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SLIP RING EXPERIENCE IN LONG DURATION SPACE APPLICATIONS

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INTRODUCTION

In 1978 SEASAT suffered a disastrous power system failure after three months of successful operation. The probable cause was a short somewhere inside a slip ring assembly. It was also concluded that mistakes had been made in the original slip ring specification (for a project other than SEASAT) and in the way the slip ring was used. The power transfer requirement could easily have been satisfied except for these mistakes. Unfortunately, few in the aerospace community have had an opportunity to read the SEASAT failure report. The widely disseminated news that a satellite was destroyed by a slip ring failure has led to a totally undeserved skepticism of these highly developed and very useful mechanisms.

This paper reviews Ball Aerospace System Division (BASD) experience with slip rings in space, presenting design and application experience for several different types. Ball flew the very first slip ring used in space in its first Orbiting Solar Observatory (OSO-1) satellite, launched in 1962. Since then, more than 40 BASD drives using slip ring assemblies for power and signal transfer have been orbited. Continuous operating lifetimes up to eight years at 60 rpm have been demonstrated. We have also specified, purchased, and/or lubricated as many or more slip rings for other space prime contractors. We have no knowledge of any orbit failure of a Ball-processed slip ring assembly. The cumulative orbit operating lifetime of these units comes to hundreds of years and billions of revolutions.

SLIP RING SOURCES

BASD does not make slip rings, and sources for the slip rings described in this paper are:

- Electro-Miniatures Corp, Moonachie, NJ
- KDI Electro-Tec, Blacksburg, VA
- Poly-Scientific Division, Litton Industries Inc., Blacksburg, VA

If it seems unusual for this paper to be originated at a company that does not produce the mechanism being described, it is because component users in the space community often have more visibility of results than the suppliers.

BALL AEROSPACE ROLE IN SLIP RING APPLICATIONS

When a slip ring is to be used in a BASD drive, our role includes the following:

- Preparation of a definitive procurement specification. Often this is preceded by preliminary design studies of the slip ring assembly itself to establish approaches compatible with the overall drive concept as well as realistic envelope and performance requirements. It is important to maintain some initial flexibility at this stage to be

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able to take full advantage of the supplier's special knowledge and experience. For instance, despite his objections, the SEASAT slip ring supplier was forced to put more rings into the assembly than available space permitted for a sound design. The excessively crowded assembly may have contributed to the eventual problem.

- Detailed reviews of the supplier's design, materials selections, and processes
- Inspection of critical manufacturing and test operations at the supplier's facility
- Lubrication of bearings used in the assembly
- Lubrication of the rings and brushes when self-lubricating materials are not used
- Hard vacuum run-in tests at Ball followed by disassembly, run-in wear debris removal, reassembly, and checkout
- Brush force measurement (100%) and tweaking if necessary during final assembly
- Slip ring performance evaluation during drive acceptance tests, which always include thermal vacuum operation

Our suppliers' contributions should not be minimized. The early OSO slip rings, which will be described here, were built up from discrete standard components and were completely disassembled and rebuilt at Ball. Subsequent major slip rings used by Ball have come from Electro-Tec or Poly-Scientific and have been complete special assemblies for each application, designed in detail by their suppliers. BASD hard vacuum materials technology was very important, especially in the early days, but now both Poly-Scientific and Electro-Tec have more than 20 years experience with hundreds of slip rings for space use. On the other hand, before self-lubricating brush and ring combinations came into use for space drives, Ball Aerospace lubricants for hard vacuum played a very major part in our slip ring success, and continue to do so when lubricated assemblies are called for.

FIRST OSO SLIP RINGS

Ball's OSO scientific satellites were spin stabilized at 30 rpm and received power and signals from a despun solar array on which sun-pointed instruments were mounted. OSO-1, launched in 1962, was the world's first dual-spin satellite, and contained the first slip ring used in an unsealed mechanism in space. Between 1962 and 1969, six OSOs of the initial configuration were flown, accumulating a total of more than 18 years of operating time before shut down. With the despin drive turned off during orbit night, about 200 million drive revolutions or three billion slip ring revolutions were accumulated with no known slip ring problem.

