N94- 33294

ROLL RING ASSEMBLIES FOR THE SPACE STATION

J. Batista, J. Vise, and K. Young
Satellite Systems Operation
Honeywell Inc.
Phoenix, Arizona

ABSTRACT

Space Station Freedom requires the transmission of high power and signals through three different rotational interfaces. Roll ring technology was baselined by NASA for rotary joints to transfer up to 65.5 kW of power for 30 years at greater than 99 percent efficiency. Signal transfer requirements included MIL-STD-1553 data transmission and 4.5 MHz RS250A base band color video. A unique design for each rotary joint was developed and tested to accomplish power and signal transfer. An overview of roll ring technology is presented, followed by design requirements, hardware configuration, and test results.

INTRODUCTION

Space Station Freedom required high-efficiency transfer of up to 65.5 kW of power for 30 years. Signal transfer with low electrical noise resistance was also required for communication and control. These primary requirements challenged the state of the art of the two existing electrical rotary transfer devices, slip rings and flex capsules. Table 1 shows that flex capsules are limited with respect to rotation and fatigue life. Slip rings have wear limitations due to sliding electrical contact, generate debris, and require lubrication.

Roll rings are a new technology developed to perform the same function as a slip ring/brush assembly, but by means of rolling instead of sliding electrical contact. Consequently, there is no measurable wear, lubrication is not required, and long fatigue life can be met. Two types of roll rings have been developed: one type for signal and low power, another for high-power applications.

The Space Station Freedom design featured three rotary joints. Figure 1 shows the location of the three rotary joints. The Solar Alpha Rotary Joint (SARJ) provides continuous rotation of the solar arrays to account for orbital rates and transfers 65.5 kW of power as well as signals. The Beta Gimbal (BG) rotates the solar arrays to track the seasonal changes of the sun angle and transfers 45 kW of solar array power, low power, and signal. The Thermal Radiator Joint (TRRJ) keeps the radiators pointed at deep space and transfers low power and signal. Each rotary joint incorporates a unique roll ring design.

This paper describes how roll rings have been designed and built to meet the challenges at each of the Space Station rotary joints. Test results are then presented to validate the designs.

ROLL RING BACKGROUND

The roll ring electrical signal/power rotary transfer device evolved from ball-bearing and electrical transfer technologies and has been under development since mid-1970. The device consists of two or more concentric conductive rings and at least one rolling, flexible, conductive element (Figure 2). The conductive element, or flexure, is fitted to, and captured in, the annulus space between the concentric rings. When the rings are suitably attached to two structures that are aligned with a common axis, the conductive flexure provides a precise, mechanically stable, electrical coupling between the two structures.

The theoretical torque of the roll ring is zero. Actual torque levels are very small and exist because the flexure and the ring grooves cannot be fabricated perfectly. The bulk of roll ring life testing has been conducted in a vacuum environment. This imposes the most severe conditions from a life and wear standpoint because water vapor is present in a laboratory environment and acts as a lubricant. The ring tracks and flexures are plated with a gold/cobalt alloy, which acts as a dry lubricant during vacuum operation and ensures the integrity of the electrical contact surfaces. The gold plating is backed by a nickel plating to enhance the wear life, reduce porosity in the gold plating, and act as a migration barrier to the copper in the base metal. Wear and flexure fatigue testing has been conducted to over 3.2×10^7 revolutions of the inner ring in a vacuum environment and 1.6×10^8 revolutions in air. The resultant wear debris of the latter unit was of extremely low volume and consisted of gold dust adjacent to the running tracks. In summary, the roll ring design exhibits low and consistent torque, has near zero wear debris, and has no time-related effects; thus, it is an excellent choice where long-life requirements are to be met.

Alignment considerations are taken into account by developing the geometrics of the ring grooves and the flexures such that the rolling dynamics and kinematics are stable. This stability is required not only to ensure that the flexure does not escape the ring grooves, but so that the flexure/ring contact tracks are uniform and predictable. The design that has evolved is tolerant of normal radial, axial, and angular misalignments such that two contact footprints are ensured at each inner and outer ring tracks independent of reasonable misalignments. The radial preload is controlled by the machined-in geometrics. No adjustments are required nor desired after assembly.

The relatively high radial preload between the flexure and the ring groove results in a contact pressure that is of significant magnitude to dispel accumulated organic films and/or lubricants should they somehow migrate or condense onto the track area. Because the mass of the flexure is low and the flexure preload is relatively high, the combination of these two attributes ensures high vibratory and mechanical shock integrity. Operating temperature ranges of -55 to 80 °C can be accommodated with the roll rings as well.

Roll ring electrical noise is identified as momentary, distinctly periodic but short (few milliseconds or less) resistance spikes. The resistive magnitude of these spikes is not related to current and is essentially the same for both air and vacuum environments, remaining constant over running time. Peak noise resistance on circuits comprised of a single flexure range from 0.01 to 0.10 ohm.

Development of power roll ring technology for use on the Space Station was funded by NASA Lewis during the 1980s. Power roll rings were tested by NASA Lewis to the equivalent of 200 years of Space Station operation and have carried currents of 200 A per circuit and 500 VDC; transfer efficiencies of 99.9% were demonstrated.

The roll ring design offers flexibility in meeting system requirements because the design is based on modules containing sets of circuits. The number of modules can be increased or decreased due to system design requirements and are assembled into stand-alone units that can be individually tested. This design feature provides for separation of shielded and nonshielded circuit sets, high-voltage and low-voltage sets, low-current and high-current designs, and various other arrangements. Typically, power crossings are used for currents in excess of 5 A, while signal roll rings are employed where currents are less than 5 A.

HARDWARE DESCRIPTION

Roll Ring Description (General)

Signal and low-power applications utilize a multiple-crossing module design made up of inner and outer housings, as shown in Figure 3. The inner and outer housings consist of inner and outer contact rings, each encased in a dielectric epoxy material. Depending upon the application, each crossing utilizes one or more flexures. Multiple flexure designs employ parallel tracks in each contact ring. A typical signal module design utilizes a pair of flexures in parallel tracks and can transfer up to 10 A at 120 VDC. Isolation of 45 to 70 dB can be provided between crossings. Surge currents to 100 A, shock loads to 300g, and frequencies from DC to 200 MHz, have been tested. Assembly of roll ring modules is straightforward, requiring only installation of flexures between inner and outer housings.

