Flexible Waveguides for RF Transmission across PSP HGA Rotary Actuator

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Abstract

The High Gain Antenna (HGA) on the Parker Solar Probe (PSP) spacecraft was mounted on a single axis rotary actuator with a range of motion of ±45 degree. During the early phase of the program, a trade was performed to select the appropriate technique to manage the Radio-Frequency (RF) transmission across the rotary joint. The Flexible WaveGuide (FWG) option seemed attractive, due to its low mass and good RF characteristics. However, the performance of these waveguides across rotary joints under repeated articulation was not well understood. So a development program was conducted and flight-like FWG assemblies were subjected to various tests. The successful performance of the waveguide resulted in the selection of the FWG for the PSP HGA assembly. As the flight design progressed, additional structural and thermal analyses were performed on the HGA assembly to evaluate the use of these waveguides. The flight batch of waveguides were subjected to a comprehensive batch qualification and screening program. Special tools and procedures were developed for installation of the flight waveguides on to the HGA assembly. The PSP spacecraft was launched in August 2018 and the FWGs have been performing well as planned. The paper discusses the development, qualification and flight activities and the key lessons learned along the way.

Introduction

The PSP spacecraft is equipped with a Ka-band Cassegrain-type High Gain Antenna as shown in Figure 1. The main reflector is a 0.6-meter diameter composite dish with a notched area on the edge for increased dynamic clearance to the spacecraft in stowed configuration

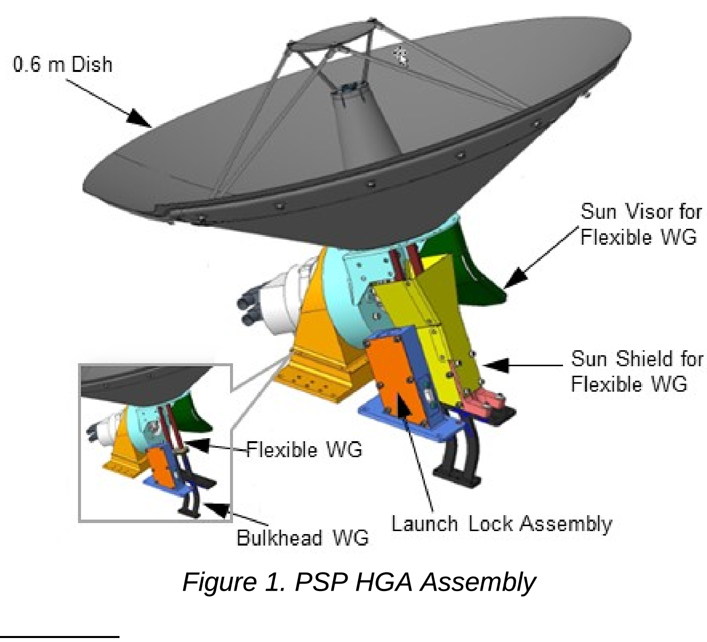

Figure 1. PSP HGA Assembly

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The reflector assembly is mounted on a single axis rotary actuator with a range of motion of ±45 degree. This system required two RF channels for receive and transmit across this rotary joint, and accordingly the HGA assembly was designed to accommodate two FWGs connecting the feed assembly to the RF module inside the spacecraft through the bulkhead waveguide. The use of the FWG was explored and validated by a development program which consisted of detailed analysis and extensive testing. The structural, thermal and life cycle characteristics of the waveguide were evaluated with specially developed tests and techniques. This program also experienced a process issue during the flight batch qualification. In coordination with the manufacturer, Custom Microwave, the root cause was quickly identified and an improved process was employed, resulting in a robust component.

Trade Study

The PSP HGA actuator had a relatively small range of motion and a low life cycle requirement of 110 cycles but was required to fit within a tight mass budget and envelope. A trade study was performed to identify the most suitable RF transmission technique. The RF requirement precluded the use of a flexible coaxial cable. The options considered for this trade were an RF Rotary Joint and an FWG. The waveguide considered for this application was electroformed Ni-Co waveguide. This type of flexible waveguide is highly elastic and is capable of repeated cycling in bending without permanent deformation. The PSP RF system required a WR-34 waveguide and the flexible length was chosen in consultation with the vendor to minimize bending stresses while limiting launch loads due to vibration environment. The RF rotary joint is an electromechanical device consisting of a rotor assembly mounted to the stator through duplex bearing pairs. The part considered for this trade was a standard WR-34 joint with waveguide interfaces at input and output. These devices have good RF performance and spaceflight heritage.

Both options were evaluated for mass, volume, alignment requirement and heritage for the proposed usage.

- The mass of each waveguide was 40 grams. The mass of each RF rotary joint was 300 grams and the two waveguides were mounted to a bracket of mass 250 grams. The total mass of the RF joint system was 850 grams compared to 80 grams for the FWGs.
- The FWG option required a much smaller envelope than the rotary joint assemblies. Accommodation of two of the rotary joints along with the routing of the waveguides required a larger envelope. This envelope was particularly significant for the PSP mission since the volume available for HGA accommodation was very limited. One of the unique features of the PSP spacecraft is a Thermal Protection Shield (TPS), which was a sandwich panel made up a carbon-carbon composite facesheets and a carbon foam core. During close flybys of the Sun, the spacecraft is oriented with the TPS facing the Sun so as to protect all spacecraft components within the umbra of the TPS. This need to fit within the umbra of the TPS imposed severe restrictions on the envelope.
- RF rotary joints consist of preloaded duplex bearing pairs and require very tight alignment with the actuator axis. Any misalignment due to installation or on-orbit thermal deformations would impact the RF performance of the rotary joint as well as the actuator mechanical performance. The FWGs can tolerate higher misalignments relative to the rotary axis.
- The cold operational temperature of the RF joint is driven by the bearing lubrication which is typically about -40°C for wet lubricated systems. The flexible waveguide can be operated at much lower temperatures.
- RF rotary joints have been used successfully for thousands of cycles on multiple space missions. The FWG considered for this application has extensive flight heritage but its primary function was to accommodate misalignments. There are a few instances of FWGs used on one-time deployment mechanisms. However, there is very limited information on the use of flexible waveguides for cyclic operations in space over the life of the mission.

The FWG seemed better on every criterion except heritage. So a development testing program was implemented to evaluate the FWG for PSP requirements. The FWG performed successfully in these tests and was chosen for the HGA assembly. The development test details are discussed later in this paper.