Figure 1 shows three views of the 22-ring Electro-Miniatures assembly used on OSO-6. Previous units were similar but used fewer rings. Slip rings are coin-silver discs clamped against opposite sides of a laminated phenolic washer by short tubular phenolic spacers. Brushes are silver graphite buttons on the ends of beryllium copper leaf springs, two per ring. The buttons are 0.090 in. in diameter and 0.060 in. long, with hemispherical ends. The hard vacuum rating was 3 amperes per ring. Brush springs are stacked between rectangular phenolic spacers. The two large cylindrical objects are porous sintered nylon blocks impregnated with lubricating oil. No bearings were used in the slip ring itself; the rotor was mounted on the end of the despin drive shaft and the brush rigging was fastened to the drive housing inside a sheet metal cover.

It is difficult to believe that one of these units with its tiny brushes operated at 30 rpm for more than five years (60 minutes on, 30 minutes off) in OSO-5. One contributing factor was the effectiveness of the lubricating oil (used to replace the effect of water vapor in air for terrestrial applications) and the wear mechanism that this oil helped to promote. A small amount of brush wear, generated during early operation, remained under the brush pad, effectively eliminating further wear (see Reference 1).

This simple design from the earliest days of space mechanism experience is included because it illustrates one viable approach for which components are still available from Electro-Miniatures, although the phenolic insulators have been replaced by more modern plastics.

WIRE BRUSHED SLIP RING, SINGLE GROOVE TYPE

Another type of slip ring widely used for low power and signal applications has hard gold wire brushes and soft gold rings with a hard gold flash. Rings are V-grooved so that brushes are laterally stabilized while the bottom of the groove provides a lodgement for wear debris away from the brush track. In the more common configuration, the brush wire is formed into a U-shape with both ends in the ring groove, as seen in Figure 2.

The advantage of this design is high ring density. Ball Aerospace has used them with 25 rings per inch in 40- and 66-ring assemblies. Many more rings can be provided, and even closer ring spacing is used, especially with very tiny slip rings. With 15 mil brush wires, a ring and brush set would be conservatively rated for 2 amperes in vacuum.

The rotor consists of rings embedded in epoxy cast over a metal shaft rather than being assembled by stacking individual components. Rings are plated into grooves machined in the plastic, machined to final shape, and then flashed with hard gold. For space applications, a ceramic filler is usually added to the epoxy to bring its expansion coefficient down into the range of the shaft and ring materials. Brushes are made from gold alloy wire rolled into rectangular cross-section or flattened at the ends in the ring contact zone. An epoxy casting creates a brush block which holds the brushes for every other ring as seen in Figure 2. The housing is slotted to let the brushes onto the rings and provide access to the brush ends for brush force checking and adjustment. Brush force must be set carefully. Our rings have used 3-5 gm and, with our lubricants, the friction coefficient may vary between 0.3 and 0.8.

A liquid lubricant is necessary if significant rotation is involved. Ball's most widely used lubricant consists of a highly refined mineral oil with EP additive. Recently, a synthetic oil with improved characteristics has come into use. With the mineral oil, reservoirs are placed along the brush access slots in the housing, as seen in Figure 2. Vapor pressure of the new oil is so low that surface films are sufficient for multi-year missions and reservoirs are not required.

It might seem that these slip rings could not possibly last very long with their tiny brush wires, but such is not the case. When suitably lubricated, the brushes, for practical purposes, do not wear. Rings only wear until the hard flash is penetrated, then wear effectively ceases. In hard vacuum tests on 40-ring assemblies running at 30 rpm, Ball demonstrated this in two tests lasting 6 and 18 months. In both units, ring wear scars stopped at the soft gold interface. Ring wear in the 18-month sample, based on measured wear scar cross-sections, was actually slightly less than that of the 6-month specimen, possibly because the hard gold was not quite as thick. Figure 3 includes microphotos of four representative ring wear scars from the 18-month life test specimen.

This wear-limiting phenomenon suggests a means of reducing the amount of wear debris occurring during flight. Units are run-in to establish the wear scar, then debris is removed. Debris occurs in the form of microscopic particles.

A high-resistance short between two rings occurred during the 18-month life test. A minute crack in one of the 0.010 thick epoxy barriers between rings was discovered, into which wear debris had infiltrated. Cracks in debris barriers cannot be tolerated and must be weeded out by microscopic inspection. Fortunately they rarely occur.

When we needed a new OSO slip ring with 40 rings in the same space as the 22-ring assembly on OSO-6, the wire brushed configuration, was adopted. The units were made by Poly-Scientific and two of these underwent the life tests referred to above. The assemblies were 2.15 in. in diameter by 2.5 in. long.

Two BASD spacecraft flew with these slip rings. OSO-7 operated continuously at 30 rpm for 2.8 years and then re-entered. P78-1 operated continuously for 6.4 years at 30 rpm until it was intentionally shut down. We are not aware of any slip ring problems on these two spacecraft.