Power crossings utilize a multiple-flexure design for high-power transfer. Each power crossing consists of an equal number of flexures and idlers, an inner and outer contact ring, and two idler guide tracks. A typical power crossing is depicted in Figure 4. Power is transferred from one contact ring, through multiple flexures, to a second contact ring. Idlers separate each flexure and are captured by idler guide tracks, which are in turn attached to the inner contact ring. Idlers allow contact velocities of each interfacing component to be matched, minimizing sliding and associated drag torque and wear. Operational drag torque less than 1.1×10^{-2} N-m (0.1 in.-lb) per crossing is a measure of near-zero interface sliding.

Utility Transfer Assembly

The Utility Transfer Assembly (UTA), Figure 5, provides high power and signal transfer across the SARJ. The UTA consists of three parts: the power section for transferring primary power, the signal section for transferring MIL-STD-1553 data, and dual resolvers for indicating rotational position. Angular contact bearings support the rotating assembly. Continuous rotation in either direction or alternating

UTA was designed for a rotational rate of 0.07 radian per minute. The resolvers are capable of providing angular position to within 175 milliradians. The unit is designed for random vibration levels of 12.6g rms and was tested to levels exceeding 6g rms. The UTA was designed to be Extravehicular Activity (EVA) replaceable. Handles, tether attach points, and EVA-compatible fasteners are provided. Figure 6 shows the fully assembled UTA development unit.

The power section consists of 24 crossings for transferring 65.5 kW at 160 VDC. Eleven crossings are used to transfer positive voltage, eleven transfer negative voltage, and two transfer case ground. Each crossing contains 14 flexures to distribute the power and 14 idlers to maintain flexure separation. Electrical power is brought to the inner and outer rings by 1/0 AWG, multistranded, superflex cable.

The signal section consists of four, 12-crossing signal modules. Redundancy is obtained by having single flexures run in parallel grooves for each crossing. Standard MIL-STD-1553 twin-axial cable is connected to both outer and inner module rings. Each module transfers positive, negative, and shield across the rotating interface. Twelve MIL-STD-1553 data buses, two RS-170A-3 video-plus sync circuits, and case ground are all transferred through the UTA's signal section. Drag torque contribution from signal crossings is negligible at 7×10^{-5} N-m per crossing.

<u>Power and Data Transfer Assembly</u>

The Power and Data Transfer Assembly (PDTA), Figure 7, provides low power and signal transfer across the TRRJ. The PDTA consists of two parts: the signal section for transferring power and data and dual resolvers for indicating rotational position. Angular contact bearings are again used to support the rotating assembly. The PDTA was designed for continuous rotation in either direction with a rotational rate of up to 0.52 radian per minute.

The PDTA was designed to be EVA replaceable. Handles and EVA-compatible fasteners are provided. Figure 8 shows the PDTA development unit.

The PDTA signal section consists of two, 12-crossing signal modules. Redundancy is again obtained by having single flexures run in parallel grooves for each crossing. Standard MIL-STD-1553 twin-axial wire is connected to both the outer and inner module rings. Each module transfers positive, negative, and shield across the rotating interface. Four MIL-STD-1553 data buses, 300 W of power at 160 VDC, and case ground are all transferred through the PDTA's signal section.

<u>Beta Gimbal Roll Ring Subassembly</u>

The Beta Gimbal Roll Ring Subassembly (BGRRS), Figure 9, transfers high power, low power, and signals across the BG. High-power transfer is handled by a source power module, while low power and signal transfer are handled by a secondary power module and a signal module, respectively. The BGRRS also features fixed and floating duplex bearing pairs, a resolver/transformer assembly, and EVA interfaces. Figure 10 shows the BGRRS development unit.

The source power module is comprised of five power crossings that provide two source power circuits (two crossing each) and a source power ground (single crossing). Each power crossing is capable of transferring 113 A continuous current at 200 VDC. Chassis ground is carried from stator to rotor through the power ground crossing. Each of the five power crossings consists of 11 flexures, 11 idlers.

The secondary power module consists of six crossings that provide two secondary power circuits (two crossings each) and one DC control power circuit (two crossings). Each crossing utilizes three flexures in parallel paths and is rated at 6.3 A maximum current at 127 VDC.

The BGRRS signal module consists of six crossings that make up two MIL-STD-1553 circuits (three crossings each). Each crossing utilizes a pair of flexures in parallel paths. Each MIL-STD-1553 circuit consists of high- and low-signal leads and a shield. The shield is tied to chassis ground on the stator and rotor and is carried through the signal module on an individual crossing. The signal module is wired with standard twin-axial cable.

The platform interface connector plate allows for EVA removal and installation of the Beta Gimbal Assembly (BGA), the Orbital Replaceable Unit (ORU) into which the BGRRS assembles. The station connector plate is mounted on a flexible metal bellows to provide stiff torsional interface for the transfer of torque with little wind-up, while providing a flexible interface to accommodate mounting misalignments and runouts within the BGA. Four EVA-compatible connectors are installed on the rotor connector plate.

TEST RESULTS

All three roll ring development units were tested to qualification-level environments. Functional testing included drag torque, resolver error, MIL-STD-1553 word error rate, signal roll ring noise resistance, and power roll ring throughput resistance. During functional testing, the units were rotated in each direction at 70 milliradians per minute for the majority of test time and at up to 2π radians per minute for brief periods. Environmental testing included random vibration, thermal cycling, and thermal vacuum testing. A typical mechanical test setup for full functional testing is shown in Figure 11. Each unit was exposed to environmental test levels, described in Table 2.

Signal Roll Ring Noise Reduction

Noise testing has been the standard performance test for signal roll rings. As discussed in detail in Reference 3, a prime objective of roll ring development was reduction of noise spikes. To accomplish this, significant progress has been made in fabrication techniques, control of plating processes, plating purity, and cleaning processes. These improved techniques were developed during fabrication of the UTA and PDTA and implemented on the BGRRS roll rings. Progress in noise reduction is evident by the comparison made in Table 3. Noise spikes on UTA and

PDTA were attributed to signal module and flexure runouts and flexure size variation. These lessons were used to make improvements in flexure and module geometric control during fabrication. Improvements in machining, inspection, and cleaning techniques also were made. High-purity plating and elimination of metallic oxides from surfaces by stringent reduction of low-nobility metals in gold plating also contributed to improvements in noise reduction. The BGRRS benefited from the latest techniques as demonstrated by the noise resistance in Table 4.

Excellent resultant noise resistance is seen in Figure 12. This data shows actual noise graphs obtained after completion of BGRRS testing. The noise test results presented are for a pair of crossings connected in series at the rotating end of the roll ring to permit continuous rotation of the unit without cable binding. Noise testing was performed by looping 100 mA of current through all the roll ring pairs. Voltage peak detectors operating at 16 kHz detect the highest and lowest voltage over a 0.25-second span. Resistance is then calculated and plotted as noise.

