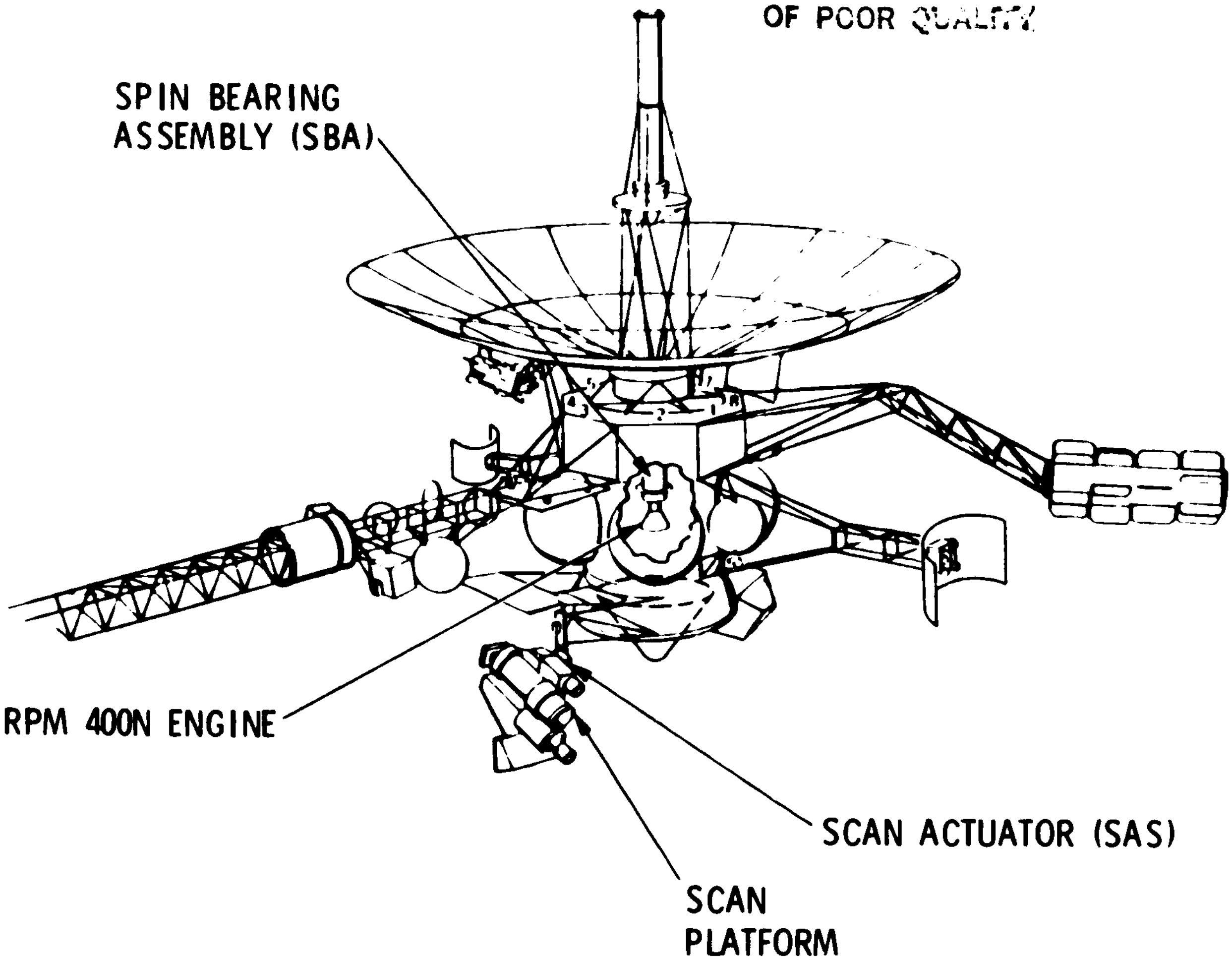

Figure 1. Galileo Spacecraft

SPIN BEARING ASSEMBLY CONFIGURATION

The SBA, Figure 2, has a fairly complex structure because it must provide a spun mounting for the 400 newton retropropulsion engine and a path for its fuel lines in addition to providing mechanical and electrical coupling between rotor and stator. This engine spins with the rotor so that any thrust vector misalignment will be averaged out during the long Jupiter orbit insertion burn. An engine support assembly is tied through the central engine support tube and a top cap to the SBA outer case. This case is mounted at the spacecraft rotor spin axis by struts which bolt to the central and lower case flanges.

Midway between the outer case and the central engine tube is a concentric despun tube whose end flange supports the spacecraft stator after flight deployment. A duplex bearing pair in the SBA