Flexible Waveguide

The flexible waveguide considered for this application is made by Custom Microwave. Inc. of Longmont, CO. The flexible part of the waveguide is Ni-Co alloy and is manufactured by electroforming. This waveguide was built to length specified by JHUAPL. The interior of the waveguide is coated with silver to improve RF performance. The development test article had copper flanges that were attached to the waveguide by soldering. Operational high temperature of the waveguide was limited to +180°C due to this soldered joint. The exterior of the waveguide was nickel plated.

During the development phase, the qualification temperature range was -125°C to +100°C and the development article successfully survived these temperatures. However, by the time the flight articles were procured the qualification temperature limit had changed to -105°C to +170°C. At this time the manufacturer had improved processes available, but the program decided to stay with the qualified version of the waveguide, since the revised temperature was still within specifications. The first batch of flight waveguides were identical to the development article and was tested to the revised temperature limits. During thermal cycling some discoloration was observed at the soldered joint, along with significant degradation in RF performance. Investigation by the manufacturer determined that this was due to a processing defect that resulted in incomplete removal of the flux from the solder, and this was also confirmed by radiography. This problem was further exacerbated by the higher revised qualification temperature. The manufacturer proposed waveguides with electroformed flange joints, which were considered superior to the soldered joint. After a thorough review of all options it was decided to change the waveguide configuration to the electroformed flange joint as proposed by the manufacturer. The program also decided to switch the exterior finish to black paint instead of nickel plating to lower the temperature of the middle section during operation.

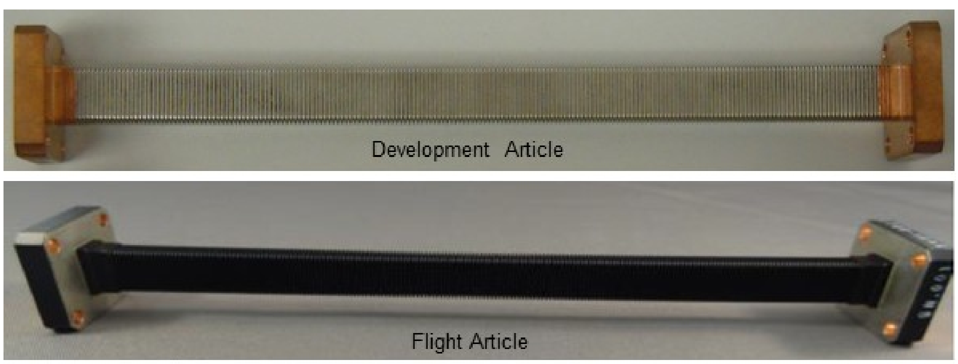


Figure 2. WR-34 Flexible Waveguide

The flight waveguide was made up of electroformed Ni-Co flexible section with the copper flanges attached by the electroforming process. The interior surfaces were silver plated and the exterior surfaces were painted with BR-127 black paint. Following a successful batch qualification and acceptance program, these waveguides were installed to flight HGA assembly. The development and flight waveguides are shown in Figure 2.

Waveguide Analyses and Tests

The FWG was subjected to a comprehensive evaluation program that included testing in three phases, development test, flight batch qualification test and acceptance tests. These tests consisted of environmental tests and mechanical functional tests. The condition of the FWG was monitored by RF performance tests, nondestructive examination and visual inspection. Following is a brief description of the various inspection and test techniques employed in the test program.

Resistance Torque and Flex Life Cycle
Resistance torque was measured over the range of motion on a torque test rig as shown in Figure 3. The maximum resistance torque was less than 30 mN-m and did not have an influence on the torque margin. The resistance torque was also considered as a good measure of the uniformity of the waveguide thicknesses and was viewed as an indicator of consistency and process control.

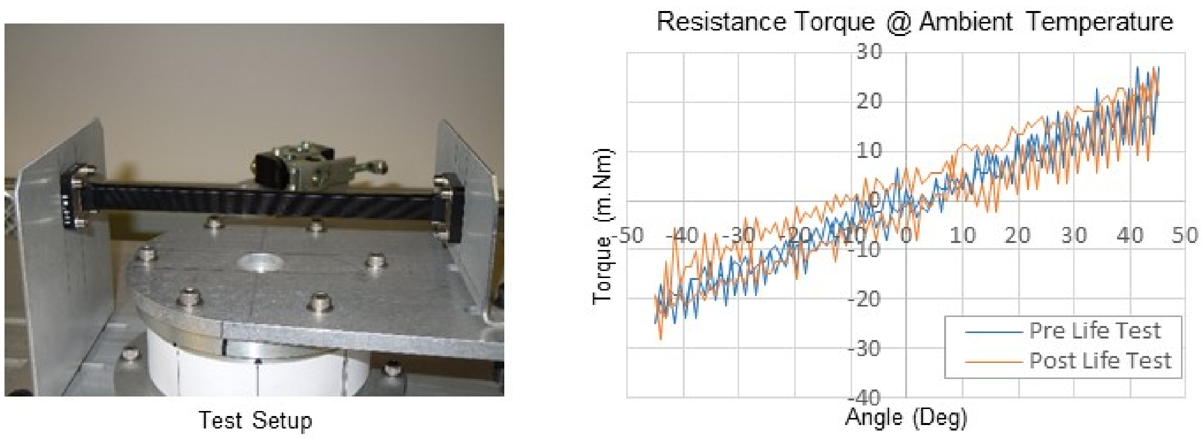


Figure 3. Resistance Torque and Life Cycle Test

The stresses induced due to the ±45-degree motion were well below the elastic limit, yet life tests were performed to ensure that cyclic loading does not cause any damage or performance degradation. The cycling test was performed at ambient, hot and cold temperatures, in ambient GN_2 atmosphere (Figure 4). The test article was flexed inside a thermal chamber by a drive system made up of a motor and a torque sensor. The flight batch qualification unit was subjected to 330 cycles, equally divided between ambient, +170°C and -105°C. The resistance torque was monitored to observe any trend.

Structural Evaluation
The key structural feature of the FWG is the thin, corrugated Ni-Co wall of the waveguide that allows it to flex. The waveguide length was chosen to minimize the elastic stresses due to the cyclic motion. The long unsupported length also meant lower resonance frequencies and higher load due to launch environments. One particular area of interest was the natural frequency of the waveguide in its launch configuration. The intent was to not have the waveguide resonances couple with the spacecraft frequencies. In the launch configuration, the high gain antenna is stowed at 45°, which put the waveguides in a gentle curvature (Figure 5).