WIRE BRUSHED SLIP RING, DOUBLE GROOVED TYPE

A variation of the slip ring just described uses rings with two V-grooves. Brush wires are bent into a tight hairpin and the ends lie side-by-side in the two grooves, instead of straddling the ring. This design was used in the slip rings for DSCS-II despin drives developed in the early 1970s. At that time there was some indication from our suppliers that wear on a slip ring with trailing brushes (brushes put in tension by the friction force) might be less than on stubbing brushes. It also seemed likely that with a single brush in each groove, the brushes would seat more perfectly. Since DSCS-II drives required 5-year design lives and at that time we had only the 18-month life test on gold-gold rings to guide us, we adopted the double V-groove ring design, shown isometrically on Figure 4.

Two variations of the DSCS-II slip rings were built, one with 90 rings and another with 100. Each of these had 58 signal rings on a 0.5 in. diameter section of the rotor, with the balance being power rings rated at two amperes each on a 1 in. diameter. Signal brushes used 0.012 in. diameter wires flattened at the ends while power brushes were 0.015 in. diameter. Axial ring pitches were 0.066 and 0.078 in. for signal and power, respectively, including 0.015 in. wide debris barriers. The 100 ring unit was 9.38 in. long by 2.62 in. in diameter and weighed less than 3 lb.

The DCSC-II slip rings, made by Electro-Tec, were very successful. A 6-year thermal vacuum life test at 60 rpm was conducted on one unit by Aerospace Corporation, while TRW tested several others for up to three years. Ten units have been flown in space, and six are still in operation. Launched in pairs, these six had been going 8.1, 7.1 and 6.1 years as of January 1986.

In light of the demonstrated life beyond five years at 30 rpm with single groove rings in the P78-1 spacecraft, which was not launched until 1979, it would now appear that the precaution of side-by-side brushes is unnecessary. Wire brush single-groove gold-gold slip rings, which are made by both Electro-Tec and Poly-Scientific, will be smaller and lighter. Furthermore, it is likely that the amount of new wear debris after cleanup of run-in wear will be less. Although wear debris has not been a demonstrated problem, less must be better.

SLIP RING WITH SELF-LUBRICATING CONTACTS

Toward the end of the 1960s, Ball Aerospace participated in a slip ring materials test program with INTELSAT and Poly-Scientific. Several brush and ring combinations in self-lubricating and fluid-lubricated combinations were evaluated at the COMSAT Laboratories of INTELSAT in two multi-specimen test sets. Each set was run in a hard vacuum at 100 rpm for more than a year (52.5 E+6 revolutions/year). Of the self-lubricated materials, composite brushes of silver, molybdenum disulfide and graphite (85, 12 and 3 percent respectively) running on coin silver (90/10 silver/copper) were found to be most satisfactory. Although noise and wear occurred in air, little or no wear occurred during the vacuum test and noise was low (Reference 2). This material combination has subsequently been widely used by Ball and other United States space equipment designers. Details of some BASD experiences follow.

GPS SOLAR ARRAY DRIVE

The Global Positioning System (GPS) spacecraft made by Rockwell International has two solar arrays, each driven by a separate single-ended drive made by BASD. Since axial space for solar array drives was very restricted in the initial block of GPS space vehicles, the slip ring assembly was installed inside the shaft with the brush assembly bolted into the shaft, and the slip ring rotor cantilevered from a nonrotating plate at the inboard end of the housing. No separate slip ring bearings were used. These assemblies contained 35 rings including 4 power rings (10 amperes each), 30 signal rings, and one electrical bonding ring. Figure 5 shows this assembly from the back of one brush block and from one side looking through a brush inspection slot. The assembly is 4.75 in. long by 1.75 in. in diameter. In the GPS slip ring, brush assemblies consisted of small rectangular blocks of the $Ag/MoS_2/C$ brush material on the ends of U-shaped beryllium copper finger springs. Power rings used four brushes, each operated at a nominal 147 amperes/in.^{2}. Braided copper shunts in parallel with the springs helped carry current from the brush pads to the leads. Signal rings used two brushes each that were individually fastened to a molded plastic brush support structure. Rings were solid coin silver molded in ceramic-filled epoxy over a stainless steel cruciform arbor.

Early in the development of this drive a vibration test on sample brushes in contact with a dummy slip ring rotor showed brush resonance at approximately 300 Hz. Brushes moved laterally and twisted from the weights of the overhung brush pads. The random input was 0.5 g^2/Hz in the brush resonance range.