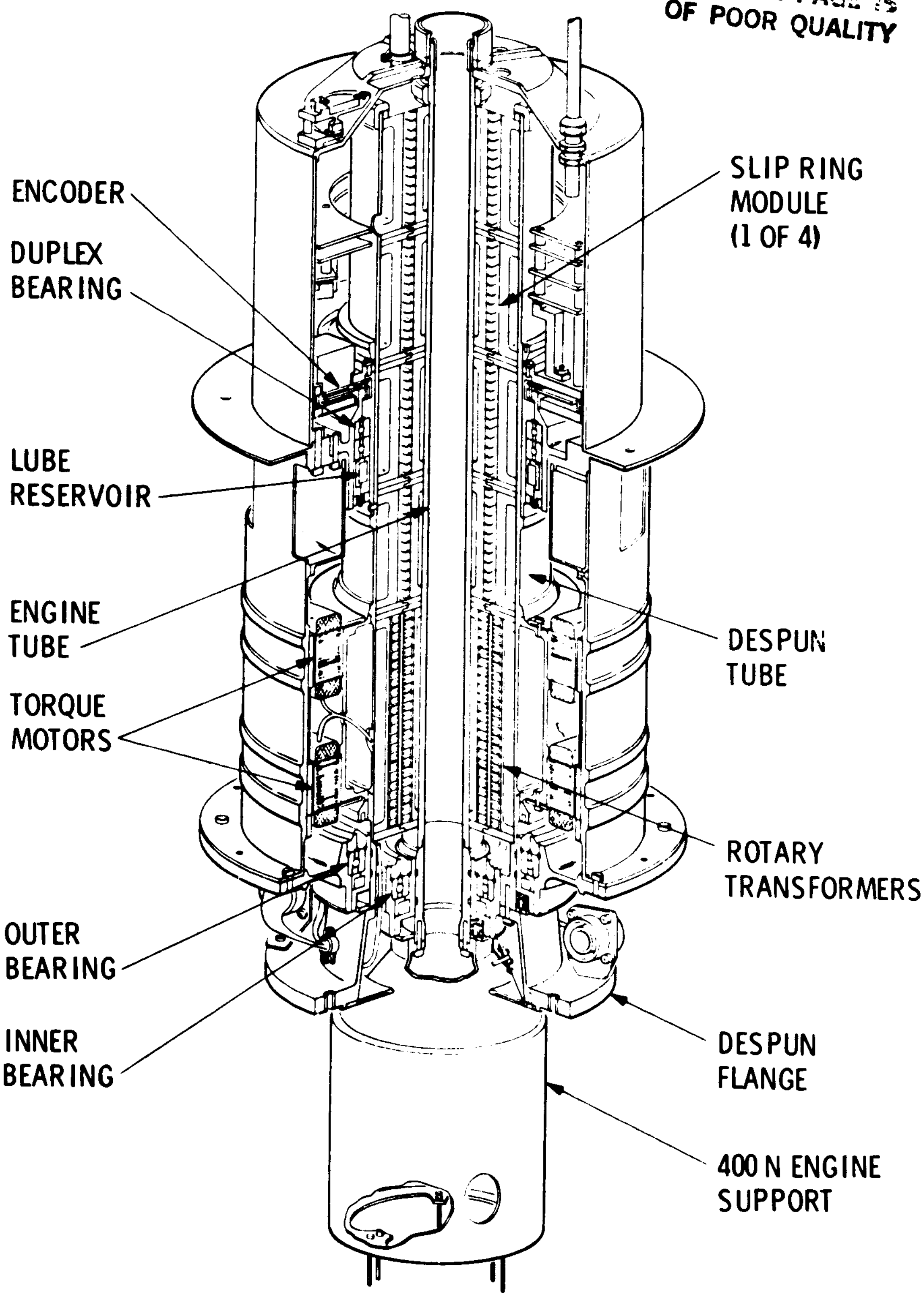

Figure 2. SBA Configuration

encoder is the primary rotating axial load transfer path between the spacecraft rotor and stator. Inner and outer bearings at the aft end of the SBA maintain the concentricity between the case, the despun tube, and the engine tube. These aft bearings are mounted in sliding sleeves so they cannot carry axial loads. They are preloaded by sets of coil springs which maintain a relatively constant preload in the presence of the radial thermal gradients which exist during portions of the mission. A more detailed description of the bearings and their lubrication system is provided below.

The annular volume between the despun tube and the engine tube contains a stack of 23 rotary transformers and 4 slip ring modules which, together with their associated wiring, provide electrical power and signal transfer between the spacecraft rotor and stator. In the annular space between the despun tube and the outer case are two redundant brushless DC torque motors and an optical encoder for rotor/stator relative position sensing.

Obviously, the complexity of the Spin Bearing Assembly created some difficult design and assembly challenges.

SPIN BEARING ASSEMBLY CHARACTERISTICS

The SBA is 0.75 m (29.5 in) long, the case diameter is 0.22m (8.6 in), and it weighs 31.2 kg (68.9 lb). All major structural elements are titanium. Each motor can provide a torque of 4.5 Nm. The drag torque is approximately 0.5 Nm (4.4 in-lb), primarily from the slip rings. Torque ripple must be less than 0.01 Nm except within discrete frequency bands where it is allowed to rise to 0.08 Nm. Ripple torque must be limited to minimize excitation of the spacecraft rotor flexible modes.

Rotary transformers allow 23 channels of digital data transfer at 800 kilobits/second and there are 48 slip rings for power and low frequency data transfer.

The 16-bit optical encoder provides a digital grey code output with a position resolution of 96 micro-radians (20 arc-seconds).

SCAN ACTUATOR SUBASSEMBLY CONFIGURATION

The SAS, Figure 3, is not as complex as the SBA. Its main housing mounts on the side of the spacecraft despun stator and contains the optical encoder position sensor. On a hollow shaft,