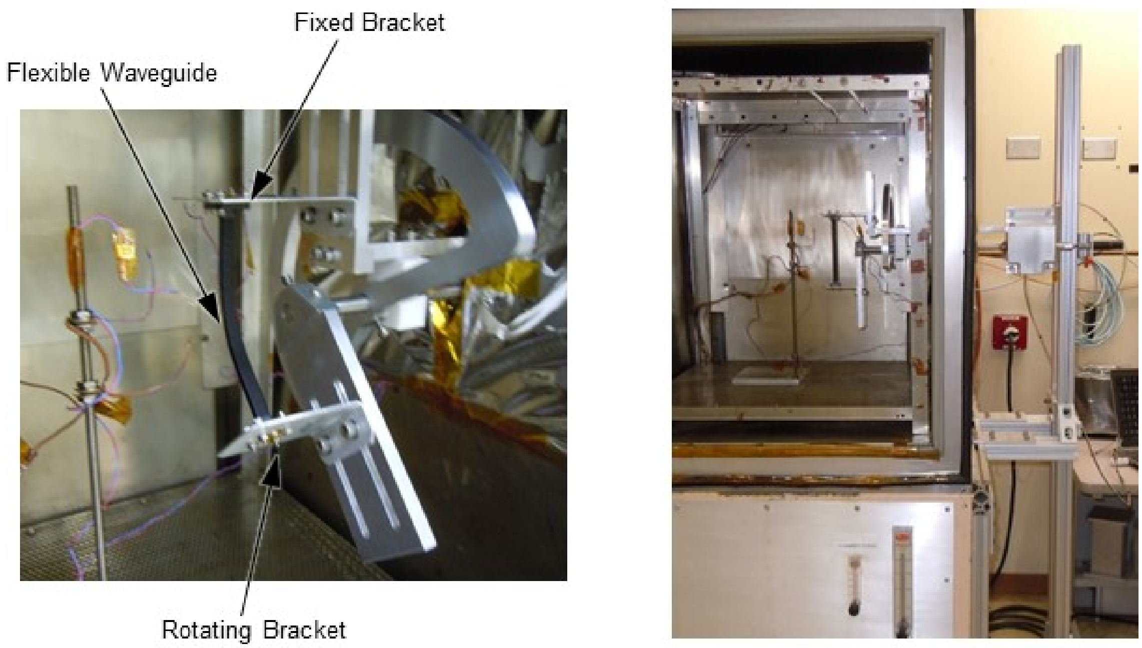
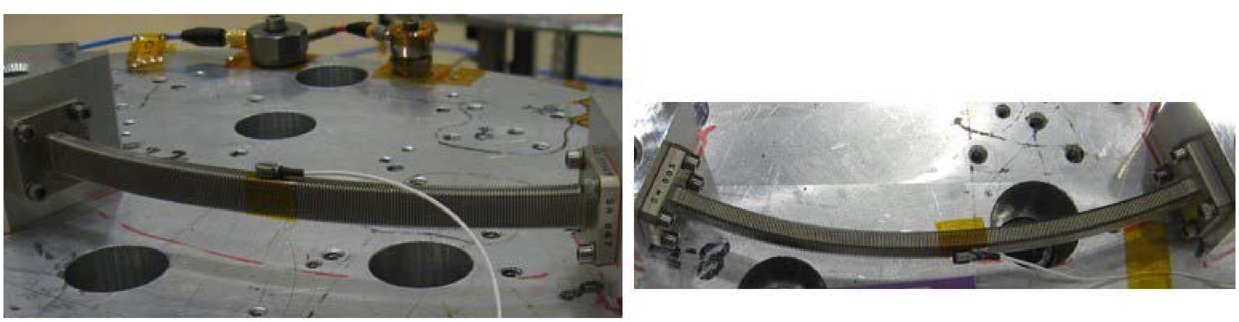


Figure 4. Life Cycle Test at Temperature Extremes

During the development phase, a set of six waveguides with soldered flanges were subjected to low-level sine sweep from 5 Hz to 500 Hz, to determine the natural frequencies in the off-axial directions. The waveguides were mounted on test blocks that flexed the waveguides by 45 degrees flange-to-flange, as in launch configuration. A miniature, single-axis teardrop accelerometer was attached to the middle of each waveguide, aligned in the direction of the test axis. There was a concern that the accelerometer attachment might by itself influence the resonance of the waveguide. To address this, the test was repeated on one of the waveguides with a non-contact laser vibrometer. There was no difference in the resonance values or amplification measured by the accelerometer and the vibrometer. All subsequent tests only used an accelerometer.

The natural frequencies in the narrow section direction ranged from 51 Hz to 60 Hz, and the wide section direction ranged from 60 Hz to 65 Hz. Because of the curvature of the waveguide in the launch configuration, the waveguide is somewhat preloaded and therefore stiffer in the wide direction, which led to a higher natural frequency when compared to the narrow direction. The variation in natural frequencies between waveguides was attributed to minute variations in wall thickness due to the electroforming process control. Regardless, the minimum resonant frequency was 51 Hz, which was well separated from the spacecraft frequencies, and would pose no problems with over-amplification of its acceleration responses during launch vibration.



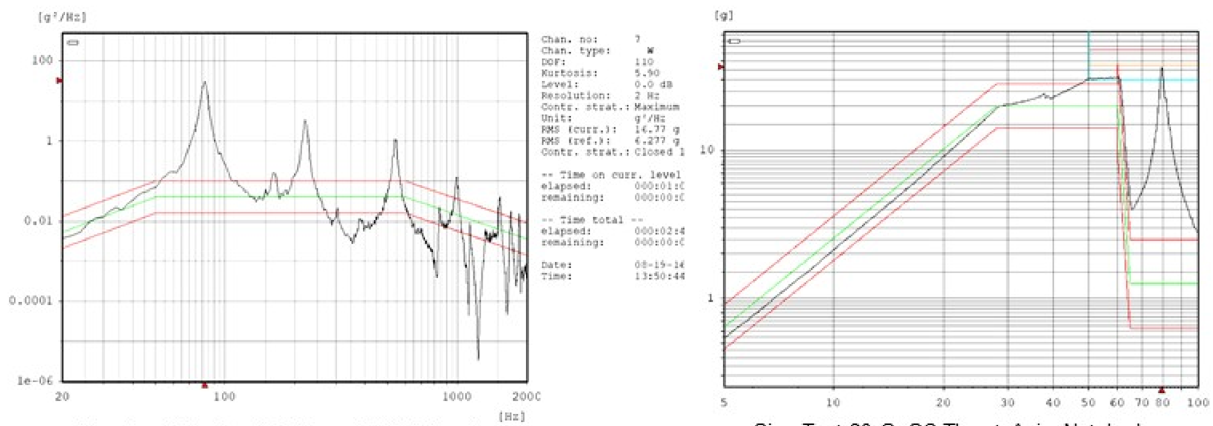
Vibration in Narrow Direction

Vibration in Wide Direction

Figure 5. Vibration Test in 45 Degree Bend Configuration

Sine vibration was performed to qualify the strength of the FWG for its expected flight levels, 15 G in the spacecraft lateral axes and 20 G in spacecraft thrust axis. Any resonance response was limited to 36 G according to its mass-acceleration limit load. The strength verification was accomplished by applying a sinusoidal vibration at the qualification level in the frequency range less than resonance so that the acceleration load approximated a static loading. All waveguides passed this test and demonstrated the capability to handle expected launch loads. The maximum response recorded was 37 G after notching (Figure 6).