Brush resonance caused chipped brush pads resulting from brushes beating against the raised plastic debris barriers between rings. Coating the brush springs with thin films of polyurethane completely eliminated this problem. Since it was suspected that thermal expansion coefficient mismatch between the urethane and beryllium copper brush springs could cause brush force changes, measurements on several brushes were made at room ambient temperature and -30°F. Changes of approximately 1 gm from initial test fixture settings of 15 gm were observed; in all cases these were increases and considered entirely acceptable.

To minimize vibration problems on brush assemblies of this type, brush pads should be of minimum height ($\leq$0.090 in.). There is a natural tendency to provide relatively long brushes in long-life applications, but with these brushes running on silver rings, wear is negligible even under continuous rotation at 60 or 100 rpm. The best brush design will only be long enough to allow conformity to the ring curvature plus a shallow layer above any infiltration of solder or brazing material from the brush-spring interface.

Power brushes are operated at current densities in the 100-150 ampere/in.^{2} range for space applications, and contact pressures of 6 psi. Signal brushes commonly have pad face areas in the 7E-3 in.^{2} range (0.06 x 0.12 in.) or less, and brush force is set at about 20 gm. Reference 3 describes an experience with brush spring force settings that is worth being aware of, although we at Ball have never encountered the problem described therein.

For calculating friction torque, a friction coefficient of 0.25 to 0.50 will cover the range.

While the Ag/MoS_2/C brush on silver is outstanding in vacuum, it is not so good in air. The MoS_2 helps provide lubrication in the absence of air but may lead to formation of intermittent high-resistance films in air, especially at higher humidity levels. Ball Aerospace has experienced high electrical noise levels during or immediately following operation of slip rings of this type in air. The noise can be eliminated by operation in dry nitrogen or vacuum but sometimes many revolutions are needed for ring cleanup. For this reason, slip rings with this brush material should only be operated in dry nitrogen or vacuum. If exposure to humidity occurs statically, subsequent vacuum or dry nitrogen exposure to remove any adsorbed water before operation is started will prevent any problems.

As of 1 January 1986, nine GPS satellites with 18 array drives have been launched. Array motion varies from a few degrees to 360 degrees per orbit (two orbits per Earth day) and occurs in steps of approximately 0.1 degree. Total drive operating time on 1 January 1986 was 89.5 years with 7.8 years on the oldest pair. No slip ring problem known to Ball Aerospace has ever occurred.

HIGH POWER SLIP RINGS

Within the past year, two 50,000 revolution thermal vacuum life tests were successfully completed at Ball Aerospace on 61-ring slip ring assemblies from Electro-Tec. These units included four 48-ampere and two 24-ampere 125 Vdc rings (15 kW total power capacity). Features of this slip ring will be discussed for the insights they provide into the high power transfer units required for new large spacecraft such as Space Station.

The 48 ampere rings were 2.38 in. diameter fine silver with a hard silver flash, plated up in 0.25 in. wide grooves in a ceramic-filled epoxy. Raised barriers 0.188 in. high and 0.20 in. wide separated pairs of high side and return rings. The barriers were grooved 0.090 in. deep and stationary discs mounted on the brush blocks fit down into the grooves, providing virtually complete isolation between rings and preventing line-of-sight between exposed hot elements and ground. Surface creepage distance between rings of opposite polarity was 0.75 in. (enough for more than 500V). The remainder of the power

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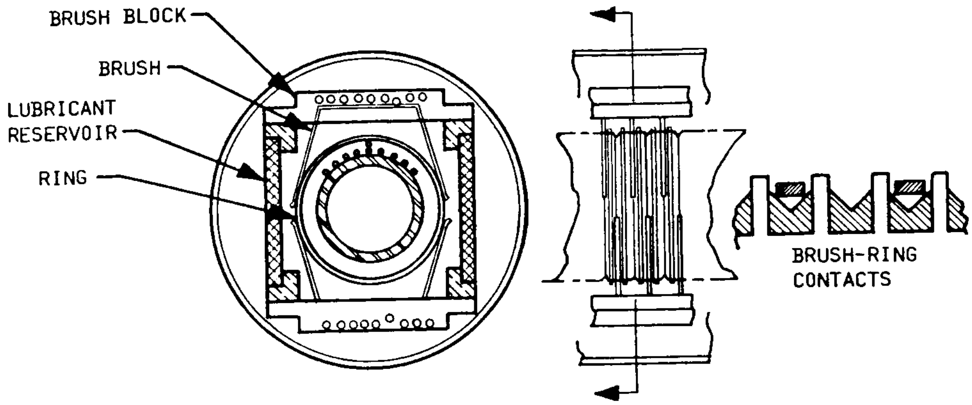

Figure 2. - Wire brushes slip ring details.