<u>Signal Roll Ring MIL-STD-1553 Word Error Rate</u>

All three roll ring assemblies will become a part of the Space Station MIL-STD-1553 data bus. Table 4 summarizes MIL-STD 1553 test results. For the UTA, 43 separate tests were conducted for a total transmission of 85.5 billion words. Out of the 43 individual tests performed, two tests that transferred 1.1 billion words had 378 errors for a word/error ratio higher than the required 10^7; however, it should be noted that the UTA and PDTA were tested with all crossings (circuits) connected in series and, therefore, test results are the cumulative errors for all crossings. The test conducted was therefore much more severe than the required single-circuit transmission of data. The BGRRS was required to demonstrate compliance to MIL-STD-1553 while configured into a simulated Space Station data bus. Sixty-six different send/receive combinations were tested to determine if the presence of the roll ring assembly would affect the performance of the bus. During testing, source power and secondary power were also transferred while the unit rotated. The BGRRS passed each of the 66 individual tests. The largest number of errors observed for an individual test was 43 out of a specification limit of 55 errors. Table 4 gives a summary of the cumulative results for all 66 tests. The measured crosstalk isolation between individual data circuits for the three roll ring assemblies was between 66 to 70 dB at 2 MHz. This satisfied the 45-dB isolation requirement.

<u>High-frequency (Video) Test</u>

Two signal circuits designated for transfer of video on UTA were tested with the requirement that resolution be sufficient for cable identification. This objective was satisfied. Results showed that over the frequency of DC to 5 MHz, loss was 1 dB, isolation was -54 dB, and the signal-to-noise ratio was 72 dB. Relative chrominance-to-luminance variation demonstrated a gain of 1 IRE with a delay of -1.6 ns; between 5 to 200 MHz, the loss was -3 dB.

<u>Power Roll Ring Resistance</u>

The UTA successfully conducted 95 A through 24 crossings at ambient conditions and 76.5 A at 43 °C in a vacuum. Resistance for a pair of crossings in series was typically 1.9 milliohms at ambient conditions including the resistance of the loop-back connector at the rotating end. The power transferred during this test was greater than the requirements shown in Table 5.

The BGRRS transferred 226 A across two parallel circuits (113 A per crossing). The circuits consisted of a parallel set of two power crossings, looped back at the rotating end, and back through across on the two power return crossings. Resistance for this parallel configuration, including 1.2 meters of size 1/0 wire for each crossing configured in parallel at the nonrotating side, was typically 1.43 milliohms at ambient temperature and pressure conditions. During thermal vacuum testing at the hot temperature of 60 °C, power crossing resistance measured 1.6 milliohms with wire temperatures at 88 to 93 °C.

Power Roll Ring In-Rush Fault

The BGRRS is required to survive a 1-millisec in-rush fault current pulse of 4500 A. Before the BGRRS unit was assembled, Reference 2 and its authors provided guidance for conducting a development test on a parallel arrangement of two power crossings within the BGRRS power module. The fault current was applied with the test item kept stationary and at ambient temperature and pressure. The actual in-rush fault applied was 5000 A, peaking at approximately 0.27 ms with a 1.0-ms period. Comparison of the pre- and post-fault resistance measurements indicate essentially no change in resistance and thus no damage to roll ring crossings. Disassembly and inspection showed all components to be normal with no detectable damage caused by the application of the fault currents.

The BGRRS development unit was then assembled with new crossing components and after all functional and environmental testing was completed, the BGRRS was subjected to the in-rush fault current test. Functional test results after application of the fault current were normal.

Drag Torque (UTA and PDTA)

The UTA had a 9.0 N-m drag torque after initial assembly, which increased to approximately 27.1 N-m during functional testing after X-axis vibration. This was considered a failure because the drag torque requirement was < 13.6 N-m. The unit was disassembled, inspected, and analyzed to determine the cause of the failure. The high drag torque was caused by two design problems:

1. The outer contact ring track geometry was spoiled by a twist in the ring caused by the radial clamping pressure of the heat transfer spring between the ring and the housing. This resulted in flexure interference and then higher drag torque.
2. The idler guide tracks had windows manufactured in them to reduce weight and to aid in assembling the power circuits. It was found that an idler got lodged in the window, causing a flexure to break, and created high drag torques. This created the 27.1 N-m drag torque.

The software for sizing power roll ring components was improved to allow complete analysis of geometric tolerances and to maximize rolling efficiency. Design modifications were made to the flexures, contact rings, and outer guide tracks. The window size on the outer guide track was decreased. After the UTA was refurbished, drag torques remained low throughout the remaining tests with peaks at ambient conditions measured at 1.7 N-m.

On the PDTA, drag torque measurements were typically 0.35 N-m, well below the required 1.36 N-m.

Drag Torque (BGRRS)

Measurement of BGRRS drag torque became a problem. It was not possible to obtain accurate torque data with the original test setup, which featured an in-line strain gauge torque sensor. The torque sensor capability was 3.5 N-m and inherently had low torsional stiffness. Rotation of the BGRRS at the ultra low speed of 70 milliradians per minute caused the soft torque sensor shaft to wind-up and not release until the breakaway torque of the bearings was exceeded. This manifested as large torque oscillations on the torque plots. Cost and schedule constraints demanded a speedy solution, while maintaining as much of the original test setup as possible.

To eliminate the oscillation problem, the low stiffness torque sensor was removed and a stiffer force sensor setup was designed and fabricated in-house (Figure 11). Modifications to support the drive motor with bearings at each end were made. A lever arm was attached to the drive motor to translate force back into 222-N load cells. As the motor rotated the BGRRS, torque was reacted by the load cells and torque was derived from the force measurement. Lateral loads were minimized by use of a ball to provide point contact at each load cell. Calibration of the force sensor was accomplished by rotating a known weight at the end of a lever attached to the drive shaft (point C in Figure 11). The improved test setup allowed for temporary substitution of the original torque sensor in order to verify calibration.

BGRRS drag torque during thermal vacuum testing at the 70 milliradians per minute speed (including up to 0.15 N-m of fixture torque) was 0.85 to 1.13 N-m at the cold temperature of -29 °C. and 0.35 to 1.13 N-m at the high temperature of 60 °C. This met the <1.36 N-m requirement.

Electrical Characterization of UTA at NASA Lewis

Reference 1 reports the results of the electrical characterization of the UTA, using the Space Station Power Management and Distribution (PMAD) DC test bed at NASA Lewis. A summary of the reported results follows.

Impedance of the UTA was characterized. Inductance was found to be higher than anticipated, and a recommendation was made that roll ring inductance be considered in the design of the power network. Corona test results showed onset values above 1 kV.