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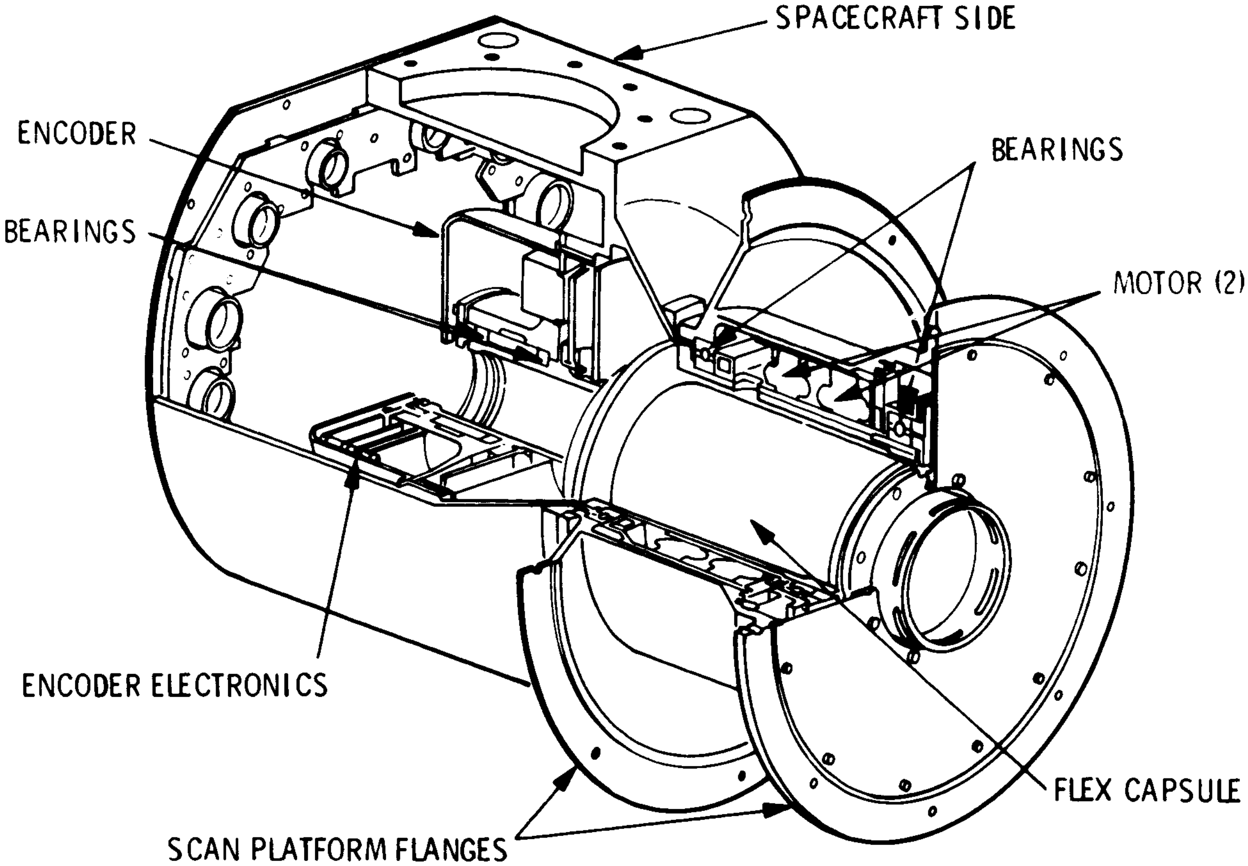

Figure 3. Scan Actuator Configuration

extending from the housing, are two bearings which support the SAS rotor. These bearings are spring loaded by a diaphragm within the rotor. The honeycomb scan platform, with its science instruments, is bolted to the rotor flanges. A 200-wire Flexible Circuit Assembly (FCA) is located within the hollow shaft to furnish electrical power and signal transfer between the stator and the scan platform. An FCA inner shaft drives the encoder rotor through a coupling diaphragm. This FCA shaft is supported at one end by the encoder bearings and at the other end by the SAS rotor end plate. Two redundant brushless DC torque motors drive the SAS rotor for scan platform pointing. Rotation is limited to 210° by stops on the case and the lower rotor flange.

SCAN ACTUATOR SUBASSEMBLY CHARACTERISTICS

The SAS is 0.35 m (13.8 in.) long, the lower rotor flange diameter is 0.26 m (10.3 in.), and it weighs 10.4 kg (22.9 lb.). All major structural elements are beryllium. Each of the redundant motors can provide a torque of 1.0 Nm. The average drag torque is 0.04 Nm (5.7 oz-in.). Dahl parameters were established for system performance modeling at low tracking rates, and a maximum torque stiffness, σ, of 85 Nm/rad (12,000 oz-in./rad) was measured on the SAS engineering development unit.

As in the SBA, the 16 bit optical encoder provides a digital grey code output with a position resolution of 96 micro-radians (20 arc-seconds).

BEARING AND LUBRICATION SYSTEM

Certainly the key elements in the long term reliability of the actuators are the bearings and their lubrication. All bearings are ABEC Grade 7T with AFBMA Grade 5 balls. Rings are 52100 chrome alloy steel, balls are 440C stainless steel. The ball separators, chosen for a low and consistent drag torque, are TEFLON toroids. The large SBA bearings have a 11.43 cm (4.75 in.) bore, a 1.27 cm (0.5 in.) cross section, with 0.635 cm (0.25 in.) balls. All SBA bearings operate with a 22.7 kg (50 lb.) preload at a 20° contact angle for the encoder duplex pair and a 30° contact angle for the spring loaded aft bearings. The inner SBA bearing has a 5.08 cm (2.0 in.) bore and the same cross section and ball size as the larger bearings.

The SAS rotor bearings have a 10.16 cm (4.0 in.) bore, a 1.27 cm cross section, with 0.635 cm balls. They operate with a 18.1 kg (40 lb.) preload at a 30° contact angle. The SAS encoder separated duplex pair has a 5.08 cm (2.0 in.) bore, a 0.635 cm cross section, with 0.32 cm (0.25 in.) balls and they run with a 9 kg (20 lb.) preload at a 30° contact angle. All of the flight bearings were supplied by the Split Ball Bearing Division of MPB Corporation, Lebanon, New Hampshire.

All of the bearings receive a tricresyl phosphate pretreatment followed by lubrication with Kendal KG-80 oil. This lubricant was chosen for its radiation resistant qualities and its successful performance history in numerous similar applications. Each bearing cavity contains an acrylic copolymer (MICROWELL) lubricant reservoir which provides a sacrificial vapor supply to minimize the loss rate of the bearing oil through the 0.018 cm (0.007 in.) bearing cavity gaps. Sperry Flight Systems' lubrication loss analysis predicts, as the worst case, that at least 65% of the bearing lubricant will remain at the end of a seven-year mission.

A bearing design verification unit, using flight quality SBA parts, was built and subjected to flight unit vibration and thermal-vacuum test environments. It ran, in vacuum, at Sperry for about one year prior to shipment to the Jet Propulsion Laboratory, where it continues to run. Bearing drag torque, about 0.06 Nm (8.0 oz-in), has been relatively stable, as have the bearing torque ripple characteristics. Since the SAS bearings and lubrication system are very similar to the SBA, the test is also furnishing confidence in the reliability of the SAS design.

