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IMPROVING SLIPRING PERFORMANCE

DONALD N. MATTEO*

ABSTRACT

The use of dry film lubricated, silver bearing slipring/brush combinations is not new to space applications. General Electric's product line of solar array drive and power transfer assemblies (SADAPTA's), dating back to the mid 1970's, all include slipring assemblies with this material combination. These slipring assemblies (including very similar designs flown by other contractors) have enjoyed considerable on-orbit success, however, recent experiences have indicated the need to improve the dynamic noise performance of the sliprings.

This paper describes the original slipring design for the DSCS III spacecraft, the handling and testing of the slipring assembly before launch, the on-orbit performance indicating the need for improvement in dynamic noise, the subsequently incorporated design improvements, and the results of testing to verify noise performance improvement.

INTRODUCTION

Any Earth orbiting spacecraft that is equipped with a continuously rotating solar array and is attitude controlled in such a way that one axis is continually pointed at the Earth, requires a means of transferring electrical power and signals across the rotating joint (solar array drive) from the solar array to the spacecraft centerbody. This transfer is usually accomplished with a slipring assembly that is integral with the solar array drive assembly.

A typical slipring assembly is shown in Figure 1. This unit is part of the solar array drive and power transfer assembly (SADAPTA) for the DSCS-III spacecraft, a synchronous altitude communications satellite developed by General Electric for the United States Air Force. The unit, shown in a partially assembled state, is built integrally with the solar array drive shaft. (For the purpose of this paper, the array will be considered to be the rotating body and the satellite centerbody stationary.) Wires carrying electrical power and signals from the rotating array are routed down the ID of the shaft (from the right in the figure) and pass through slots in the shaft where they are soldered to the sliprings as part of the slipring rotor assembly. Brushes, fixed to the housing by the brush block assembly (shown as the upper surface of housing in the figure), contact the sliprings and "pick off" the power and the signals from the rotating assembly. The

*General Electric Company, Space Systems Operations, Valley Forge, Pennsylvania

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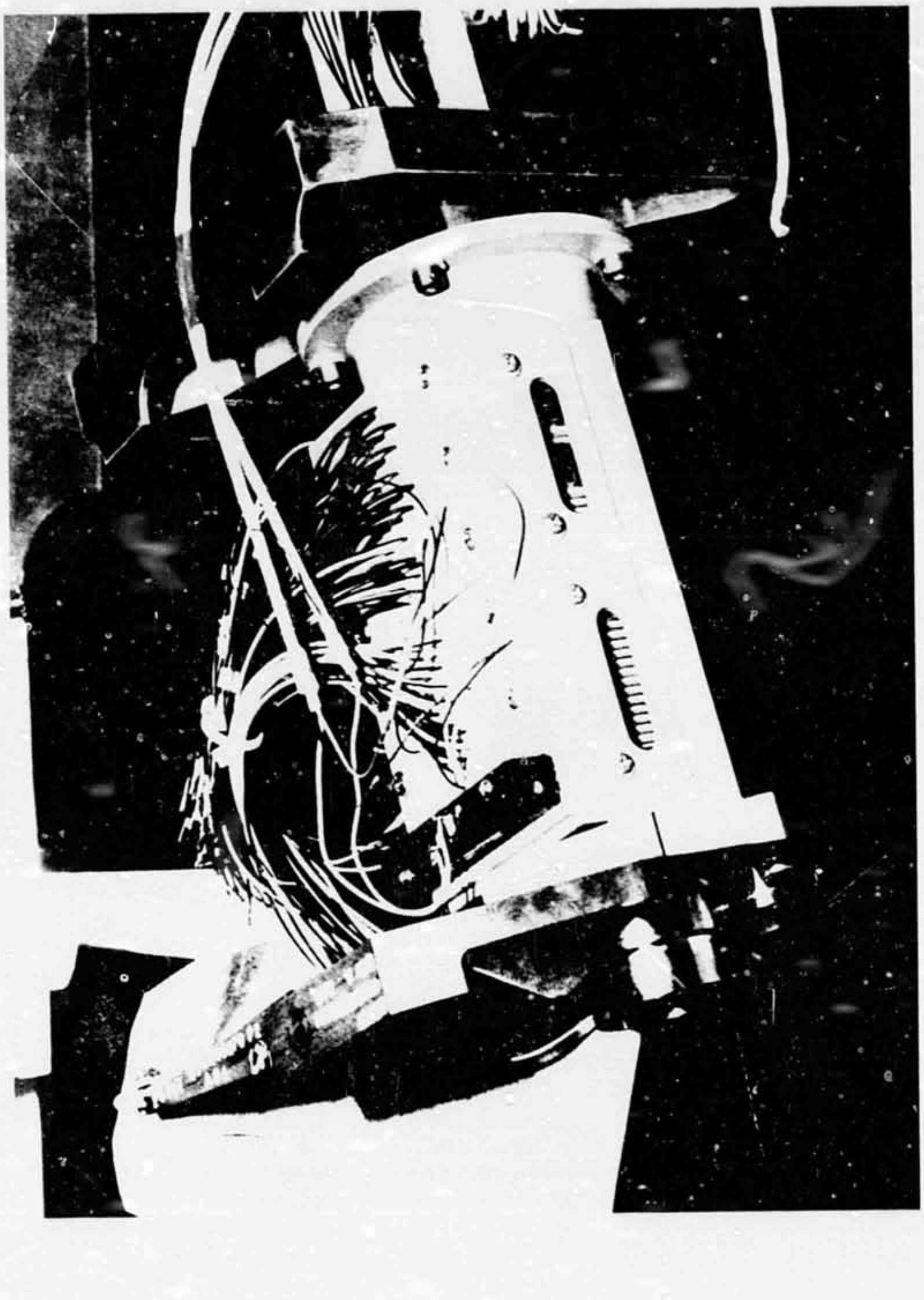

Figure 1. DSCS III Slipring Assembly

wires, shown protruding through the top surface of the brush block assembly, are soldered to the brush holders and carry the power and the signals to connectors (not shown) which mate with the vehicle harness.