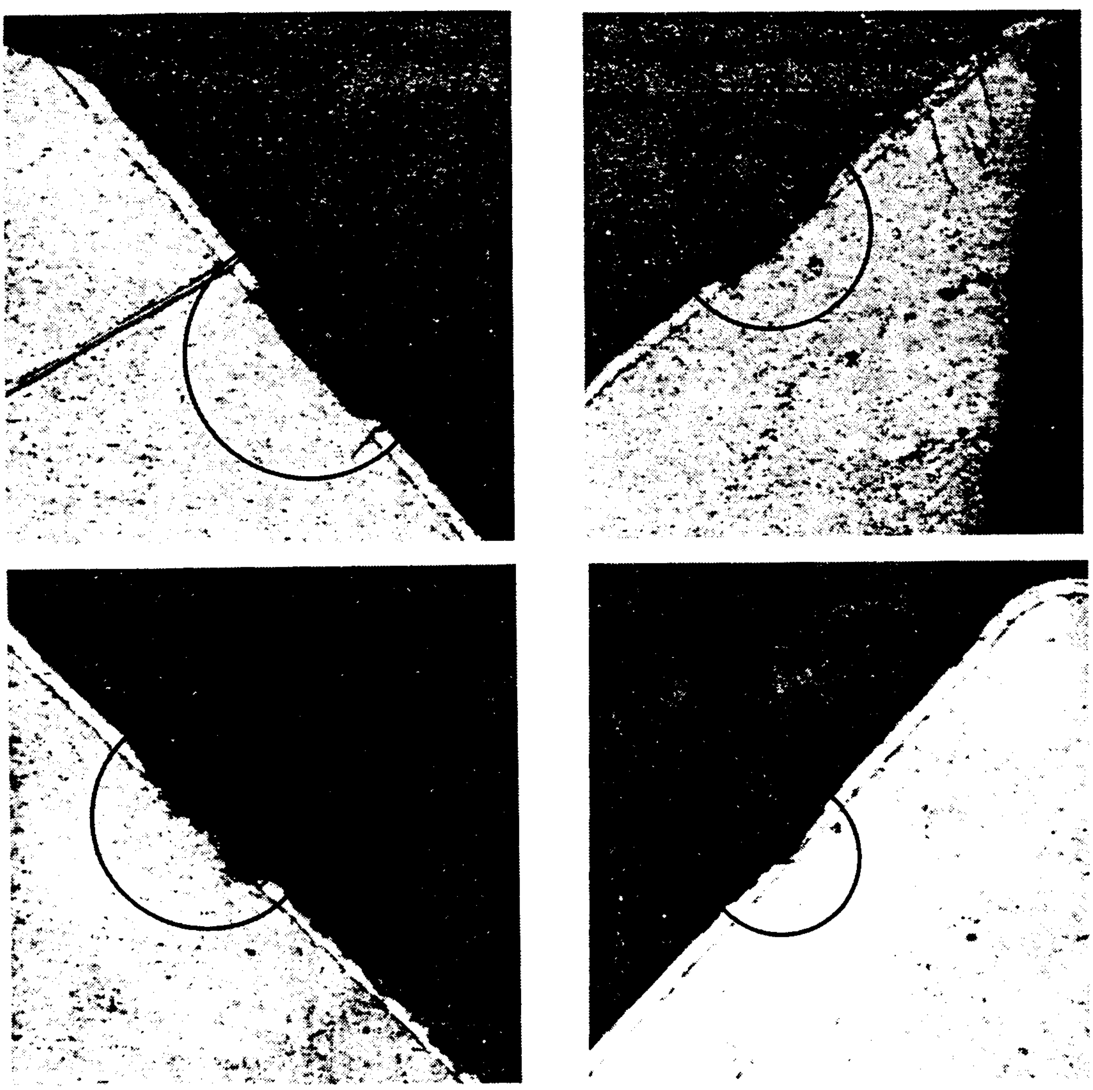

Figure 3. - Wear scars on gold slip rings after 18 months at 30 rpm.