Crosstalk coupling was determined to be largely capacitive, but attenuated so that power transients did not interfere with the MIL-STD-1553 data bus. Power-signal crossing coupling was measured to be -67 dB at 1 MHz. Signal-signal coupling was measured to be -71 dB at 1 MHz.

Verification was made that the UTA was capable of withstanding normal PMAD voltage and current transients. The MIL-STD-1553 data bus was active during transients, with no data bus errors recorded.

Electrical rolling noise resistance was found to be extremely low at 0.3 milliohm for the signal crossings.

CURRENT STATUS OF SPACE STATION ROLL RING ASSEMBLIES

As the configuration of the Space Station has evolved, numerous changes have been made to all three of the roll ring assemblies during the qualification design phase of the projects. All three units have completed qualification design. Procurement of qualification unit parts is almost complete as this paper is submitted for publication in December 1993.

CONCLUSIONS

Considerable progress has been made on roll rings for power and signal transmission during development of the UTA, PDTA, and BGRRS. Improvements in fabrication, process controls, and inspection techniques have been validated. Signal roll rings prove to be very suitable for MIL-STD-1553 data bus applications, video transmission, and low-power applications. High transfer efficiency and low drag torque of the power roll ring have been verified for Space Station applications.

REFERENCES

1. Yenni, E. J. "Electrical Characterization of a Space Station Freedom Alpha Utility Transfer Assembly." 27th Intersociety Energy Conversion Engineering Conference, 1992.
2. Yenni, E. J. and Birchenough, A. G. "Large Transient Fault Current Test of an Electrical Roll Ring." 26th Intersociety Energy Conversion Engineering Conference, 1991.
3. Smith, D. W. "Signal and Power Roll Ring Testing Update." 23rd Aerospace Mechanisms Symposium, 1989.
4. Renz, D. D. "Multi-Hundred Kilowatt Roll Ring Assembly Evaluation Results." 23rd Intersociety Energy Conversion Engineering Conference, 1988.
5. Porter, R. S. "A Rotating Electrical Transfer Device." 19th Aerospace Mechanisms Symposium, NASA, 1984.

ACKNOWLEDGMENTS

The authors are grateful to Ken Huck, Steve Jones, and Pete Jacobson for their contributions to the background and hardware description sections.