Random vibration testing was performed on the FWGs to the protoflight levels. The development and flight batch qualification waveguides were exposed to a random vibration input of 6.3 Grms in the wide section direction, and the maximum overall response recorded was 16.8 Grms (Figure 6). At 3σ, the acceleration response would be 50.4 Grms, indicating that the waveguide could withstand loads higher than the design limit of 36 g. In spite of the large responses seen in the tests, the waveguide is relatively light (40 grams), and therefore the load supported in its own structure during vibration is less than 22 N.



Random Vibration 6.3 Grms, Wide Direction, Response 16.8 Grms

Sine Test 20 G, SC Thrust Axis, Notched, Max Response 37 G

Figure 6. Vibration Test Responses

Another area of interest was to assess the tolerance of the FWG to axial loads, either due to installation misalignments or on-orbit thermal mismatch. The maximum estimated extension with margin, due to all possible sources was about 0.7 mm. One of the development model waveguides was subjected to 300 cycles of extension on a Universal Testing Machine and the load was monitored. For this extension, the waveguide was within the elastic limit and the load at maximum extension remained stable at 1.42 N. The waveguide was also subjected to compression, the waveguide flexed slightly to accommodate this with very little change in load.

<u>Thermal Concern</u>

A few thermal concerns with the use of the flexible waveguide were identified during the development phase of this program. They were further explored through analysis and test, resulting in design changes to both the HGA and the FWG.

One of the key concerns was that the geometry of the FWG could cause the middle section of the waveguide to become very hot. The waveguide had a relatively small cross-section and a large distance between the middle section and the flanges. The flexible part of the waveguide was very thin, and the corrugated path of this section created an effective conductive length that was several times the actual length of the waveguide assembly. Given that thermal resistance increases with length and decreases with area, the middle of the waveguide was thus strongly thermally isolated, in spite of being made from Ni-Co metal alloy. Even if flange temperatures were to be controlled, there still could be a very high temperature in the center of the waveguide due to power dissipation during RF transmission. Adding to the concern with the middle temperature of the waveguide was the fact that this portion of the waveguide could be exposed to sunlight, depending on HGA position. At certain times in the mission the sun exposure could occur at 0.7 AU, which would effectively double the solar flux on the waveguide. This was especially concerning given the optical properties of the nickel-plated exterior surface of the waveguide. Metals inherently have low emissivity, and do not radiate heat easily to space. Metals can get very hot in the sun if not properly sunk to another boundary temperature. The typical values for absorptivity-to-emissivity ratio for nickel from various sources was around 10 (0.4 / 0.04). This optical property, coupled with the high solar flux and relatively high resistance to the flange, would result in high temperatures in the center of the waveguide.

The other key thermal issue with the waveguide was the temperature of the flanges. The HGA itself was allowed to run relatively hot with a design limit of 160°C and this caused waveguide flange temperatures as high at 160°C.

Thermal Analysis

Analysis of the flex waveguide in Thermal Desktop software showed very high temperatures for the middle portions of the waveguide due to high thermal resistance between the middle of the waveguide and the flanges. A detailed model of the waveguide was created to estimate the temperature of the middle section with higher fidelity (Figure 7). This model showed temperatures around 400°C depending on the dissipation estimates. The temperature at the middle of the waveguide for the given flange boundary conditions and a high heat dissipation of 1.7 W was 416°C. Despite the high temperature at the middle, the model still showed the flange areas at reasonable temperatures. The high temperature was not of particular concern from the waveguide material point of view, but could cause severe degradation or possible loss of the silver coating at 425°C. Hence it was decided to perform a test to verify the high temperature phenomenon.

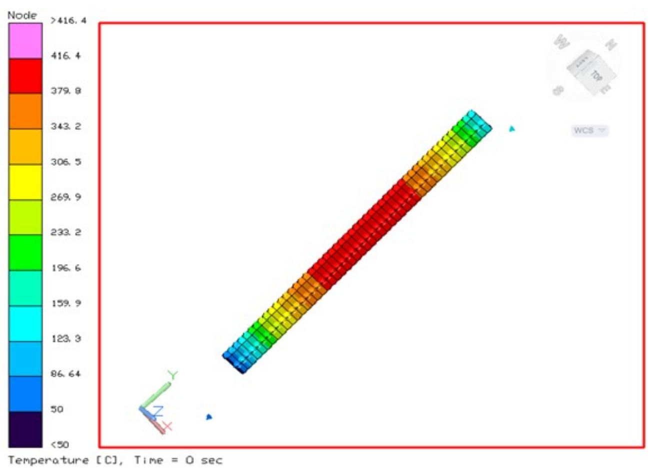


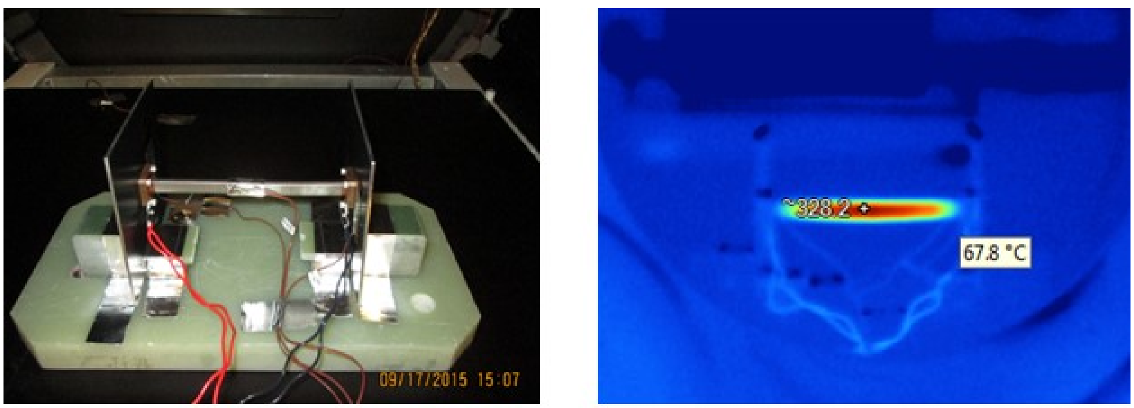
Figure 7. RF Induced Waveguide Temperature - Prediction