The subject of particular interest in this paper is the variation in sliding contact resistance at the brush/ring interface and the resultant variations in signal strength (noise) for signals carried across this interface. Although variations in contact resistance can also affect the slip-rings carrying power, this paper will concentrate on the signal carrying rings because:

- Power rings operate a higher current densities and are less susceptible to contact resistance effects.
- Power rings on all GE SADAPTA's embody two to three times as much brush redundancy and, therefore, are almost totally unaffected by individual high resistance spots.
- Small variations in current across power rings are less detrimental to system performance than similar variations on signal levels.
- Actual experience on power rings has been very good with respect to current variations.

SLIPRING CONFIGURATION

Figure 2 shows the DSCS III SADAPTA, which contains two slipring assemblies: one to transfer the power and signals from the north solar array and one for the south array. These assemblies are interconnected by a 1.8-meter (six-feet) long Beryllium shaft and are driven at orbit rate by a set of redundant drives located at the south end. Figure 3 shows some of the internal details of one of the slipring assemblies.

Each of the two slipring assemblies consists of a set of conductive rings (the rotor assembly) that rotate with the solar arrays and a set of brushes (mounted to the brush block assemblies) that are fixed to the satellite centerbody. The conductive rings are hard silver, plated over copper which is plated over the epoxy rotor. Epoxy barriers are provided between rings to prevent shorting. The brushes are stackpole SM-476, a silver, MoS_2, and graphite composition, which are soldered to Glidcop AL 20 brush arms. There are two brushes per signal ring which are electrically and mechanically interconnected by the brush arms (Figure 3). Brush force is maintained at 23 grams nominal. The rotor assembly is assembled to the SADAPTA shaft and is supported by the SADAPTA shaft bearings (Figure 4).

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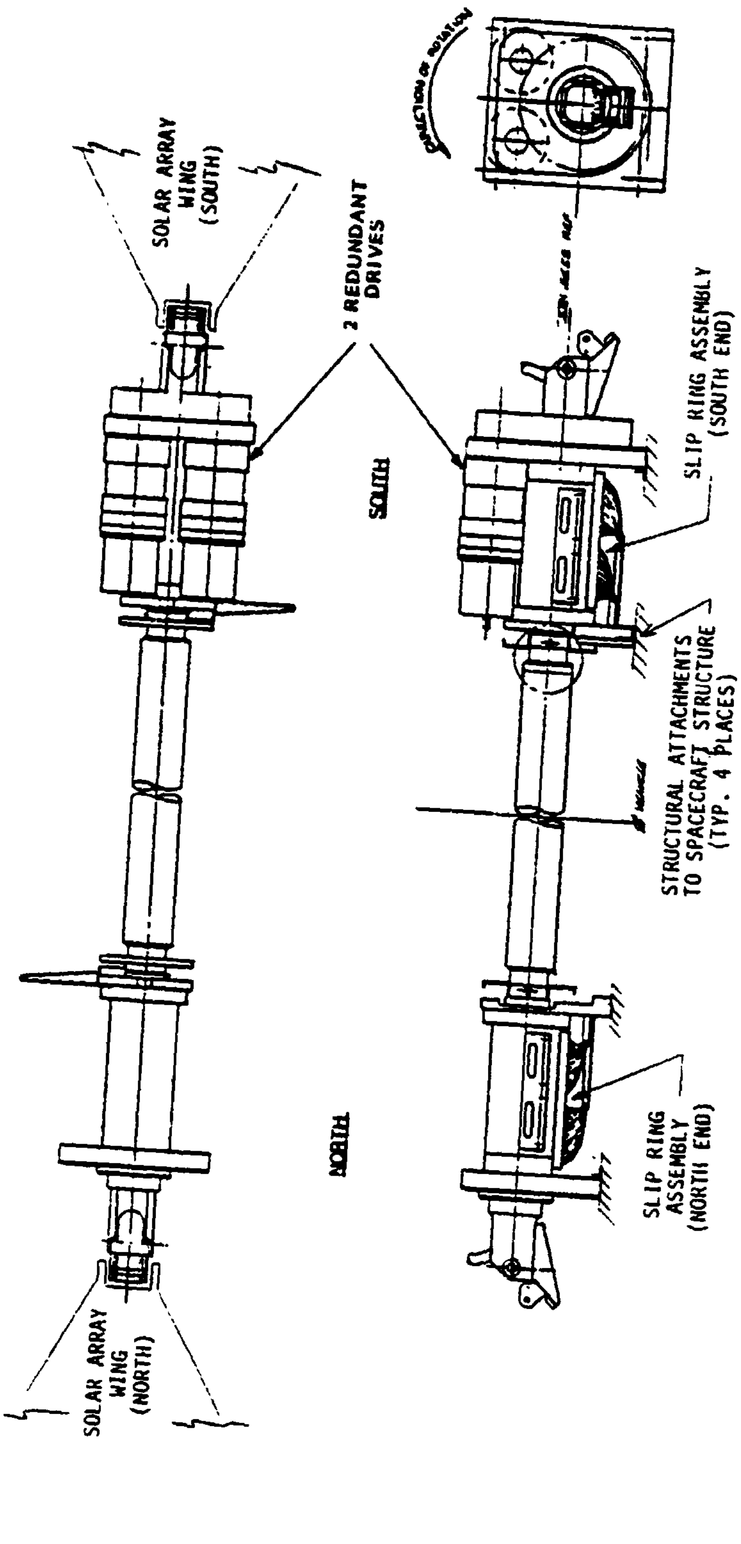

Figure 2. Solar Array Drive and Power Transfer Assembly (SADAPTA)