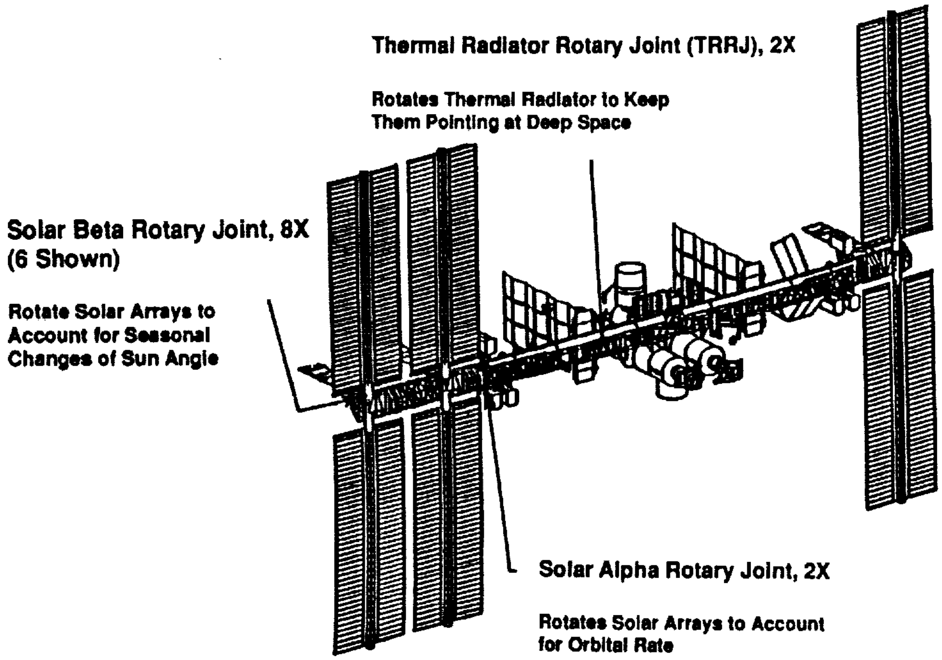

Figure 1. Roll Ring Locations on Space Station Freedom

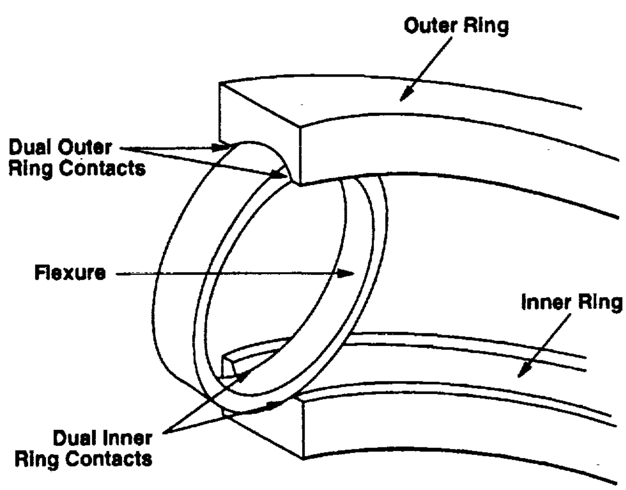

Figure 2. Signal Roll Ring

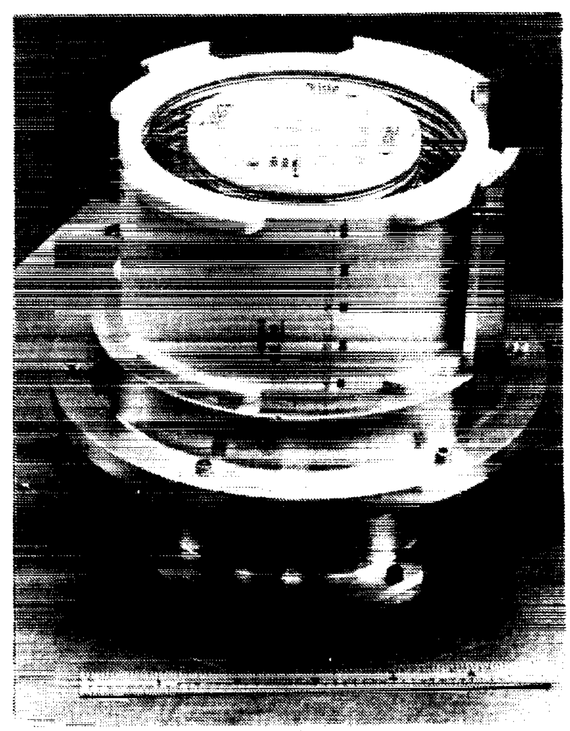

Figure 3. Signal Roll Ring Subassembly

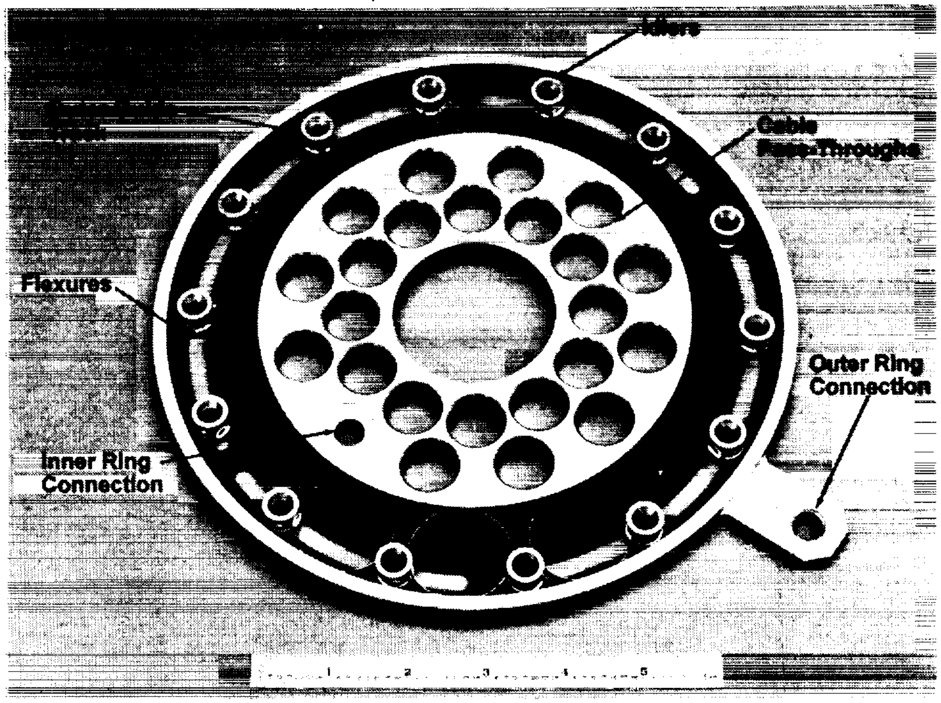