Bearing system design required difficult tradeoffs between good bearing design practice, the "zero" torque desires of the pointing control system designers, and the stiffness requirements of the spacecraft structural analysis group. The bearings are very lightly loaded in space, yet they must carry significant loads during shuttle launch and environmental tests. The aft SBA bearings approach their stress limit during sine vibration tests at the "heart stopping" retropropulsion engine/engine tube cross axis resonance. Lead times for high quality bearings always present fabrication schedule problems. Some bearing deliveries were delayed by a chlorine corrosion problem which was traced to the trichloroethylene used to clean parts prior to the TCP treatment.

TORQUE MOTORS

Sperry Electro-Components of Durham, NC, supplied the two-phase, 24 pole, brushless DC torque motors for the SAS and the SBA. Torque constant for the SAS motors is 1.27 Nm/A (0.94 ft-lb/A) and for the larger, heavier SBA motors it is 5.29 Nm/A (3.9 ft-lb/A). Both utilize samarium cobalt magnets.

Individual motors in a pair are rotationally oriented to minimize the magnetic cogging torque and external magnetic field of the combination. Even with this cancellation, the external field of the SBA pair exceeded the 10 nano-tesla maximum allowable radial field at one meter, so the SBA will require external compensation. Spacecraft fields must be tightly controlled to preclude interference with the measurement of external fields by the Galileo magnetometer.

OPTICAL ENCODERS

Optical encoders are used in both actuators to supply position information to the system control computer and for torque motor commutation. These encoders were supplied by BEI Electronics, Inc. of Maumelle, AR. The SAS encoder, Figure 4, is a direct design derivative of the encoders used in the Shuttle Remote Manipulator System (Canadarm). Its big brother, the SBA encoder shown in Figure 5, has a larger center bore to fit over the SBA despun tube.