Thermal Test

A test was developed using a development waveguide in a vacuum chamber. This test used a Direct Current (DC) voltage to apply dissipation across the waveguide. During different configurations of the test, the temperature was measured with thermocouples and with an Infrared (IR) camera. Both methods were prone to high errors, the thermocouples at high temperature, and the IR camera on a low emissivity surface. However, the test was more to gain a general understanding of the issue, not necessarily to completely quantify the temperatures. The setup for the test in a thermal vacuum chamber is shown in Figure 8. In this setup a thermocouple (TC) was placed in the middle of the FWG to get a direct measurement of the temperature. In another set up this TC was removed and photos were taken with an IR camera. The red and black wires attached to the flanges of the waveguide were connected to a power supply and used to run current through the waveguide and simulate the dissipation from an RF signal.

The test showed results that were somewhat consistent with the analysis. Temperatures in the testing were not quite as high, however there was a concern that TC adhesion to the WG could have been affected at the high test temperature and results might not have been completely accurate. The highest observed temperature of the waveguide TC during testing was 276°C. Temperature measurements were also done with the IR camera and the IR image is shown in Figure 8. This clearly showed the relatively cold temperature at the flanges and increase in temperature towards the middle. The testing was considered successful since it confirmed high temperatures predicted by analysis and also showed that the predictions were conservative relative to the test. The test also demonstrated that flange temperatures would stay close to their interface temperatures and would not overheat due to the dissipation in the waveguide. RF testing after the thermal vacuum test showed no degradation to the waveguide characteristics.

Despite the fact that the test showed generally positive results, concern remained that additional heat on the waveguide from the sun could still result in excessive temperatures. For this reason, sun shields and a sun visor were added to the HGA assembly to prevent direct exposure of the waveguides to the sun, without interfering with the waveguide or the swept volume. Another takeaway from the test was the significance of the RF dissipation and the desire to run RF power through the HGA assembly during the HGA level thermal balance testing. This testing was completed but is beyond the scope of this discussion.



Test Setup Infrared Image

Figure 8. RF Induced Waveguide Heating - Measurement

The exterior finish on the flight waveguides was changed from Ni plating to black paint and this further reduced the temperature of the middle section. The thermal cycling limits for the flight waveguides were established based on the flange temperatures. The waveguides were supported in the free-state and RF performance evaluated pre- and post- thermal cycling. As explained earlier, the upper temperature of the development model was underestimated. But this was revised prior to the flight article batch tests as the thermal design matured. Also due to the criticality of the thermal environment and the issues experienced with soldered waveguides, the flight batch qualification article was subjected to a conservative 200 thermal cycles.

The thermal cycling limits of the various models were as follows:

Development tests:	6 cycles, -125°C to +100°C
Qualification tests:	200 cycles, -105°C to +170°C
Acceptance test:	7 cycles, -105°C to +170°C

<u>Waveguide Status and Performance Monitoring</u>

The condition of the waveguide was monitored at every stage of the test program to detect any degradation. This was done by visual inspection of exterior, inspection of interior with borescope, CT-scan, and RF tests.

Visual Inspection: All surfaces were visually inspected to keep track of any surface features or defects (Figure 9). The exterior surfaces were inspected under 10X and 80X magnification. The condition of the silver plating on the interior had a significant influence on the RF performance and so the inside surfaces were inspected with a miniature borescope with a 90° aperture (Figure 10). The borescope was mounted to a linear stage and the waveguide was supported on a stationary platform that allowed fine alignment of the waveguide with the borescope. With this setup, the coating could be inspected without the risk of contact or damage. The waveguides were screened by the manufacturer prior to delivery and no significant defects were noticed on the exterior or the interior. Any minor blemishes observed were photographed and tracked over the course of the test program.

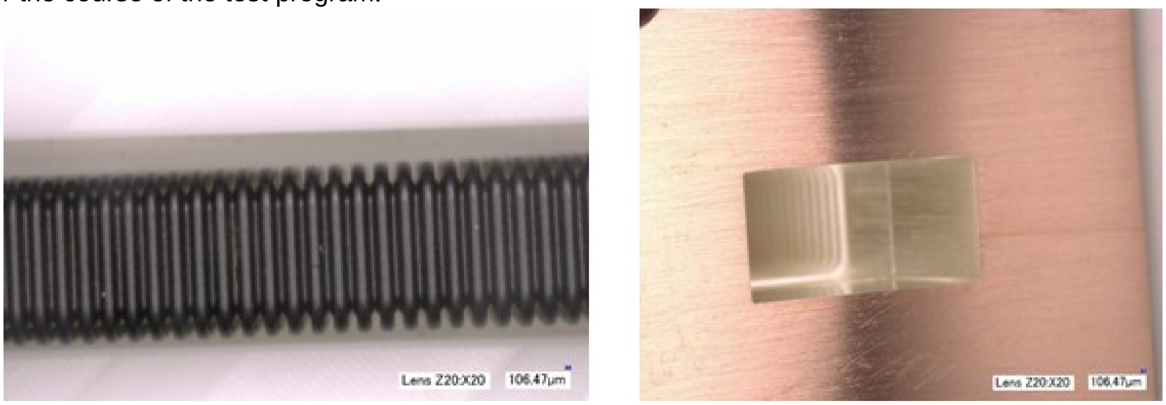
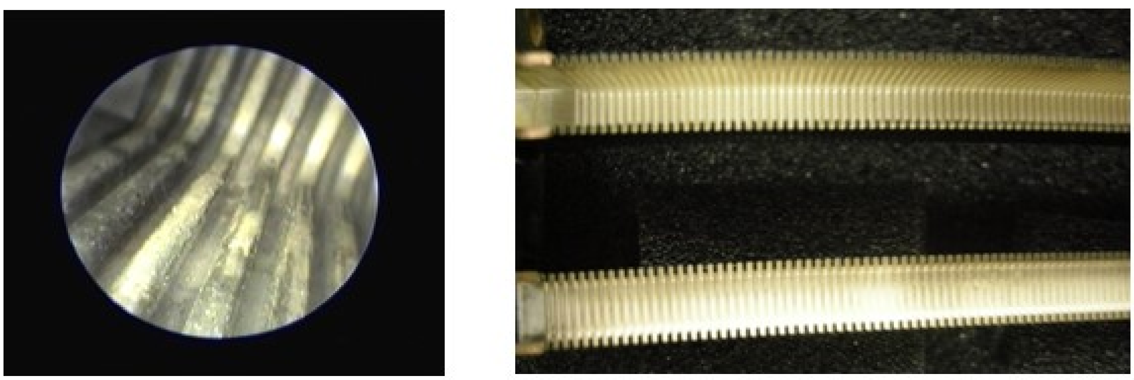