Figure 4. High-power Roll Ring Crossing

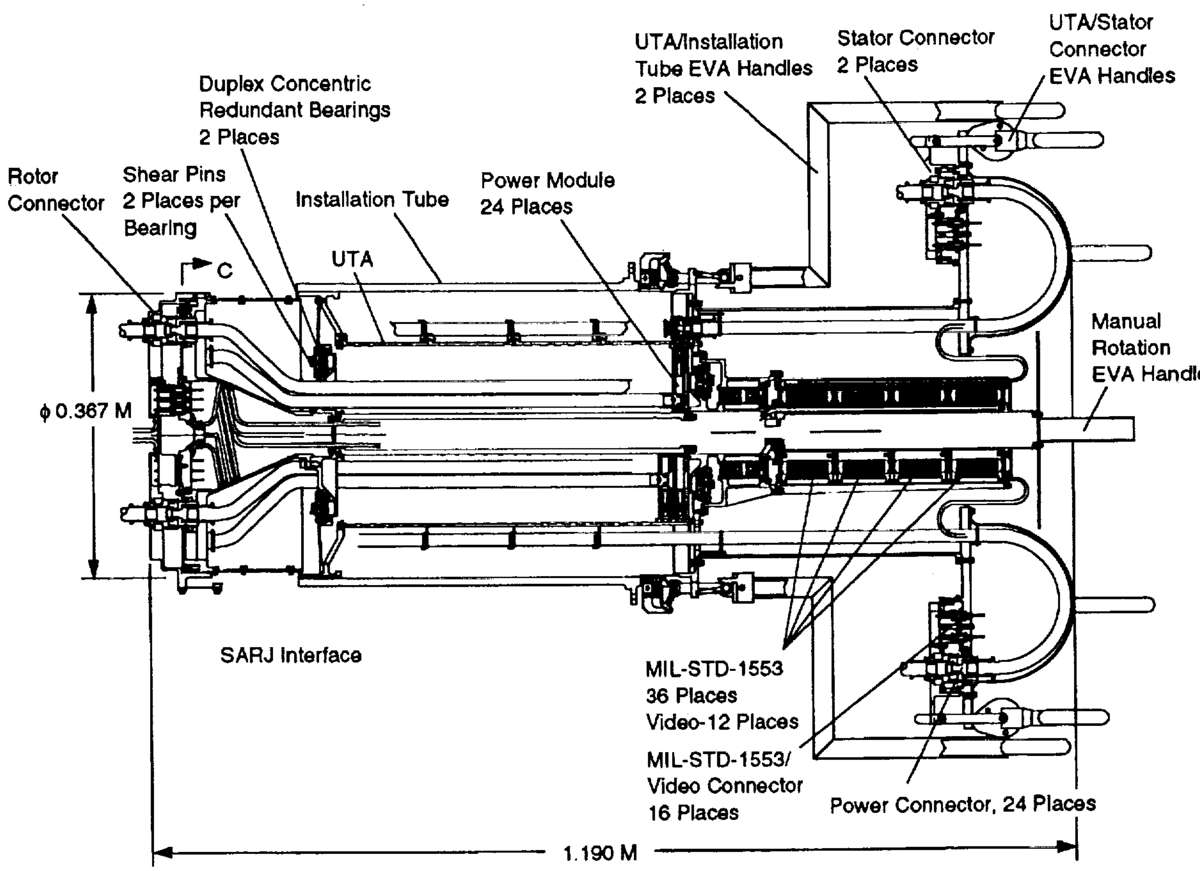

Figure 5. UTA Cross Section

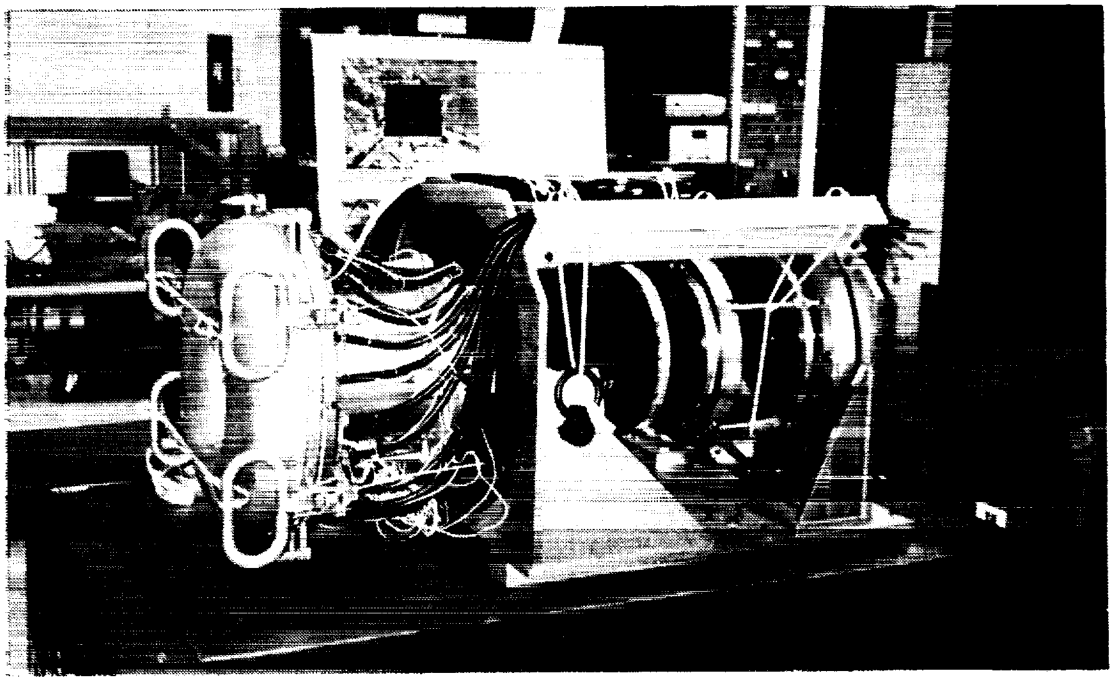

Figure 6. UTA for Alpha Joint

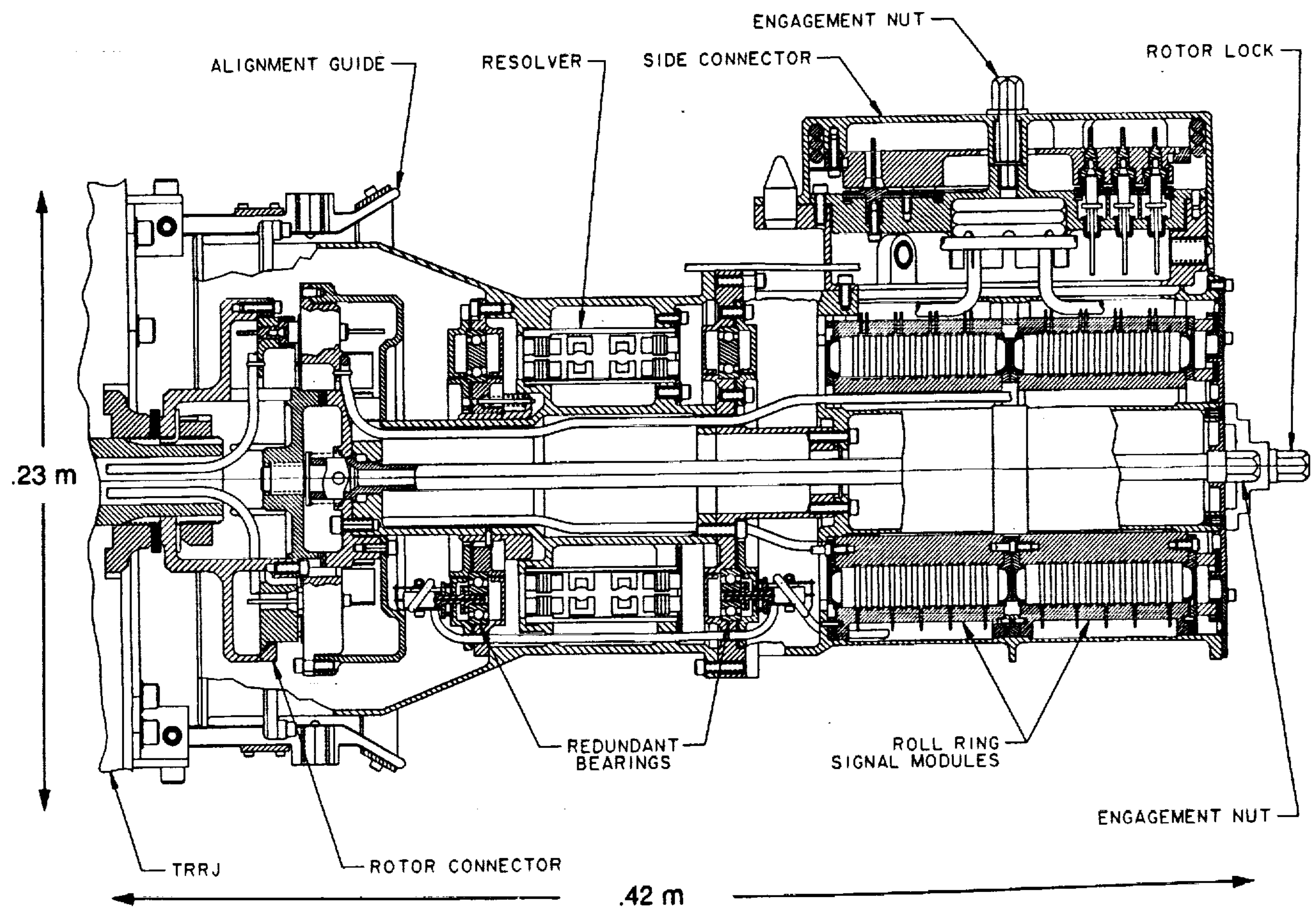

Figure 7. PDTA Cross Section