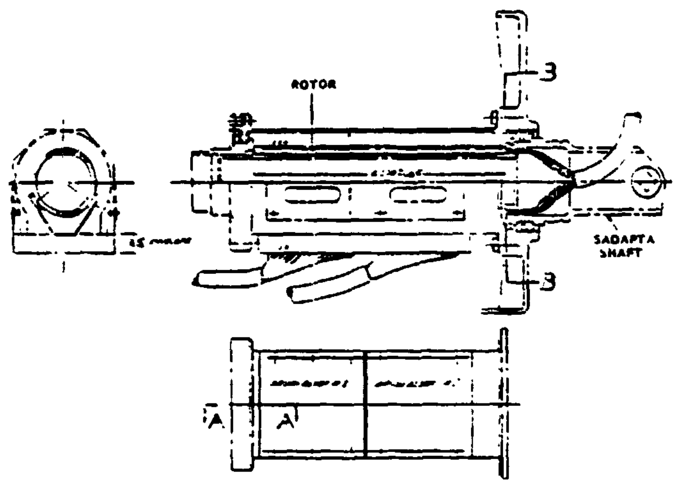

Figure 3. Typical Brush/Brush Spring Assembly

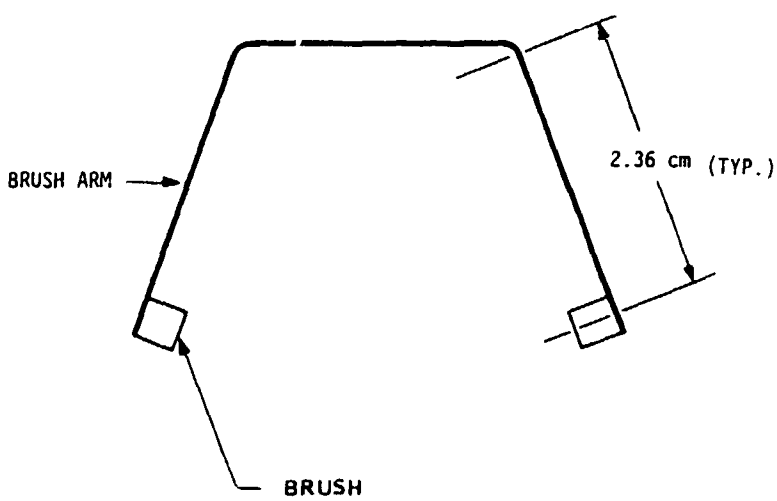

Figure 4. Typical Slipring Assembly

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FUNCTIONAL RELATIONSHIP BETWEEN SLIPRINGS AND CRITICAL SIGNALS

Figure 5 is a functional relationship schematic showing how signals from the Sun sensors (mounted on the rotating solar array) pass through the sliprings and into the attitude control electronics (ACE) buffer amplifiers. Several other signals and electrical power pass through other rings, but have been deleted for clarity to concentrate on the more critical Sun sensor signals. Figure 6 is an electrical schematic showing how Sun sensor signals from each of the north and south solar array wings pass through the sliprings, are fed to the ACE buffer amplifiers, and the outputs of the buffer amplifiers are fed to the difference amplifiers (the output of which is a direct measure of spacecraft attitude). This output, in addition to being available to telemetry, is used directly in the yaw attitude control loop.

The control of the spacecraft yaw axis during normal orbital operations is accomplished using Sun sensors mounted on the yokes of the solar array for sensing yaw attitude coupled with Kalman filter type algorithms implemented digitally in the ACE.

The Sun sensors are simple-analog silicon cells mounted in two units: one on the north solar array yoke and one on the south (Figure 7).

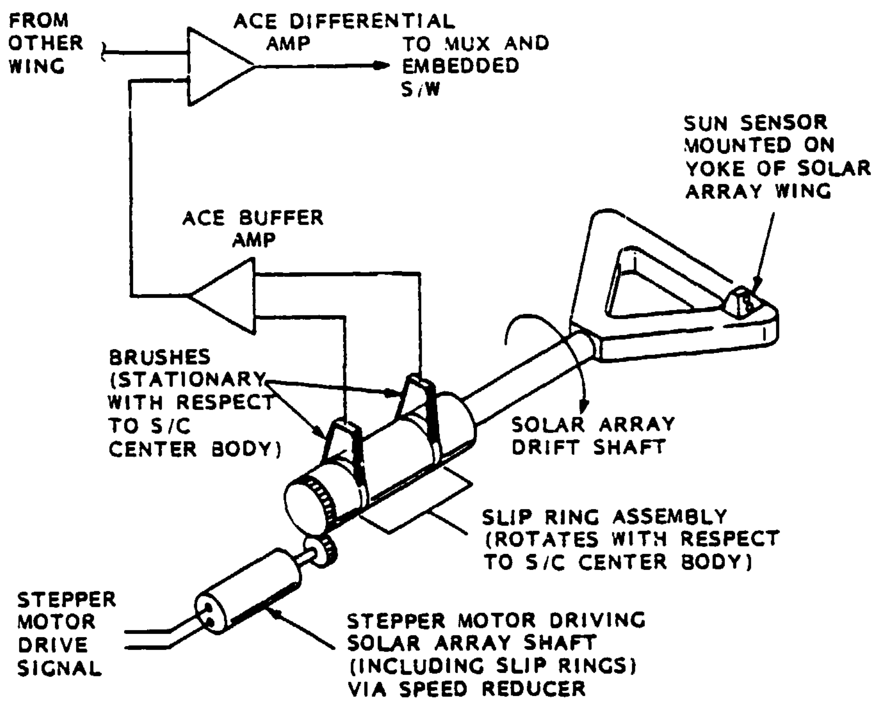

Figure 5. Functional Relationship Schematic

Each unit is comprised of four silicon detectors and a thermal control system to maintain the temperature of the Sun detectors nearly constant ($\pm 0.5°C$ variation about a nominal 25°C). The north unit is comprised of