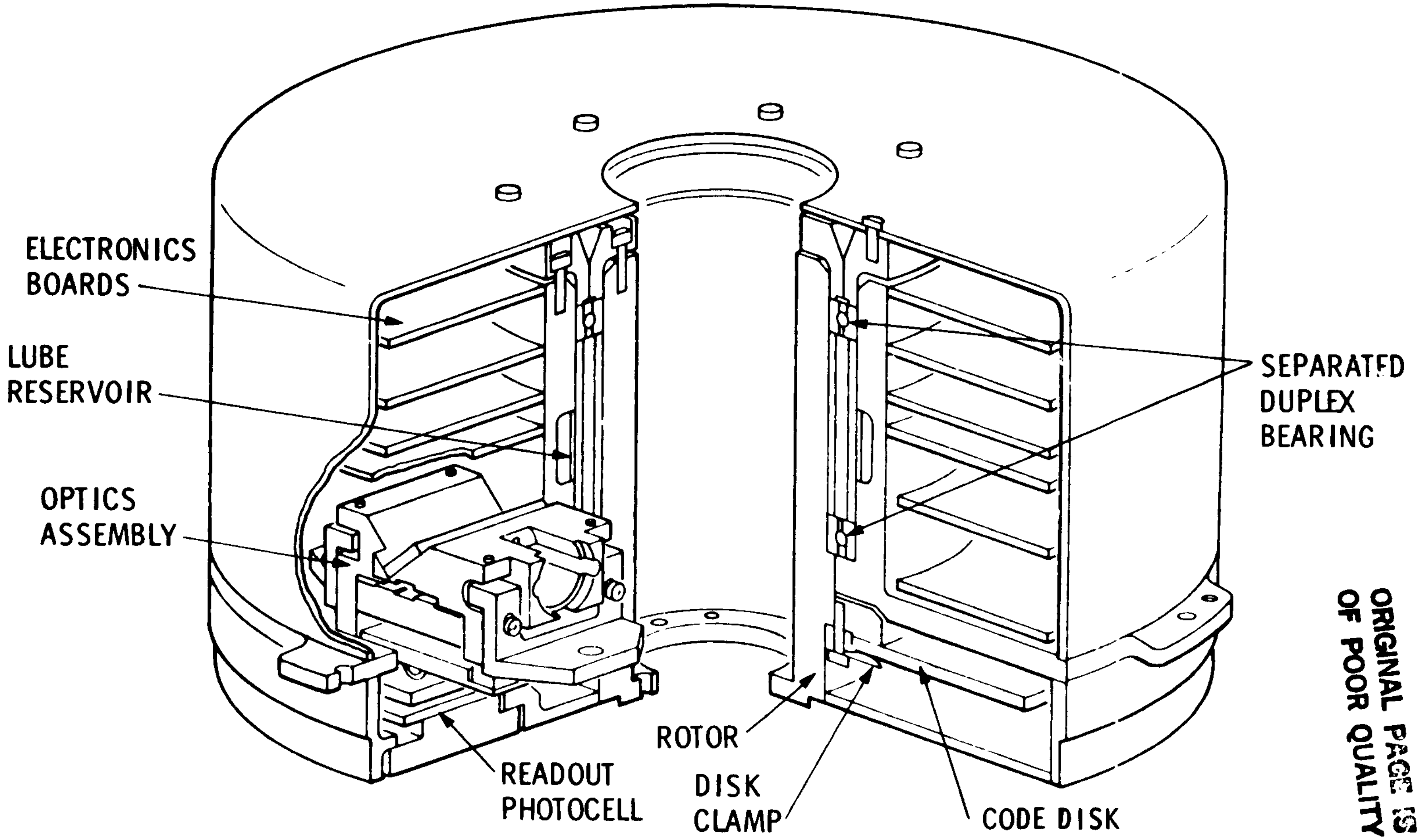

Figure 4. SAS Optical Encoder Cross Section

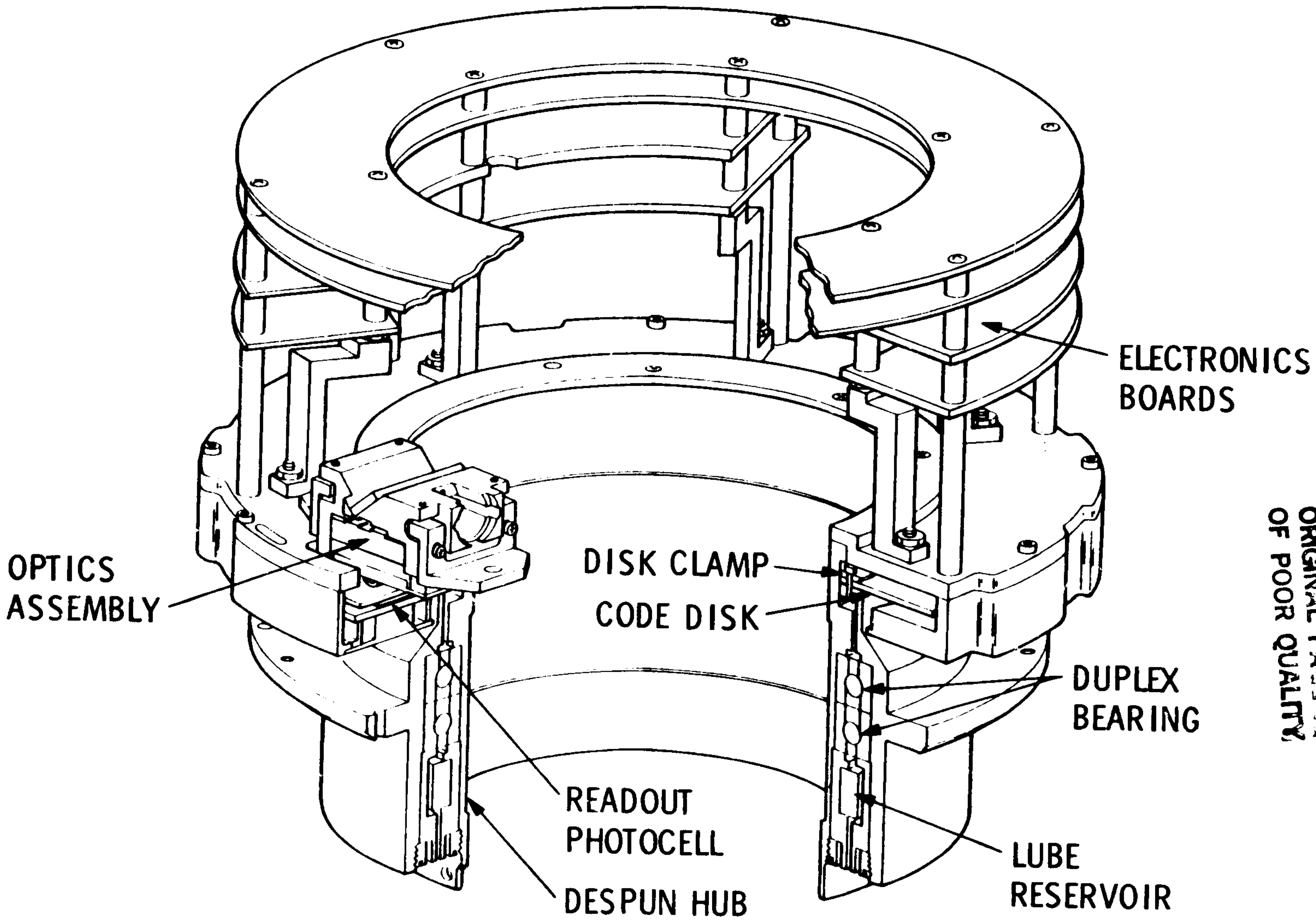

Figure 5. SBA Optical Encoder Cross Section

Redundant electro-optics assemblies, positioned 180° apart around the glass code disc, are used to read the 16-bit position information. Position resolution, as mentioned earlier, is 96 micro-radians (20 arc-seconds) and the allowable peak-to-peak error, at the code transitions, is 120 micro-radians (25 arc-seconds).

Achieving the code disc radial stability needed to meet this peak-to-peak error requirement proved to be difficult, time consuming, and, of course, expensive. Piece parts for the initial engineering development encoders were machined from 410 CRES to save schedule time. This material, the bearing material, and the glass used for the code disc have fairly closely matched coefficients of thermal expansion and the BEI procedure for mounting the glass disc on the rotor hub worked normally. Flight encoder piece parts were machined from titanium for the SBA and beryllium for the SAS. These changes were made to reduce weight and to match the other structural elements of the actuators. Stable code disc mounting for the titanium SBA encoders was fairly easy but getting a SAS code disc to remain stable throughout the thermal environment required many attempts, with attendant schedule slips. In retrospect, it probably would have been better to have changed the glass material to achieve a better thermal coefficient match.

SIGNAL AND POWER TRANSFER

The complex, and often conflicting, mechanical requirements imposed on the SAS and SBA are complicated by the added requirements imposed on them because they are also an integral part of the spacecraft electrical cabling system. As such, they must provide rotating electrical circuit paths for 28 VDC power; 2.4 kHz, 50 V, square wave power; low voltage digital logic power and signals; high frequency digital bus data; temperature transducer signals; gyro rebalance loop signals; and pyro firing circuits. Each of these circuit types comes with its own redundancy, shielding and isolation, and electrical parameter requirements. In total, the cabling system required 200 wires through the SAS and 96 through the SBA.

FLEXIBLE CIRCUIT ASSEMBLY

Because of its limited rotation, the SAS can use flexible circuit tapes to provide the required circuit paths. This Flexible Circuit Assembly (FCA), Figure 6, was supplied by the Electro-Tech Corporation of Blacksburg, VA. It contains four, 50 wire, etched copper circuit tapes manufactured from DuPont PYRALUX WA/K copper-clad laminate and cover sheet. The tapes are