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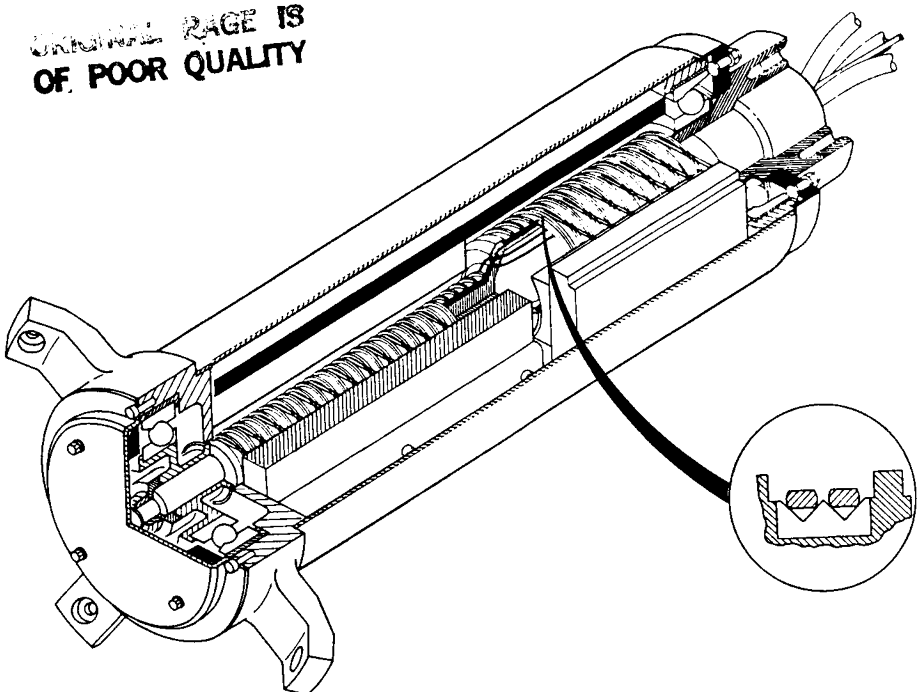

Figure 4. - Wire brushed slip ring with double V-groove rings and side-by-side brushes.

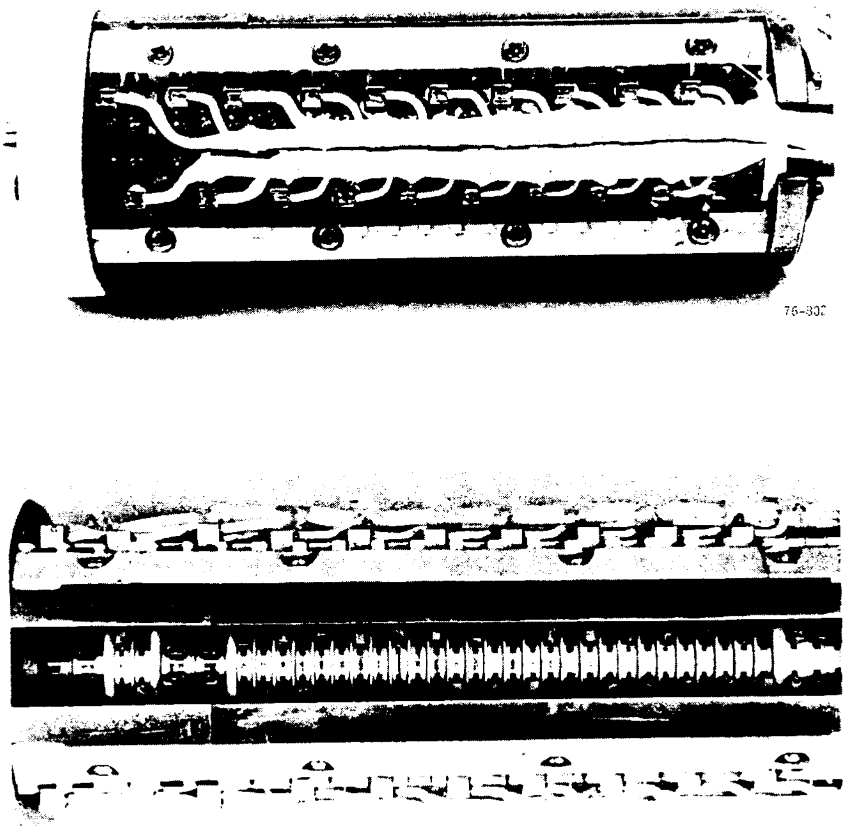

Figure 5. - GPS block 1 slip ring assembly.