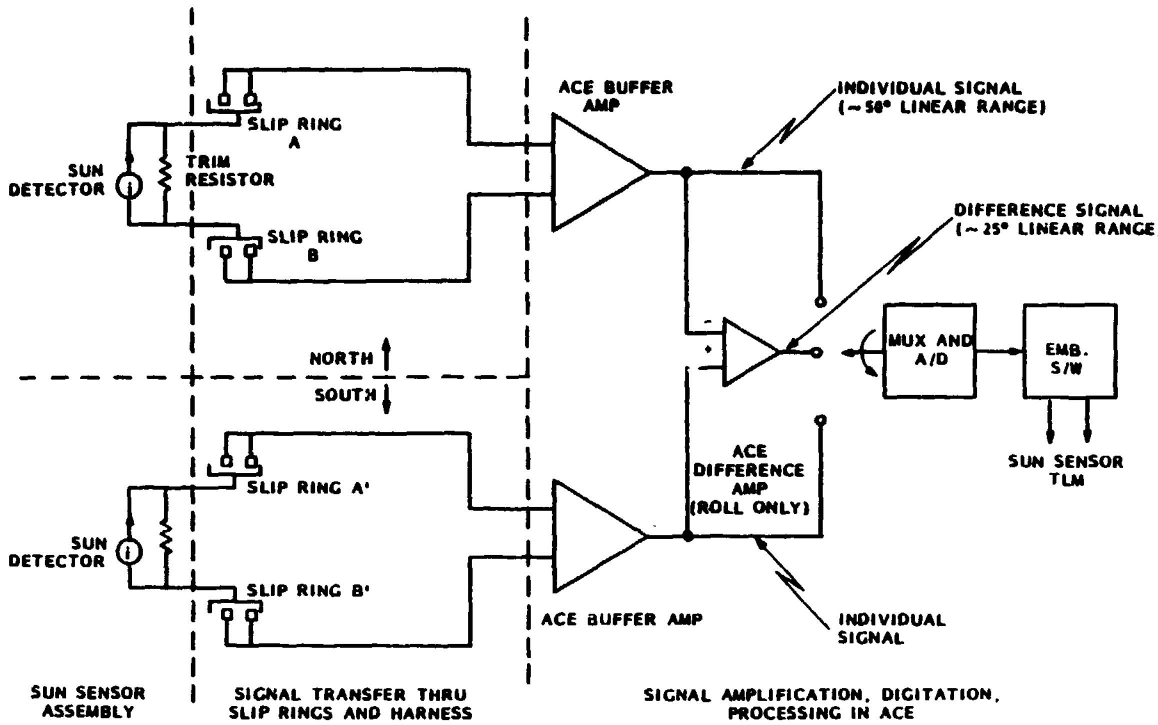

Figure 6. Electrical Schematic of Attitude Control Electronics, Sun Sensors, and Sliprings

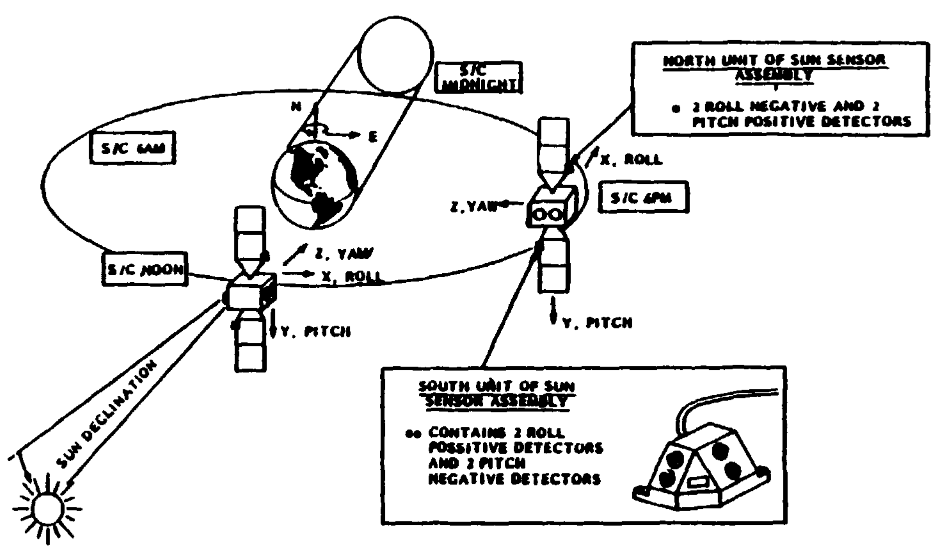

Figure 7. DSCS-III Sun Control Geometry and Sensing

two roll negative and two pitch positive detectors, and the south unit is comprised of two roll positive and two pitch negative.

The detectors that are used for yaw control are the roll Sun sensors. Note that the roll and yaw axes interchange inertial orientation every 90° of spacecraft orbit motion (Figure 7). This results in the roll eyes sensing pure spacecraft roll attitude at noon and midnight and pure spacecraft yaw attitude at 6 am and 6 pm. At intermediate orientations these detectors measure a portion of roll and a portion of yaw, the apportioning factor being a sinusoid of orbit frequency.

Pitch detectors are used to sense spacecraft pitch motion during acquisition maneuvers and to sense solar array position with respect to the sunline during normal orbit operations. Accordingly, the sliprings are directly in the spacecraft yaw attitude control loop and any degradation of slipring performance can directly affect spacecraft attitude performance.

BACKGROUND OF THE NOISE PROBLEM

Recognizing the sensitivity of the spacecraft performance to slipring induced noise, several precautions were taken (before the first DSCS flight) to control any noise to tolerable levels. These precautions were:

- A specification of 800-mΩ maximum (at the system level) was established for any variations in signal ring resistance during all ground testing. The level was calculated to be well within the limits which would yield within specification yaw performance. Component level acceptance limits were much lower (20 mΩ).

- The ACE and its imbedded software converts the analog difference signal between the north and the south Sun sensors into digital words (counts) for use in the attitude control algorithms. It was determined that proper yaw attitude control would result if noise-induced effects represented less that one count. It was calculated that the sensitivity of the system to slipring noise was 0.5 to 0.6 counts/ohm. Accordingly, the 800-mΩ limit for slipring noise content was well within acceptable limits.

- It was known that motion between the brushes and the rings in a moisture bearing atmosphere would produce a partially insulating film of MoS_2 on the rings. Accordingly, during all periods when the sliprings were rotated or vibrated during ground testing (other than in thermal-vacuum testing), the slipring assembly was purged with filtered, dry gaseous nitrogen.

- End-to-end systems tests were run, stimulating the sensor eyes and monitoring the output of the ACE difference amplifiers, verifying that the output was within tolerance limits.

- The system was designed to sample Sun sensor signals at the time when the contact resistance of the brushes/rings was expected to be most stable, that is when the sliprings/solar array drive shaft were at rest between bursts of motor pulses.

