GMI Spin Mechanism Assembly Design, Development, and Test Results

Scott Woolaway*, Michael Kubitschek*, Barry Berdanier*, David Newell*, Chris Dayton*
and Joseph Pellicciotti**

Abstract

The GMI Spin Mechanism Assembly (SMA) is a precision bearing and power transfer drive assembly mechanism that supports and spins the Global Microwave Imager (GMI) instrument at a constant rate of 32 rpm continuously for the 3 year plus mission life. The GMI instrument will fly on the core Global Precipitation Measurement (GPM) spacecraft and will be used to make calibrated radiometric measurements at multiple microwave frequencies and polarizations. The GPM mission is an international effort managed by the National Aeronautics and Space Administration (NASA) to improve climate, weather, and hydro-meteorological predictions through more accurate and frequent precipitation measurements [1]. Ball Aerospace and Technologies Corporation (BATC) was selected by NASA Goddard Space Flight Center (GSFC) to design, build, and test the GMI instrument. The SMA design has to meet a challenging set of requirements and is based on BATC space mechanisms heritage and lessons learned design changes made to the WindSat BAPTA mechanism that is currently operating on-orbit and has recently surpassed 8 years of Flight operation.

Introduction

The Global Microwave Imager (GMI) instrument is one of the payload instruments on the Global Precipitation Measurement (GPM) core spacecraft and must be spun continuously at 32 revolutions per minute (rpm) +/- 0.3% on-orbit for the 3 year operational life of the instrument to provide the desired geo-location for the science data. The GMI Spin Mechanism Assembly (SMA) is the electro-mechanical bearing and power transfer assembly mechanism that spins the GMI instrument payload, see Fig. 1. The SMA design has to meet a challenging set of requirements and is based on Ball Aerospace and Technologies Corporation (BATC) space mechanisms heritage and lessons learned changes made to the WindSat BAPTA mechanism that is currently operating on-orbit and has recently surpassed 8 years of successful Flight operation. Early WindSat mission anomalies were described and published in a NASA 38th Aerospace Mechanisms Symposium (AMS) paper [2].

Figure 1. The completed Flight 1 SMA Assembly

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland

This paper will focus on the GMI instrument system requirements, the SMA design to meet those requirements, the integration and testing of the assembly, and lessons learned throughout the GMI SMA program. The design and development of the SMA will be described with a design overview, component development with suppliers, piece-part fabrication, and the drive component level test summary. The verification and validation testing of the SMA assembly to demonstrate compliance to performance and environmental requirements has been completed and will be discussed in greater detail later.

The GMI SMA drive consists of a pair of angular contact bearings separated axially on an AlBeMet^{TM} (Aluminum Beryllium Metal Matrix) shaft and housing, driven by a 3-phase DC torque motor, with a 2-speed (1x/64x) resolver used for commutation and position feedback, a despin tube, a Slip Ring Assembly (SRA), and a rotary transformer. The rotary transformer is used to provide the electrical input to the resolver, which avoids running the low-level resolver excitation input signals across the slipring interface. The incorporation of the rotary transformer into the SMA was one of the WindSat BAPTA 'lessons learned' design improvements, after it was suspected that passing the low-level excitation signals for the resolver across the slipring interface was a potential source of, or contributor to, the WindSat on-orbit spin anomalies [2].

The SRA is mounted on the top of the SMA drive and provides an electro-mechanical interface to pass all of the GMI instrument electrical signals and power from the spun-side payload (RF receiver signals, power, telemetry, etc.) across the spinning interface to the stationary-side of the GMI instrument to the GPM spacecraft. The SRA consists of a preloaded angular contact bearing pair, gold-on-gold, double v-groove type brush to ring design, with a total of 124 electrical circuits (rings), and it is wet lubricated. A despin shaft with bellows coupling is used to provide the mechanical despin interface to the stationary upper instrument calibration assembly structure and provide a slight misalignment capability between the bearing pair in the SMA drive and the bearing pair in the SRA. Bearings, lubrication, and material choices will be discussed later in this paper along with the selection and sub-assembly level testing of the drive components. The completed SMA drive is approximately 8.6 inches in diameter by 24.15 inches long from the instrument interface base to the top of the SRA, See Fig. 2. A brief overview of the control system architecture and SMA drive electronics will also be described briefly later on in this paper.