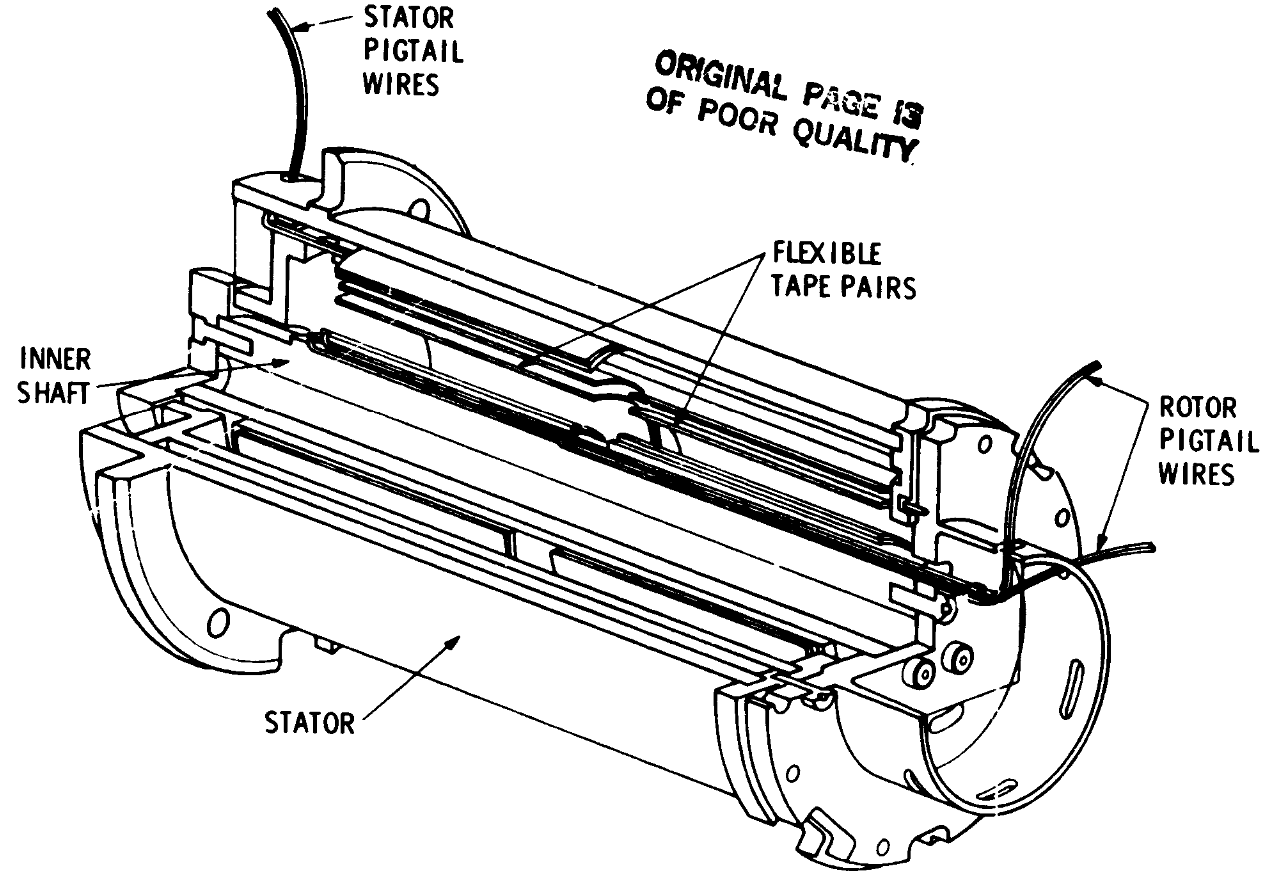

Figure 6. SAS Flexcapsule Cross Section

arranged in pairs with one pair wound clockwise and the other counterclockwise to minimize spring torque effects. Maximum allowable torque to rotate ± 105° is 0.02 Nm (3.0 oz-in.).

Cross-coupling is minimized by the assignment of circuits within the tapes. A circuit "high" has its return path on the same trace in the adjacent tape layer and the highs and returns alternate across each tape. The maximum allowable capacitance of any trace to the FCA rotor and stator is 125 pico-farads. The maximum pickup allowed in a circuit pair is 250 millivolts when an adjacent pair is excited with a 100 volt peak-to-peak, 2.4 kHz, square wave with a 0.5 micro-second rise and fall time.

Two-foot wire pigtails extend from the FCA stator end for connection to the SAS back plate connectors during SAS assembly. Pigtails on the rotor end terminate at scan platform instrument connectors. These pigtails contain a variety of wire types and sizes including #24, #26, and #28 AWG in single wires, twisted pairs and triplets, shielded and unshielded, with two different insulation types. Keeping track of all these wires through the

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assembly process and handling this multi-limbed device, without damaging wires, were major tasks.

ROLL RINGS

In its initial design stages, the SBA used the Sperry roll rings to accomplish power and signal transfer between the two sections of the spacecraft. These unique devices, illustrated in Figure 7, consist of inner and outer rings (which are much like bearing races) with a thin circular flexure rolling between them as they rotate. Flexure and ring cross-sectional curvatures are designed so that the flexure rolls on its outer edges provide redundant contact points and a small amount of wiping action to keep the surfaces clean. Predicted drag torque for a stack of 100 roll rings was 0.01 Nm, certainly a desirable attribute for a pointing actuator.

As the roll ring development and test progressed, a series of problems occurred. First, obtaining uniform platings on the rings and flexures with adequate adhesion was difficult. As these plating problems were resolved and as significant amounts