When the DSCS III first flight vehicle's sliprings were last tested for noise (before launch) the resistance variations ranged between 50 and 700 mΩ.

ON-ORBIT OPERATIONS

Shortly after DSCS III orbit injection and approximately 6 hours after three-axis attitude control was established, the solar array drive was commanded to track the Sun, and an oscillation in yaw was detected. The redundant roll Sun sensor loop (there are two complete loops, from Sun sensors through ACE) was selected for control. The oscillations were eliminated. Approximately 1 month later, the original roll Sun sensor loop was again selected for control as a diagnostic measure. Yaw oscillation immediately resulted. The redundant roll Sun sensor loop was again selected for control and the oscillations stopped. The redundant roll Sun sensor loop has successfully controlled the spacecraft ever since. Except for further diagnostics, there were no additional occurrences of yaw oscillation.

POTENTIAL CAUSES OF YAW OSCILLATIONS

All potential causes of the previously mentioned anomaly were investigated. In addition to the sliprings, those included:

- The Sun sensors
- The vehicle and solar array harnesses
- The optical effects
- The ACE

Each of the previously listed potential causes of the problem were the subject of intensive investigations. These investigations, other than the slipring investigations, are outside the scope of this paper. Although a single source of the problem was not pinpointed, the most likely cause was determined to be resistance variation noise introduced into the Sun sensor signal circuits by contact resistance changes at the slipring/brush interface. This conclusion has been determined for the following reasons:

- Measured on-orbit data have indicated variations in the output signals of the individual buffer amplifiers and of the differential amplifier
- Variation in the output of the ACE differential amplifier will directly result in the type of anomalous yaw attitude performance that has been observed.
- The only element in the loop consisting of the Sun detectors, the trim resistors, the harnessing, the sliprings, and the ACE amplifiers that has been measured to have a variable parameter that could account for the anomaly is the slipring assembly, the contact resistance of which has been measured to vary.

- Postlaunch ground tests on deliberately degraded slipring assemblies have resulted in resistance variation noise of the right order of magnitude to have caused the anomaly. (Note that all testing before launch on undegraded slipring assemblies resulted in noise figures well below the level necessary to account for the anomaly.)

CAUSES RELATED TO SLIPRINGS

Several potential causes of the yaw anomaly, which are related to the slipring assembly, were considered. These causes are discussed in the following paragraphs.

Electrostatic Discharge

The spacecraft was launched during a period of high solar-storm activity, so the possibility of build up of high electrostatic discharge (ESD) energy near entrance to the umbra was thought to be possible. Theoretical analyses were performed to predict the magnitude of the ESD discharge currents and subsequently tests were performed to validate the numbers. The tests indicated that this phenomena could result in 0.05 A surging through the sliprings for a period of 1200 ns. Tests using the engineering model SADAPTA were subsequently performed to demonstrate the effects of various ESD discharge current magnitude and duty cycle. The results of the tests indicated that, if anything, ESD discharge currents tended to clean the sliprings and brushes. In addition, no apparent pitting of the brushes or rings occurred. Accordingly, ESD was eliminated as a cause of the problem.

Temperature Gradients

Temperature gradients within the slipring brush block assembly were considered as a possibility. If the sliprings experienced a large temperature gradient, thermally induced stresses could result in failure of the signal leads. Examination of flight and qualification data, however, showed that the SADAPTA temperatures were near normal (approximately 20°C), so this type failure was eliminated as a suspected cause.

Mechanical Shifting

Also considered as potential problems were mechanical shifts within the slipring assembly that would cause the brushes to contact the sides of the track and misalignments of the brushes that would result in the brushes contacting the track in a skewed attitude for a portion of the total 360° of travel. Investigations of the track and brush tolerances indicated that displacement of the brush block sufficient to cause contact with the side of the track could not occur. Tests on the engineering model SADAPTA were subsequently run to test these hypotheses. Because the test results did not produce the noise signatures observed in the flight data, further investigations of brush displacement/misalignment were not considered necessary.

Contamination

Contamination on the surface of the sliprings was considered as a possible cause or contributor to the problem. Investigation of system test data, which indicated that contamination would be cleaned up after several rotations, also indicated that a large amount of noise could appear if the SADAPTA was quiescent for several weeks--even under constant purge. The most striking evidence of this is a 6 hour test which had been performed about 2 weeks after a thermal-vacuum test. During this time, the rings were under continuous purge, but the first orbit of the rings showed large values of Sun sensor noise over a significant portion of the orbit. Noise of amplitude of 20 counts peak-to-peak occurred on the north roll negative Sun sensor signal covering a span of 2.5 hours from near spacecraft night to 3:00 am. Because the flight spacecraft was stationed at NASA/Kennedy Space Center for a long period before launch, it is certainly possible for initial contamination to be present when the rings were first used in space.

Although it was a viable theory, all ground test results indicated that the noise would disappear within several rotations of the SADAPTA shaft. This was not happening on-orbit. Furthermore, the magnitude of slipring resistance variation apparently necessary to produce the on-orbit disturbances (20 to 30Ω) was several times the magnitude of any theoretical contamination induced contact resistance change or that which had been measured in ground testing.

Other interesting theories considered and discarded were:

- Discontinuities or bumps at the ring/lead wire attachment--CAD generated plots of design attach points (below surface of rings) showed that the locations bore no resemblance to the observed locations (solar array position with respect to time) of on-orbit or ground test noise.

- Vibration of brush/brush springs causing brushes to bounce out of contact with rings--Calculations showed that well over 100 g's would be required to drive a normally preloaded brush out of contact with its ring. Nothing in the system dynamics could cause that level of acceleration on the brushes in orbit.

ENGINEERING SADAPTA TEST RESULTS

A series of tests were run on the engineering south SADAPTA which was the life test unit. This SADAPTA had been stored in the engineering laboratory without nitrogen purging and had been exposed to varying conditions. Furthermore, the brush forces on all rings were well below the specification values of 23 grams.