Figure 8. PDTA for Radiator Joint

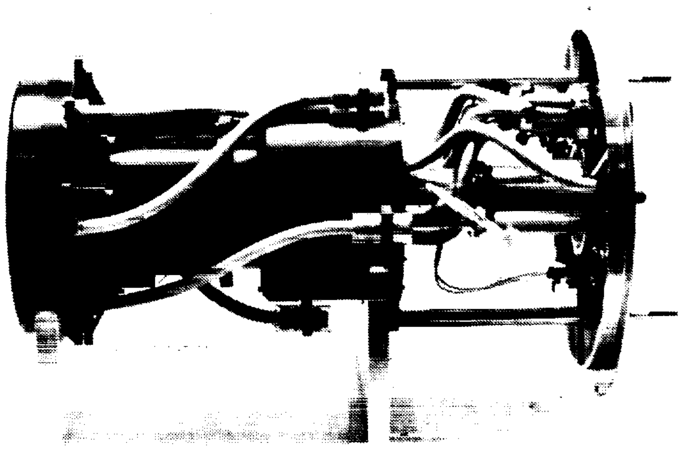

Figure 10. BGRRS for Beta Joint

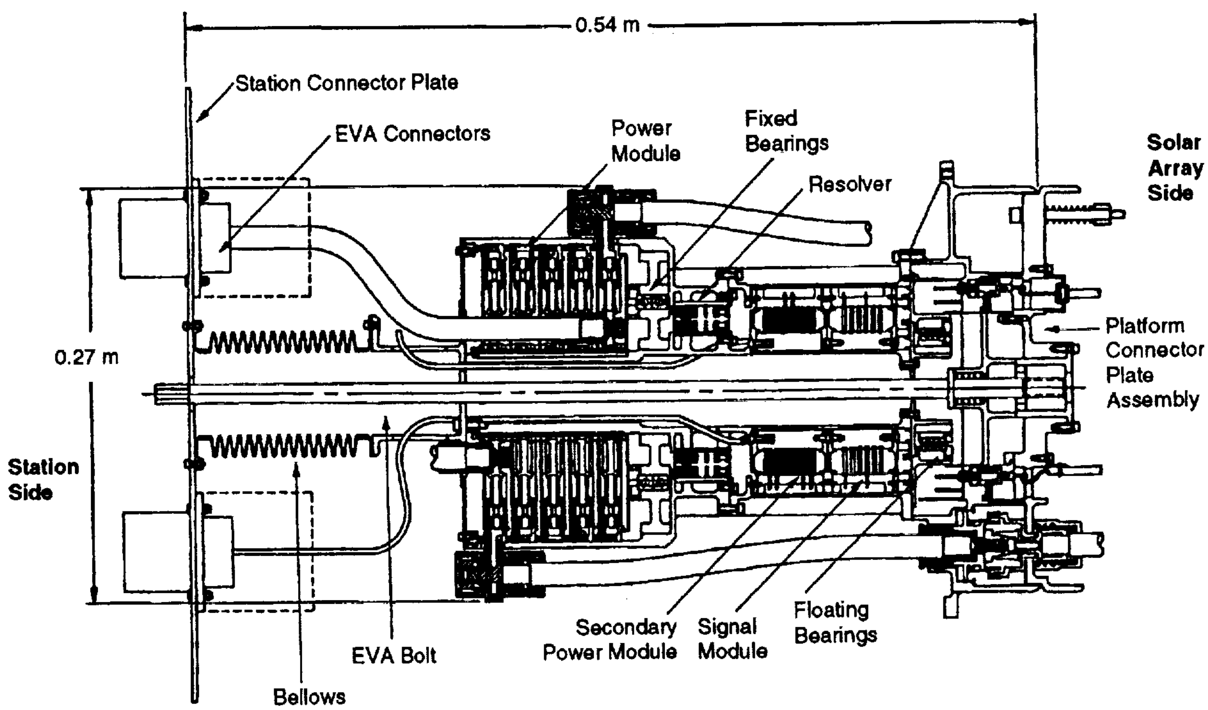

Figure 9. BGRRS Cross Section

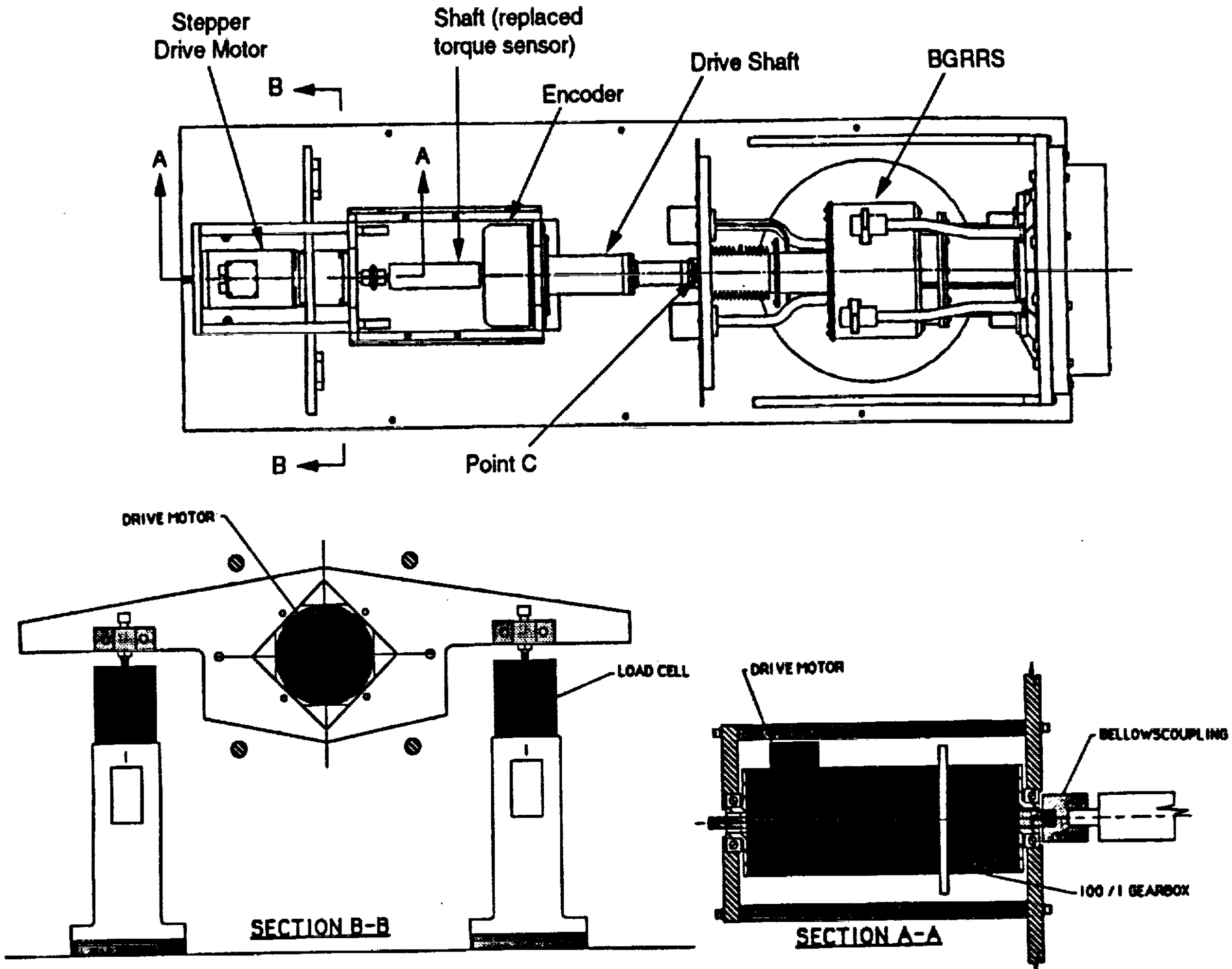

Figure 11. Typical Roll Ring Test Setup (BGRRS)