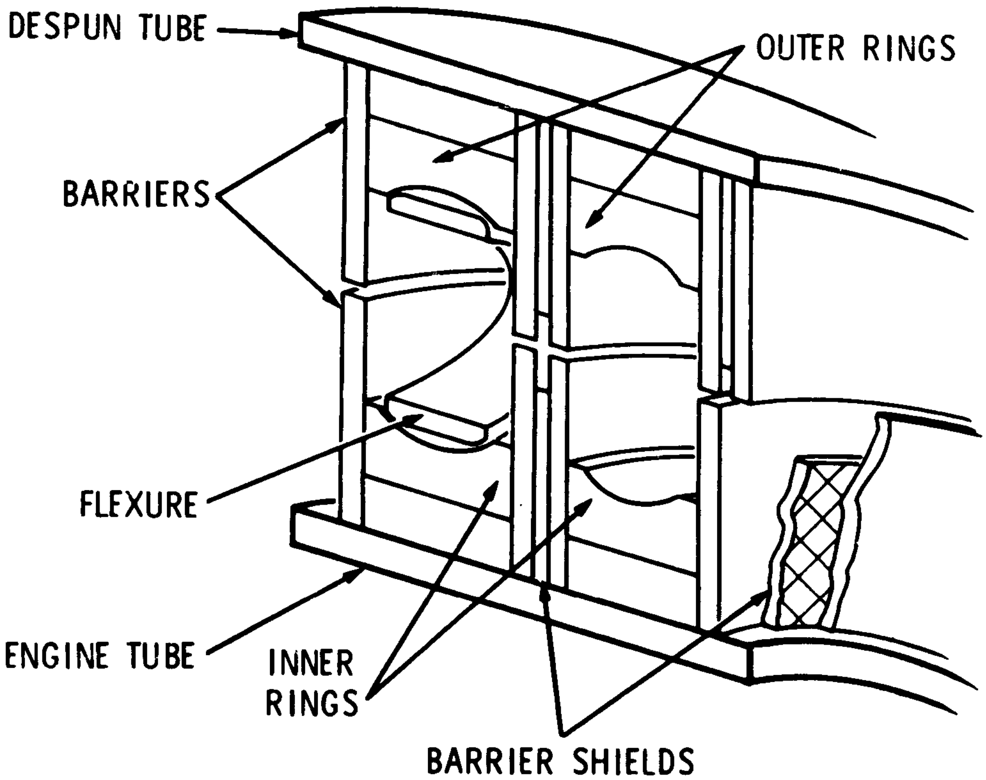

Figure 7. Cross Sectional View of Two Roll Ring Circuits

of rolling test time accumulated, flexure breakage began. Flexure stress is determined by a trade-off between desired flexibility, contact pressure, and fatigue life. Sperry had used published fatigue stress data which proved to be inadequate for the flexure configuration. They initiated a series of flexure fatigue tests which furnished the data necessary for a successful flexure design tradeoff.

Meanwhile, many of the units tested could not meet the electrical interruption requirements of the digital data transfer system. Devices which were electrically quiet while running in air became noisy after a period of operation in a vacuum. Information was obtained in a literature search which showed that the coefficient of friction between unlubricated gold surfaces increases dramatically in a vacuum. This led to an explanation for the random momentary interruptions. As the contact surfaces cleaned up during vacuum operation, the flexure could climb out of its normal track, thereby losing its redundant contact at one edge. This unstable condition would continue until the edge in contact encountered some surface anomaly, which would cause it to skid back into its normal track. During the skid, circuit interruptions could occur, particularly if the anomaly was some form of surface contamination.

The obvious answer was to lubricate the roll rings, following the practice in gold-on-gold slip ring technology. Lubrication was tried, successfully, but this led to a difficult situation. With the roll rings unlubricated, life tests could be accelerated. With lubrication, they could not, and it was not possible to adequately prove the reliability of a lubricated electrical contact in the time available.

Due to the recurring problems with the roll rings, a backup development effort had been initiated utilizing proven dry lube silver slip rings and rotary transformers and in December 1980 an SBA design change was directed.

Sperry has continued development of the roll rings with their own funds. The original lubricated devices are still running, with excellent electrical characteristics. Steady progress has been made in resolving the problems inherent in running roll rings unlubricated. In the author's opinion, these devices will eventually provide a significant improvement in rotating electrical joint technology.

SLIP RINGS

The SBA contains 4 slip ring and brush block assemblies with 12 equal width rings in each module. Two paralleled brushes ride on each ring, about 180° apart, to provide contact redundancy. Two different size brush tips are used, one rated at 3 amperes per brush pair, the other at 0.4 amperes per pair. Each of the 4 brush block assemblies contains a different mix of high and low power brush pairs to give 31 high and 17 low power paths through the SBA.

The design uses dry lube silver-on-silver technology which has been proven in many space applications. Brush tips are molded from 85% silver, 12% molydisulphide, and 3% graphite. Rings are plated up, starting with copper, followed by fine silver, which is then covered with hard silver. Ring and brush block assemblies were supplied by the Electro-Tech Corporation of Blacksburg, VA.

There were two major concerns in the application of slip rings in the SBA. The first was the amount and the characteristics of the wear debris generated during the 11-million revolution, 7-year mission life. Excess debris, containing long silver slivers, could generate internal shorts or arcing which would cause spacecraft system failures. Several measures were taken to reduce this concern. First, all interior conductive surfaces were covered with insulating materials to block shorts to the spacecraft structure. Next, physical and electrical circuit isolation was provided which will allow continued operation of the spacecraft systems in the presence of ring to ring short circuits. Then, an accelerated life test was run to demonstrate that the hard silver ring surface did not tend to generate long slivers. After 13.5 million revolutions, the longest sliver found in the debris was 0.076 cm (0.03 in.) long. Total quantity of debris formed and brush tip wear rates closely matched the results reported from several other sources.

The second major concern was that the brush tips might lift under launch vibration, causing circuit interruptions and the potential for ring surface and brush tip damage. Brush pressures were set at the high end of industry standard practice and early module testing showed that the brushes would not lift.

When the engineering development SBA was tested, brush bounce did occur during both sine and random vibration inputs. Tests and analysis disclosed an unfortunate combination of resonances in the engine tube, the despun tube, and the brush leaf springs which could cause both of the redundant brushes to lift simultaneously. Extensive brush bounce tests were performed which demonstrated that the contact surfaces would not be damaged and the brush tips would not chip or fracture under sustained vibration. Spacecraft systems using the slip rings were reviewed and some changes were made to allow continued operation with momentary circuit interruptions. Shuttle launch vibration data was analyzed and the random vibration test requirement in the range between 100 Hz to 1 kHz was reduced from 0.1 G^2/Hz to 0.068G^2/Hz. At this test level brush bounce did not occur.

ROTARY TRANSFORMERS

Rotary transformers are used for digital data transmission between the spun and despun sections of the spacecraft. Preliminary design of these devices was performed at the Jet Propulsion Laboratory with Sperry Flight Systems making the design refinements necessary for their application in the SBA.