A number of observations were made concerning this engineering unit:

a. There was no difference in noise as a result of a change in signal polarity.

b. There were small differences in noise due to radial and axial forces up to 10 pounds applied to the output shaft.

c. The noise was significantly lower with two brushes than it was with one brush (likewise four brushes produced better results than two (i.e., two rings in parallel).

d. The trailing brush appeared to be quieter than the leading brush.

e. Increasing brush force above 23 grams did not appear to reduce noise, but decreasing force below 10 to 13 grams did cause an increase in noise.

Test data plotted in Figure 8 were generated by deliberately lifting the brush off of the ring with calibrated forces when the companion brush was out of contact. The following important observations are from these data:

- The 23-gram force appears to have been optimally selected because it lies ju-t beyond the knee of the curve.

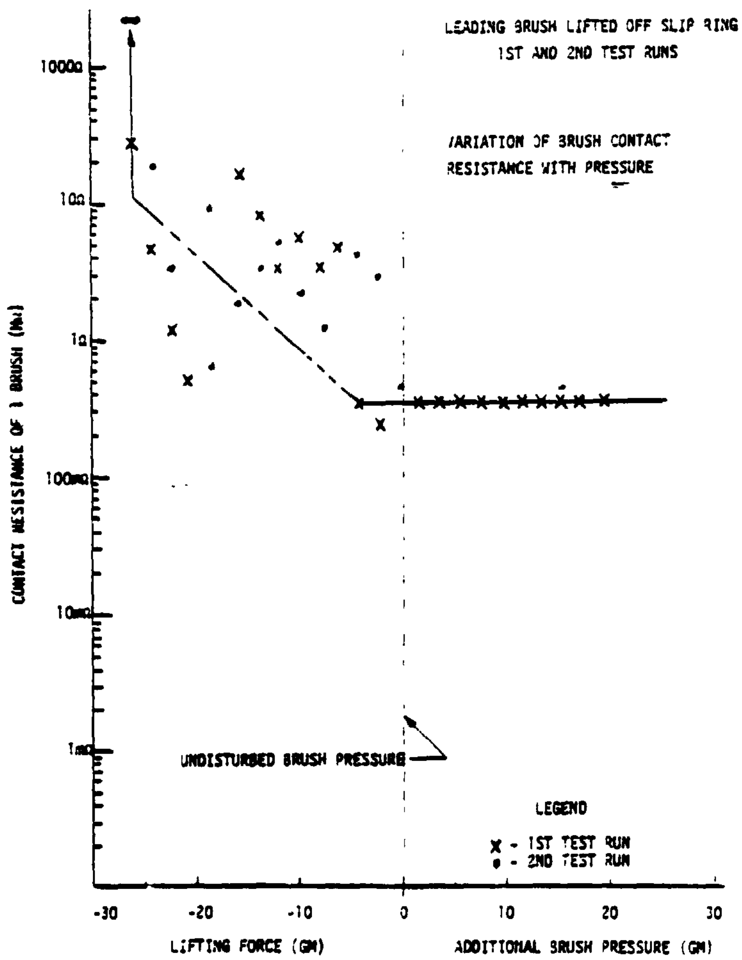

Figure 8.

- Increasing nominal brush force beyond 23 grams does not appear to improve contasct, but it can provide margin for brush force variation in production or service without degrading perfo~mance.

- Decreasing the brush force below the 23-gram nominal can produce resistance variations of the magnitude necessary to account for orbital performance (particularly when viewed in the light of subsequently discussed system nonlinearities).

With attention focused on low brush force, a series of more controlled brush force versus noise tests were run. A special fixture was designed and built for accurately measuring the undisturbed brush forces of the engineering unit slipring assemblies. As can be seen from Figures 9 and 10, the brushes on this unit (after considerable testing and handling) do not line up well and significant variations in brush forces are to be expected. In fact, on the south unit the forces varied from five to 18 grams, and on the north unit (which had always been a quiet performer) the forces varied from 16 to 22 grams. A series of dynamic noise measurements were then made (including some with deliberately altered brush force).

Figures 11 and 12 are plots of the resulting data. Again, the sensitivity to brush force is obvious, both on magnitude and frequency of noise spikes.

It was concluded that the cause and corrective action for the potential low brush force must be identified.

BRUSH SPRING INVESTIGATIONS

The material used for the slipring brush springs, Glidcop AL20, and the processes used for fabricating the springs were investigated in detail. These investigations are too lengthy to discuss in detail here, but the salient points of the investigations were:

- Soldering the Glidcop with a high temperature silver solder caused a significant drop in elastic modulus (13-percent change).

- Tests of the spring constant of Glidcop springs showed that the calculated values using published data were much lower than the test results (35-pecent lower).

- The process used to bend the springs produced nonuniform bends, some of which could result in surface cracking of the springs.

Each of the factors suggested that the force on the brush holding it against the ring may have been inadequate on some brush/ring assemblies. This concern has been removed for future SADAPTA's by changing the brush spring material to beryllium-copper and increasing brush force from 23 to 41 grams per brush to provide margin.

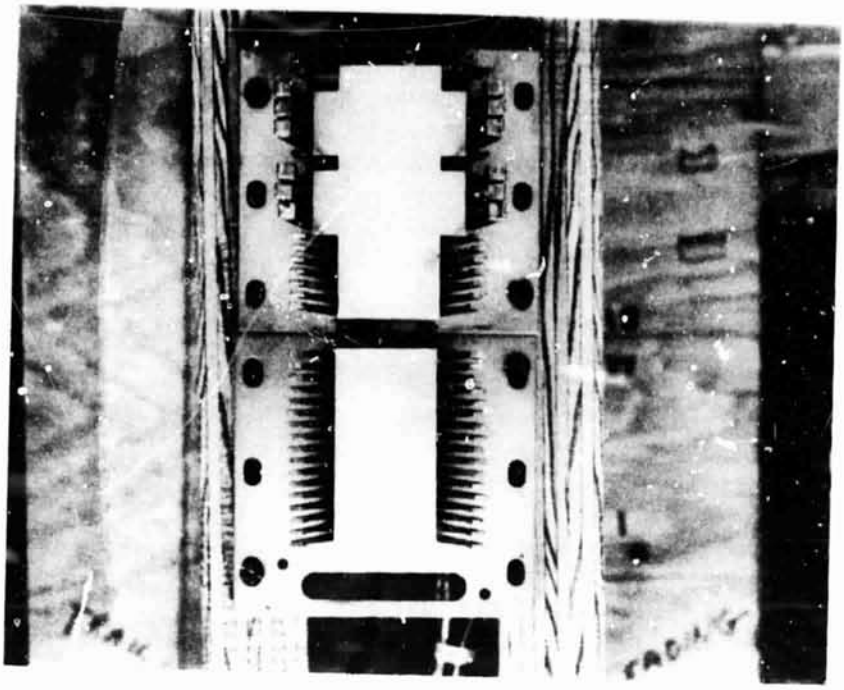

Figure 9. View of the Brush Blocks from Above. (The trailing brushes are on the left and the leading brushes on the right. Note that the brushes are irregularly aligned.)