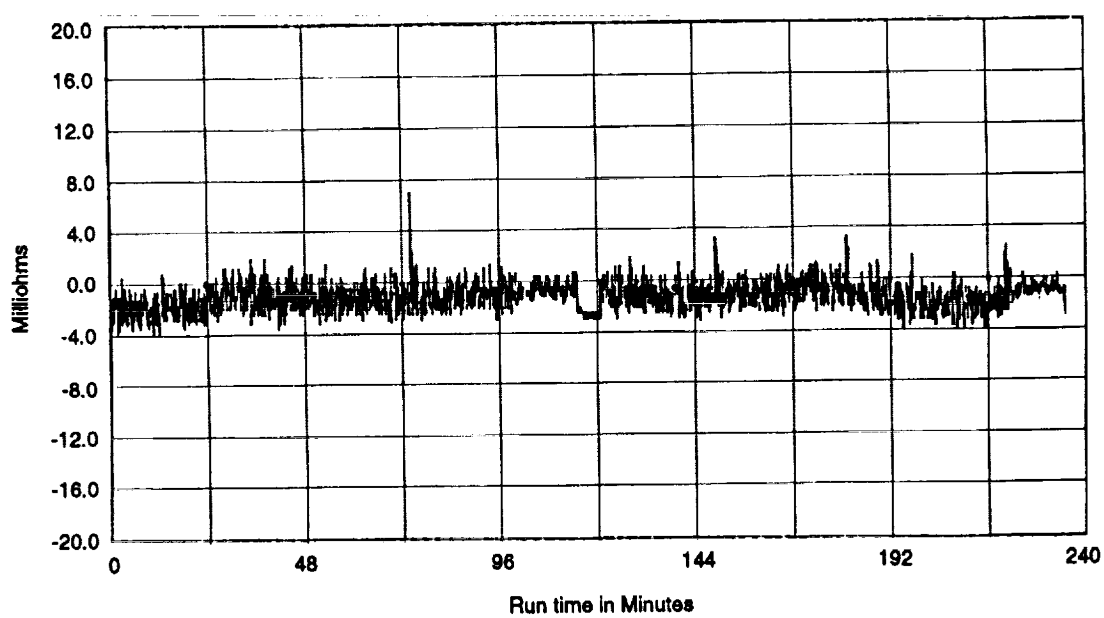

Figure 12. Noise Resistance

Table 1. Electrical Transfer Tradeoffs

Characteristic	Slip Ring	Flex Capsule	Roll Ring
Torque	T	0.05 T	0.2 to 0.005 T
Resistive noise (milliohms) at 0V A	30	Zero	10
Lubrication requirements (for vacuum)	Organic on A_u Graphite and M_oS_2 on Ag	None	None
Storage/standby	N_2 purge avoid air (H_2O)	Insensitive	Insensitive
Wear rate (in./in.)	10^{-10} initial; 6×10^{-11} final	None	Not measurable to 2×10^8 rev
Rotation	Continuous Revolutions	<±3 rev	Continuous Revolutions
Dither effects	Noise at debris piles	Fatigue limited	None
Assembly adjustments	Alignment and pressure	None	None
Run-in	Required/cleaning	None	None
High frequency	To 20 MHz (?)	To 20 MHz	to 150 MHz
Life	>200 M rev	Fatigue limited	>200 M rev

Table 2. Space Station Environment Test Level

Environment	UTA	PDTA	BGRRS
Random Vibration	Composite 6.2 grms Duration 90 sec	Composite 6.3 grms Duration 90 sec	Composite 12.2 grms Duration 180 sec
Thermal Cycle	-23 to 43 °C 9 cycles	-23 to 43 °C 6 cycles	-29 to 68 °C 12 cycles
Thermal Vacuum	-23 to 43 °C <1.33 millibar 3 cycles	-23 to 43 °C <1.33 millibar 3 cycles	-29 to 60 °C <1.33 millibar 3 cycles

Table 3. Roll Ring Noise Resistance

Unit	Background Noise (mΩ)	Peak Noise (mΩ) (3)	Current
UTA Signal (1)	<10 (13x) <20 (3x)	15-30 (4x) 15-50 (5x) 15-89 (1x) 15-143 (3x) 15-243 (1x) 20-300 (2x)	0.1 mA
PDTA Signal (1)	6-10	13-32 (1x) 18-66 (1x) 13-18 (1x) 18-347 (1x)	0.1 mA
BGRRS Signal (1)	2-4	5-9 (2x)	0.1 mA
BGRRS Low Power (2)	2	4-6 (2x)	2 A

Notes: 1. Signal Roll Rings have 2 flexures in parallel per crossing.
2. Low Power Roll Rings have 3 flexures in parallel per
3. Peak Noise levels seen by the number of circuits in parentheses, eg (4x).

Table 4. Signal Roll Ring Performance

Unit	Total Words Transmitted	Total Errors	Words Transferred Per Error	Requirement (words/error)
UTA	85.5×10^9	143	59.8×10^8	$>1 \times 10^7$
PDTA	17.7×10^9	97	18.2×10^7	
BGRRS	37.6×10^{10}	509	7.38×10^7	

Table 5. Space Station Roll Ring Requirements Matrix

Parameter	Requirement		
	UTA	PDTA	BGRRS
Data	12 1553 Buses (36 Crossings)	4 1553 Buses (12 Crossings)	2 1553 Buses (6 Crossings)
High-Power	24 Crossings 65.5 kW	-	5 Crossings, 45 kW
Low-Power	-	6 Crossings .3 kW each	6 Crossings, 0.8 kW each
Rotation	2Π rad -0.0087 to 0.0087 rad/s	2Π rad -0.0087 to 0.0087 rad/s	2Π rad -0.10 to 0.10 rad/s
Positional Telemetry	Resolver, Redundant, 1.8 mrad Accuracy	Resolver, Redundant, 1.8 mrad Accuracy	Resolver, 1.5 mrad Accuracy
Drag Torque	<2.7 N-m	<1.4 N-m	<1.4 N-m
Weight	<136 kg	<16 kg	<24 kg