Transformer construction is shown in Figure 8. Assembly of the inner and outer transformer sections is similar. Ten turn coils of #36 AWG wire are wound on ceramic bobbins. These bobbins are placed between two manganese-zinc ferrite half cores which are cemented into titanium core holders. Assembly tooling maintains concentricities while the cement joints are cured. In

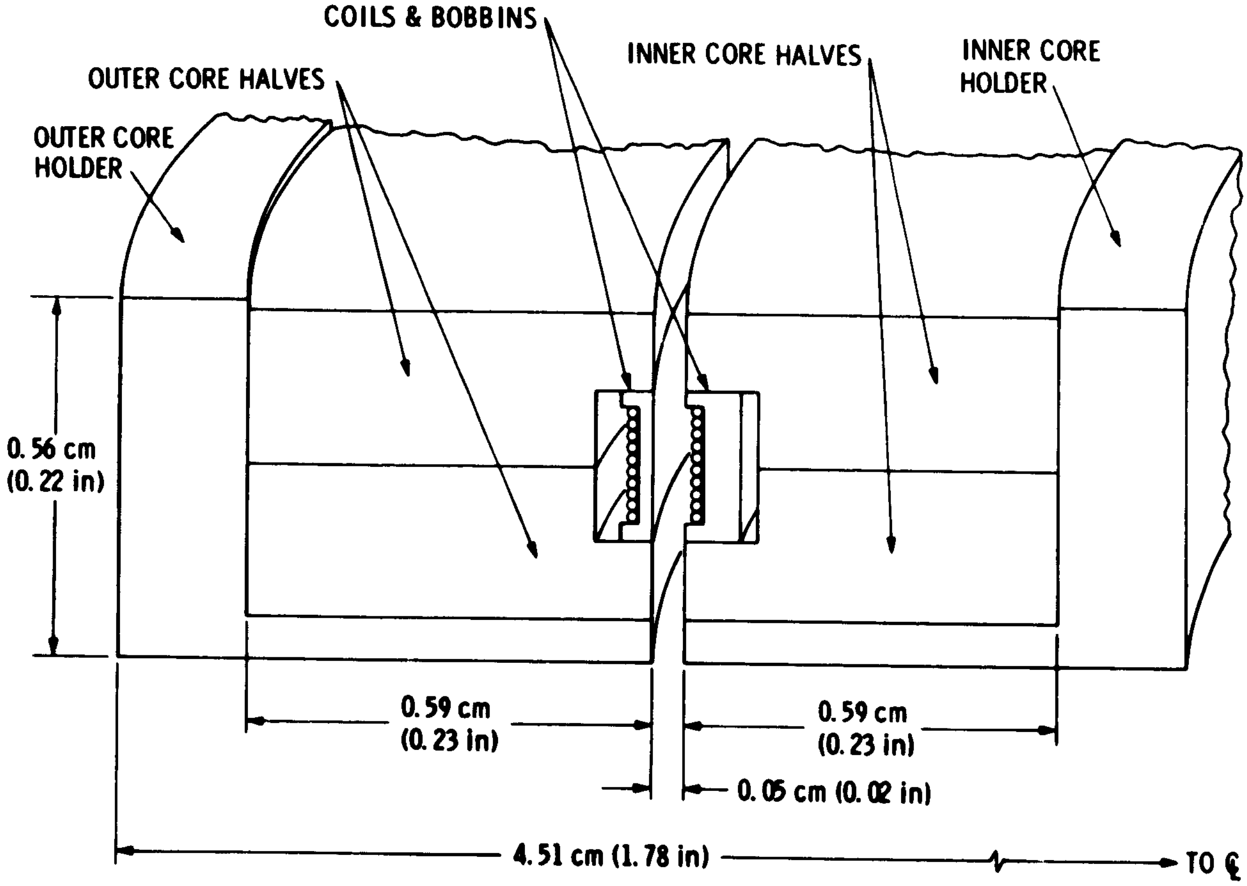

Figure 8. Rotary Transformer Cross Section

the unassembled condition the bobbins and cores are quite fragile, requiring careful packaging and handling, but once assembled, they are much less susceptible to damage. Transformer cores (MN-31) were supplied by Ceramic Magnetics of Fairfield, NJ, and the coil windings by Standard Industries of La Mirada, CA.

Rotary transformers have many characteristics which make them ideal digital signal transfer devices. There is no wear or torque drag, they are quite insensitive to axial or radial misalignments, and they are highly reliable. Their primary difficulty is associated with the design of the driver and receiver circuits required to couple data across the magnetic gap. Mechanism designers prefer a wide gap to minimize tolerance stackup problems, while circuit designers prefer a narrow gap to reduce leakage inductance. The Galileo rotary transformer radial gap is 0.05 cm (0.02 in.). The resulting nominal electrical parameters, including effects of the twisted shielded lead wire, is shown in Table 1.

TABLE 1. Rotary Transformer Electrical Parameters

	WINDING		MEASUREMENT FREQUENCY
TEST PARAMETER	INNER-SPUN	OUTER-SPUN	
Open Circuit Impedance Phase Angle	395 Ohms 84°	370 Ohms 85°	800 kHz
Open Circuit Impedance Phase Angle	33 Ohms 75°	34 Ohms 76°	80 kHz
Short Circuit Impedance Phase Angle	76 Ohms 83°	76 Ohms 83°	800 kHz
DC Resistance	3.52 Ohms	3.54 Ohms	N/A
Resonant Frequency	1.46 MHz	1.66 MHz	N/A

SUMMARY AND ACKNOWLEDGEMENT

These two actuators, and their component parts, presented a wide variety of technological challenges to everyone involved in their design, fabrication, and test. Engineering development units and flight versions have been built, sucessfully tested, and are well into integration with the Galileo spacecraft systems. The ultimate degree of success cannot be measured until mission completion, sometime in the 1990's, but the progress to date is certainly due to the professional competence and dedication of many individuals whose contributions are gratefully acknowledged.

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