Figure 9. Visual Inspection of Exterior Surfaces

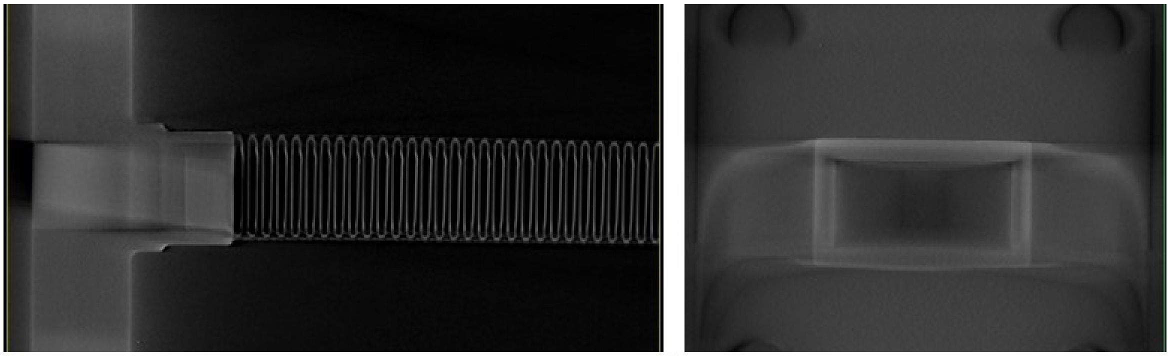


Borescope Image

Interior of Waveguide With One Side Removed

Figure 10. Inspection of Silver Plating

Radiography: The flexible parts of the waveguide as well as the flange attachment was inspected by Computerized Tomography (CT) scanning. This inspection step was performed at key points during the test flow and at the end of the test program. This allowed close examination of the exact cross-section of interest and was very effective in inspecting and ensuring the quality of the flange attachments. No defect of any kind was observed on waveguides with electroformed flange attachments at any point during the test program. CT-scan images of the flexible parts and a flange attachment are shown in Figure 11.



Flexible Section and Flange Joint **Cross-Section of Flange Joint**

Figure 11. CT-Scan of Flexible Waveguide with Electroformed Flange

RF Test: RF performance was evaluated by measuring the insertion loss and Voltage Standing Wave Ratio (VSWR) across the entire WR-34 frequency range of 22 GHz to 33 GHz. This test was performed with the waveguide held in the straight and 45 degree bent positions. Typical RF performance results are shown in Figure 12.

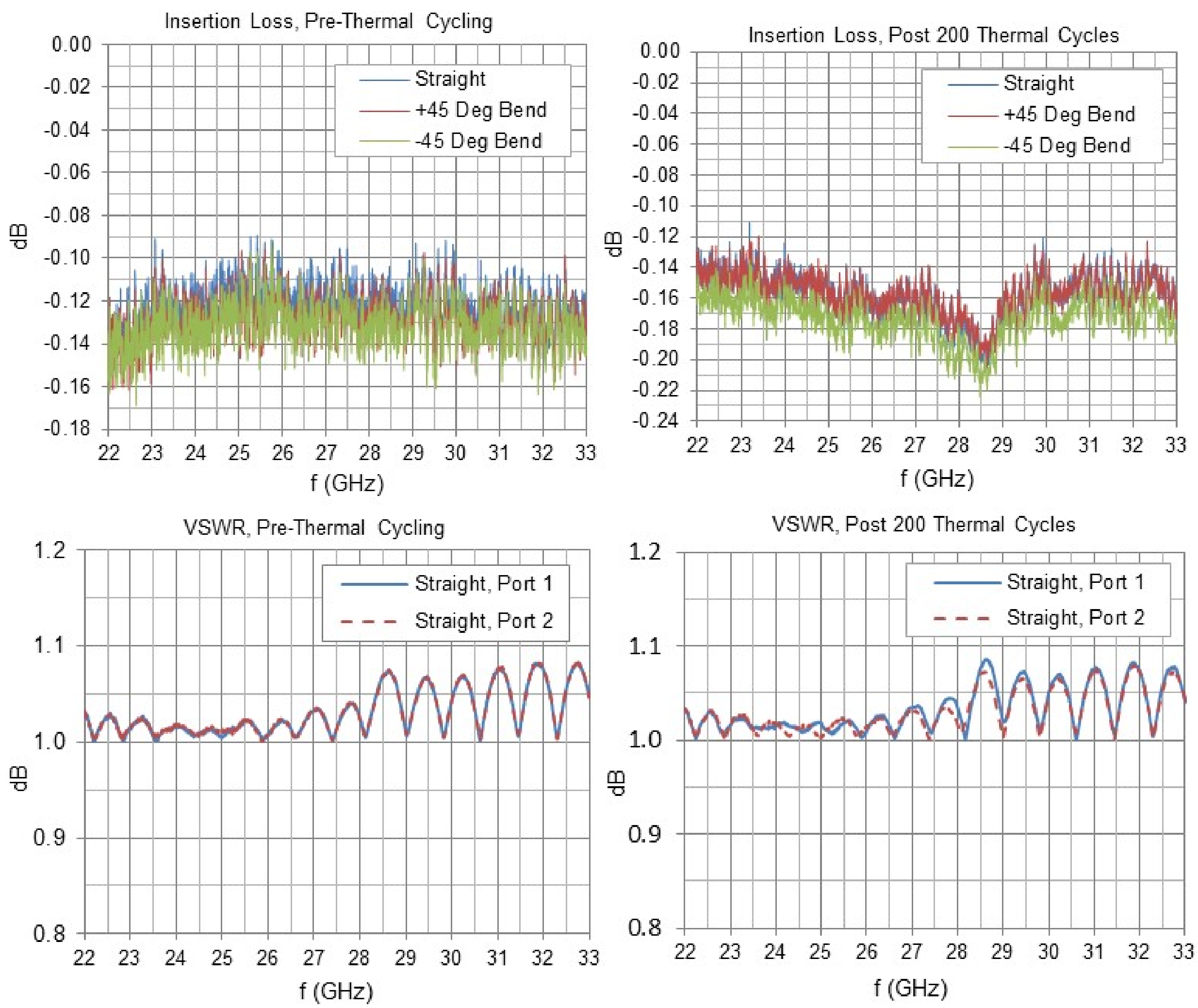


Figure 12. RF Characterization of Waveguide

Test Program

Development Tests

During the development phase, two waveguides were subjected to a very detailed development test program. The successful performance in these tests is what lead to the selection of waveguides for the PSP program. The development program was as follows:

1. Waveguide visually inspected at 80X; no significant defects observed
2. RF performance characterized in straight and 45 degree bent configuration and was acceptable
3. Resistance torque was measured; maximum resistance torque at 45 degree was less than 30 mN-m.
4. Waveguides were subjected to 400 flex cycles at ambient temperature between -45 degree and +45 degree and following this cycling, were visually inspected and characterized
    a. No change in resistance torque after life cycle test
    b. Visual inspection at 80X showed no new damages or degradation of existing surface blemishes
    c. No changes noticed in RF performance for either article
5. Waveguides were subjected to sine survey and random vibration; following vibration testing, the waveguides were visually inspected and characterized
    a. Visual inspection under 10X did not show any issues
6. Waveguides exposed to two thermal cycles between -125°C and +100°C; at each temperature extreme, waveguides were subjected to 100 bend cycles between -45 deg and +45 deg
    a. Visual inspection under 10X did not show any issues for either article
    b. No changes in RF performance for either article

Batch Qualification

The flight batch of the waveguides were subjected to a test program consisting of batch qualification test on one waveguide and acceptance testing on all flight and spare components. The first round of tests was performed on waveguides with soldered flanges and resulted in failures of some of the soldered joints as described earlier. The program described in this section was performed on the waveguides with electroformed flanges. Prior to the delivery of the waveguides the manufacturer performed 7 thermal cycles between -105°C to +170°C and RF characterization.

The qualification program was as follows:

1. Visual Inspection (20X to 80X) of exterior and inspection of silver coating on interior with borescope
2. RF performance test
3. Radiography
4. Vibration Testing - sine sweep, sine vibration and random vibration (Protoflight)
    a. Visual Inspection showed no damage
    b. No changes noticed in RF performance post vibration
5. Bend resistance measurement and 330 flex cycles over ±45° (110 @ ambient, 110 @+170°C and 110 @ -105°C)
    a. Visual Inspection showed no damage
    b. No changes noticed in RF performance post mechanical function test
6. Thermal Cycling (200 cycles between -105°C and +170°C)
    a. Visual Inspection showed no damage
    b. No changes noticed in RF performance over the course of thermal cycling
7. Radiography - no defect observed post thermal cycling (Figure 10)
8. Removal of side wall and visual inspection of the interior; silver coating was found to be in good condition (Figure 10)

Acceptance Test

Five flight waveguides were subjected to the following tests:

1. Visual Inspection (20X to 80X)
2. RF performance test

3. Radiography
4. Vibration Testing – sine sweep and random vibration (Acceptance)
5. Bend resistance measurement and 5 flex cycles, ±45 degrees @ ambient temperature
6. Visual Inspection (20X to 80X)
7. Radiography
8. RF performance

All waveguides successfully passed the acceptance test program. Two of the waveguides were installed to the flight HGA assembly.

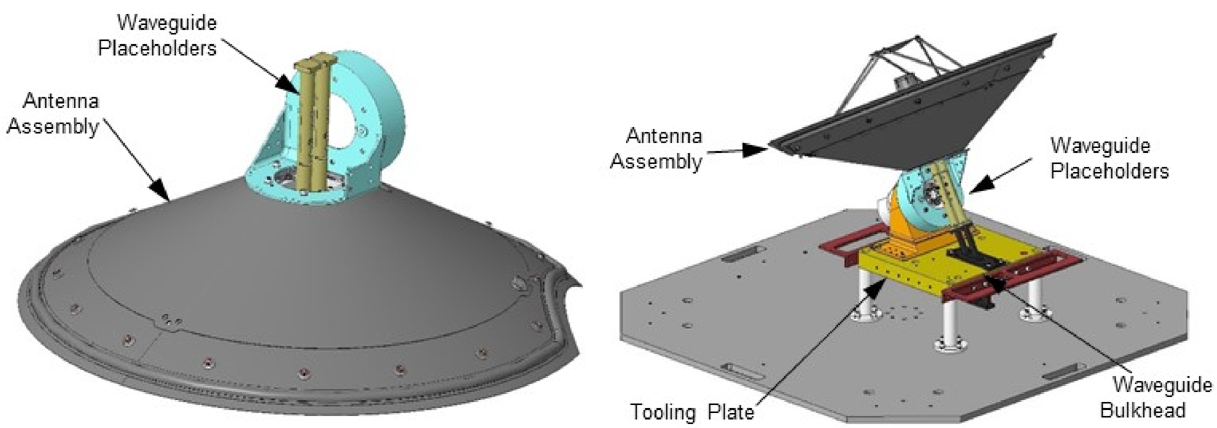


Figure 13. Waveguide Placeholders Locate Bulkhead Flange Relative to Feed

HGA Assembly Flight Installation

The flex waveguides span the gap between the waveguide bulkhead on the spacecraft side and the antenna feed assembly on the HGA side, across the axis of the drive actuator. The antenna feed assembly is installed at the center of the main reflector, which is mounted to the actuator. The bulkhead feedthrough connects the HGA to the RF components located on the inside of the spacecraft.

Though FWGs have less stringent alignment requirement than a RF rotary joint, they should be subjected to pure bending only and any extension or twisting must be avoided. Therefore, the feed assembly and the bulkhead feedthrough must be aligned and the distance between them must be controlled precisely to match the length of the waveguides. The two flange interfaces were both positioned at equal distance from the drive actuator axis. The alignment requirement was met by performing this installation on a tooling platform using waveguide Placeholders. The flexible waveguides are installed to the HGA assembly with the actuator at the 0-degree position where both waveguides are straight without bending. The HGA-actuator assembly and the waveguide bulkhead bracket were located on the tooling platform, and the two waveguide Placeholders were installed to the feed assembly on the reflector. Shims were added under the waveguide bulkhead as needed to allow proper mating to the Placeholders. The waveguide placeholders were then replaced by the FWG one at a time (Figure 13). The placeholders were machined to high precision to match the FWG length and bolt pattern. The pinned-halves design (Figure 14) allowed easy removal of the Placeholders to be replaced with the actual waveguides.