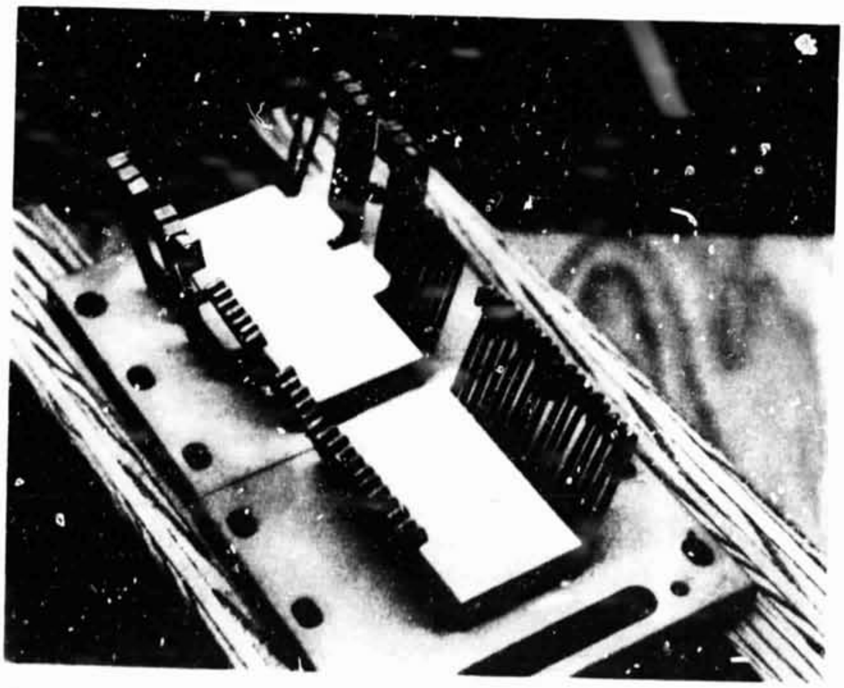

Figure 10. View of the Disassembled Brush Blocks from the Side. (The trailing brushes are on the left and the leading brushes on the right.)

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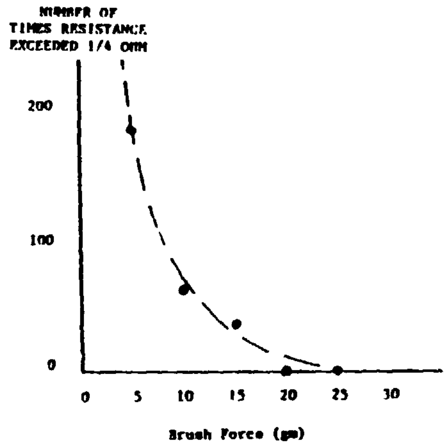

Figure 11.

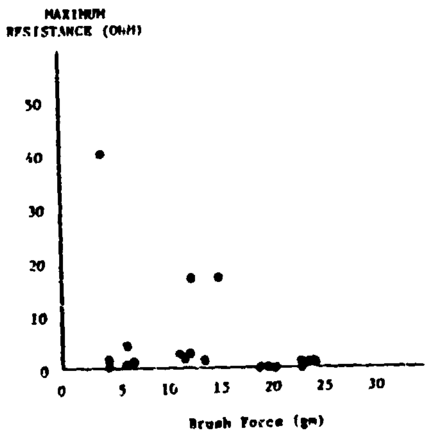

Figure 12.

SYNCRHONIZATION

The effect of synchronization between the Sun sensor signal sampling and solar array drive cycle must be considered in any discussion of the effect of slipring noise on attitude control errors. It has been determined that the lack of such synchronization will introduce errors into the Sun sensor signals (and resultant attitude control errors) which can readily be eliminated by resynchronization.

Figure 13 shows the timing relationship between the periods when the solar array drive is driven by bursts of motor pulses, the rest periods between pulse bursts, and the typical resistance variation as a function of time which results from slipring motion. As shown, the planned data sampling time was designed to occur near the end of the rest periods when resistance is expected to be most stable. Should data sampling occur during motion (or shortly thereafter), considerably larger resistance variations should be expected. In fact, early in the DSCS III mission, this lack of synchronization did occur because of certain commands that reset the relationship between onboard counters. At that time it was believed that the slipring performance was degrading rapidly with time, when in fact what had occurred was the previously mentioned desynchronization. When discovered, this problem was easily corrected by ground command to resynchronize.

NONLINEARITIES

As mentioned before, early mission performance indicated apparent increases in slipring resistance which were very high compared to any reasonable expectation of increased slipring resistance. It was discovered by analyzing and testing the Sun sensor circuitry that increases in total circuit resistance (contributed to by increases in slipring resistance) caused nonlinear effects which made the resistasnce increase appear higher than it actually was. This was corrected by circuit changes that are outside the scope of this paper.