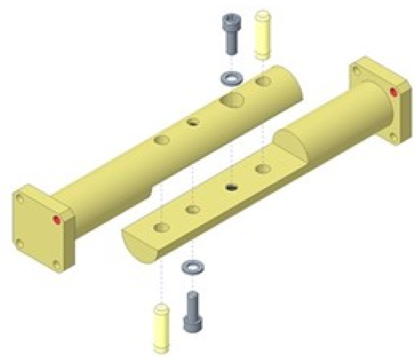


Figure 14. Exploded View of Waveguide Placeholders

To maintain the relationship between the bulkhead waveguide and the reflector assembly, a handling fixture was used during transportation and handling (Figure 15). All mounting interfaces between the HGA assembly and the tooling plate or handling fixture were designed with a nominal shim that could be adjusted as required during installation. The detailed integration and handling procedures using the associated tooling and fixtures ensured that the waveguides were installed with utmost care to avoid undesirable loading.

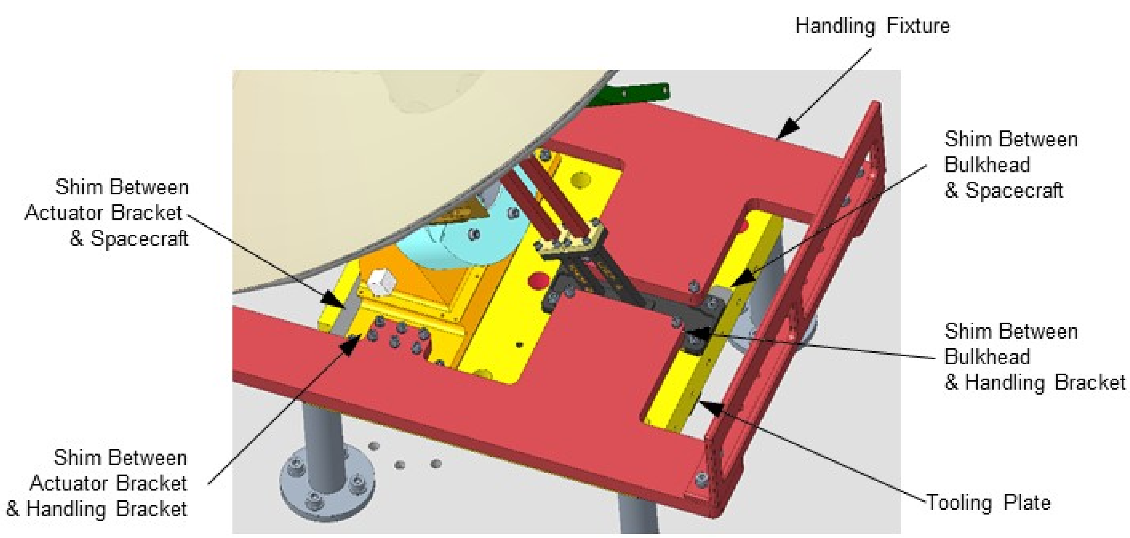


Figure 15. Shimming Opportunities

Lessons Learned

Several valuable technical, procedural and philosophical lessons were learned over the course of this task. Following is a brief description of the key lesson learned:

- Electroformed flexible waveguide made out of Ni-Co alloy, is a viable alternative to RF rotary joints and coaxial cables, under certain situations.
- End flange attachment technique has a significant influence on RF losses.
- All aspects of new product should be thoroughly examined, not just the characteristics of interest. While our program was primarily focused on the flexibility and life cycle, the only issues we faced were related to flange attachment.
- Early testing during development phase greatly enhances confidence.
- The thermal cycling test is very critical to evaluate flexible waveguides. Detailed thermal analysis can be very effective in predicting the effect of RF transmission on waveguide temperature.

- Superior technical options when available should be given due consideration and not be dismissed just due to lack of heritage.
- Laser vibrometers and miniature teardrop accelerometers can be effectively used in vibration testing of flexible parts without influencing dynamic performance.
- Borescopes can be used to inspect silver coatings on the inside of waveguides; this was validated by RF tests and destructive inspection.
- CT scan is an effective tool to inspect soldered flange joints. RF performance can be directly correlated to defective joints observed by CT scanning.

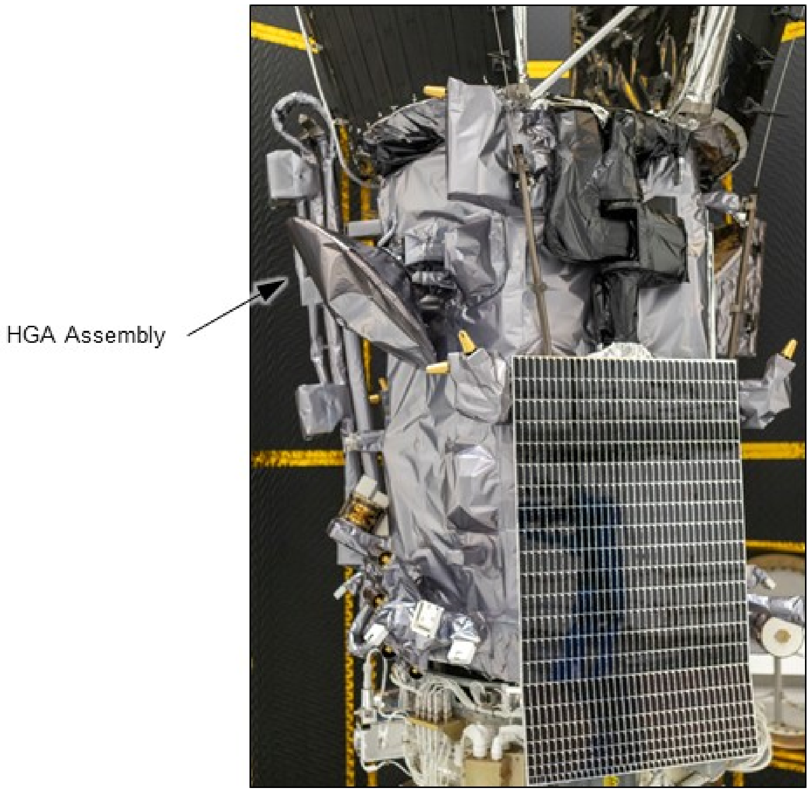


Figure 16. HGA Assembly on PSP Spacecraft

Summary

The PSP HGA assembly successfully used two flexible waveguides for RF transmission across the actuator rotary joint (Figure 16). The analysis and test programs were effective in proving the suitability of the FWG for on-orbit cyclic operations. They were also effective in detecting some latent process defects and resulted in the use of an improved waveguide with superior RF performance. The PSP spacecraft was launched in August 2018 and has completed three close encounters with the sun so far. All aspects of the HGA and the RF system are performing well as planned.

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