DESIGN AND PROCESS CHANGES

For subsequent DSCS spacecraft the following changes are being implemented:

a. Paralleling of Rings

All critical Sun sensor signals are now brought across the rotating joint on two parallel sliprings (four brushes for each signal and four brushes for each return). As previously noted, this paralleling drastically reduces slipring noise in the following manner:

(1) The contact resistance of a set of four brushes is minimized by the law governing resistances in parallel:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}$$

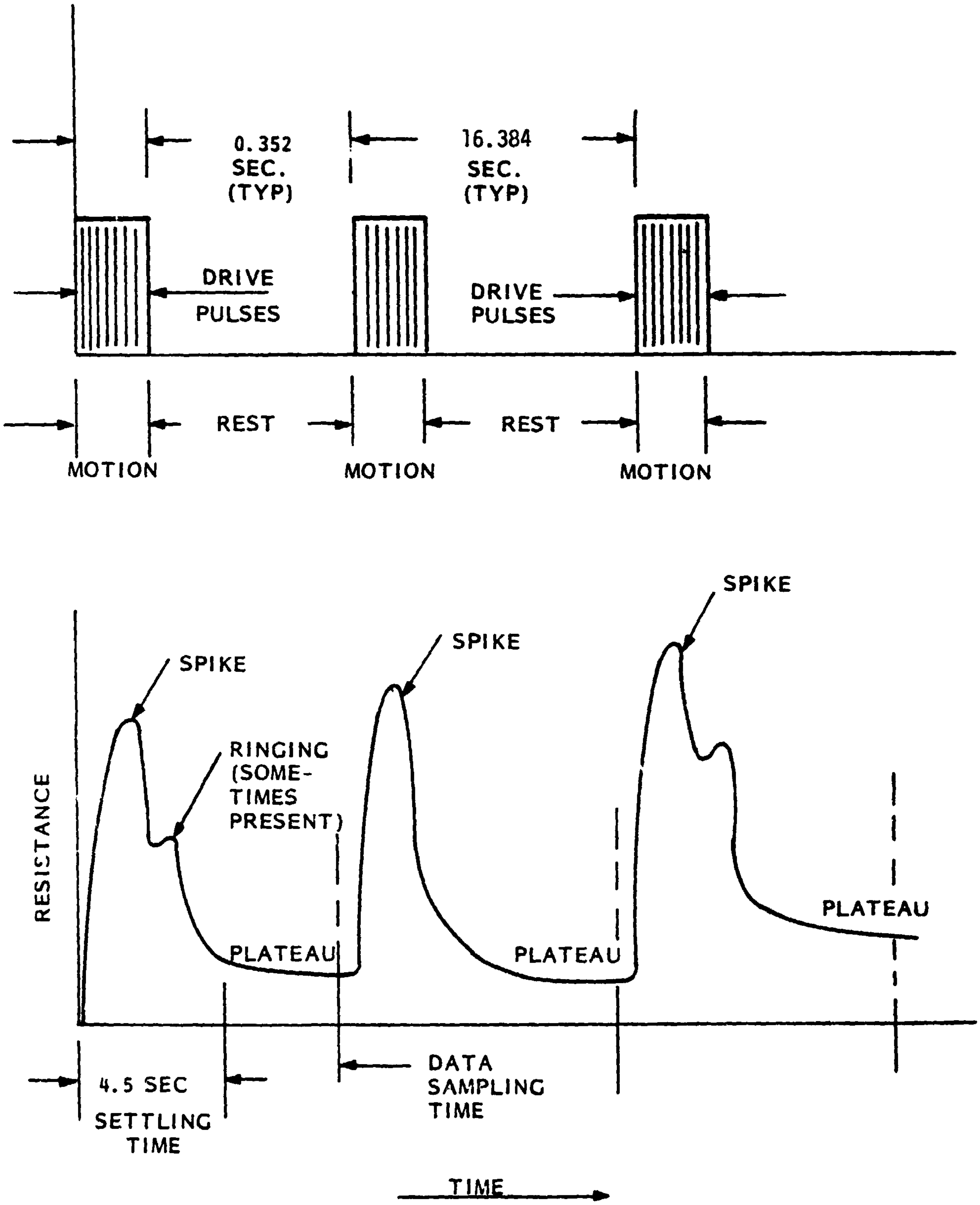

Figure 13. Typical Slipring Resistance Trace

(2) The statistical probability of having at least one low-resistance path at any instant of time is very high. If such a low-resistance path exists, it will dominate the total resistance (R_T) and maintain a '-noise signal across the slipring set.

(b) Nitrogen Purging

The nitrogen purge has been extended so that it now covers the total vehicle life (with the exception of a few hours). Purging will eliminate the possibility of contamination caused by oxidation.

(c) Brush Configuration

The brush contact force has been increased from 23 grams per brush nominal to 41 grams per brush nominal.

The brush pairs that were mechanically and electrically interconnected have been electrically separated to enable testing of individual brushes for noise during acceptance testing at the vendor.

The brush spring material has been changed from 0.010" Glidcop AL20 to 0.012" beryllium copper, and the brush attachment has been changed from silver solder to soft solder.

(d) Relocation of Buffer Amplifiers

The ACE buffer amplifiers have been relocated to the rotating array. This has the effect of transmitting amplified signals across the sliprings and reducing the system's sensitivity to slipring noise from 0.5 ohms per count to 42 ohms per count.

The changes have been tested on both engineering and prime hardware and have shown that:

- Significantly less noise is produced by the sliprings.
- The system is considerably less sensitive to any noise that is produced.

A life test to evaluate the effects of increased brush force on brush life is currently underway.

CONCLUSIONS

The following general conclusions can be reached about the management of slipring noise in a spacecraft control system.

- To initiate the noise, some form of dielectric contamination must exist at the slipring/brush interface.
- A reduction in brush spring force to significantly less than the design minimum force must occur to render the slipring assembly susceptible to the previously mentioned contamination.

- The fewer the number of brush/ring sets in contact with each signal circuit, the more statistically susceptible the circuit is to contamination induced resistance variations.

- Critical sensor signals should be carried by two parallel sliprings, thus placing four brushes in parallel.

- Synchronization of sensor sampling times and drive pulses must be maintained at all times.

- Slipring assemblies of this type must be purged with clean, dry nitrogen at all times (except when specifically precluded by test operations underway at the time such as leak testing) up to as close to launch time as possible.

- Margin above nominal brush force should be provided to account for in-process or in-service degradation (this was changed from 23 to 41 grams per brush for DSCS-III).

- The individual brushes of a brush pair should be electrically separated to enable in-process measurement of individual brush/ring contact resistances during testing.

- Whenever possible, critical signals should be amplified before passing across the sliprings.

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