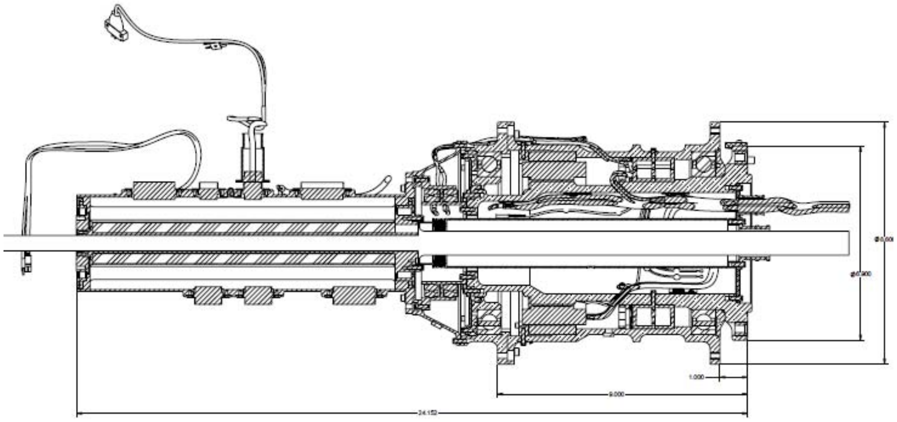

Figure 2. Cross-section view of the SMA

The SMA Assembly has to meet all of the challenging and design-driving requirements, such as: instrument deployed stiffness and pointing accuracy, minimize weight, and carry launch loads, long life reliability for continuous operation on-orbit and ground operations, integration and test demands. Tab. 1 shows the list of the main requirements that drive the design of the SMA.

Early in the design and development of the GMI instrument it was recognized that there were several risks associated with the successful completion of the SMA. The highest risk identified was the

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland

intermittent on-orbit uncontrolled spin anomalies associated with the WindSat instrument [2]. All the recommendations from the WindSat anomaly investigation lessons learned and BAPTA build were incorporated into the design of the SMA. The list includes: specific electronic design changes, procurement of the SRA, and addition of a rotary transformer to avoid passing the resolver signals across the SRA. These along with other potential SMA risks were closely tracked through the duration of the SMA design, procurement, integration, and test program.

Several risk mitigation actions were undertaken to reduce the chance of unanticipated anomalies becoming significant schedule or flight issues, including: the early procurement and testing of Engineering Model Units (EMUs) for the SRA, rotary transformer and resolver drive set components, and motor control electronics. In addition, early assembly and extensive testing of the completed SMA before it was integrated into the GMI instrument proved to be a wise strategy and well worth the investment. It provided the needed flexibility and time to identify and resolve issues before they could significantly impact the flight units, or worse, drive GMI instrument cost and schedule.

Table 1. SMA Design Driving Requirements

Requirement	Predicted Performance
Rotation Rate /Control Rate shall be 32 + / - 0.3% RPM Range shall be 0 – 33 RPM	32 ± 0.3% RPM 0 – 33 RPM
Spin axis Align to base shall be < 75 arcsec Wobble shall be < 30 arcsec 3 sigma	49.6 arcsec (RSS) 11.5 arcsec (RSS)
Position Uncertainty Tach pulses/rate control position accuracy ≤ 60 arcsec	44 arcsec (32 tach pulses / rev)
Stiffness First mode > 50 Hz (in GMI assy) Deployed First Mode > 6 Hz De-spin torsion > 7.6 Hz	60.8 Hz > 7.6 Hz > 7.8 Hz
Mass 20.4 kg maximum	20.29 kg
Torque Margin 1.5x on known's, 2x on variables	0.222 MS
Operating and Non Operating Temperatures On-orbit Op: 0 to +50C Survival: -35 to +55C	10 to 15C Op
Design Life 38 months on-orbit op + 12 months I&T + 2.4 months op storage (2 yr @ 10%); total life reqmt 52.4 months	99.721% reliability 0.13 MS SMA lube 0.38 MS SRA lube

It should also be noted here that the anomalies experienced by WindSat occurred relatively early in the on-orbit history of the satellite, an instrument and drive operational work-around was developed quickly for the instrument and drive so no significant observational time was lost. Very infrequent spin-downs

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland

(approximately 1-2x per year) have continued to occur, but the operational work-arounds developed were immediately employed and been successful. WindSat BAPTA has now recently surpassed 8 years of continuous on-orbit operation, without any additional anomalies in the past 18 months [2].

Design Description and Details

The SMA is a bearing and power transfer assembly originally based on past BATC space mechanisms design heritage and experience going back to the 1960s-70s with several spinning or spin-stabilized small satellites (i.e. The Orbiting Solar Observatory (OSO) 1–7 satellite series, 1961-71). They were designed, built, and tested by the then Ball Brothers Research Corp. (BBRC), which is now BATC, and that have all had very successful on-orbit records. The DSCS II drive in the 1980s was the fundamental architecture for the WindSat BAPTA design and one of the DSCS II drives operated successfully on orbit at 30 rpm for over 23 years. The GMI SMA is based on the WindSat BAPTA design that BATC designed, built, tested, and delivered to U. S. Naval Research Laboratories (NRL) in 2001, for the WindSat instrument that is flying on the Coriolis mission.

Since the SMA design is based on so much past, and recent, successful BATC flight heritage, there was a very real priority given, and effort made, to keep the design of the GMI SMA as close as practical to the design of the WindSat BAPTA mechanism. The only changes made were to address the issues associated with, and the lessons learned incorporated from the WindSat BAPTA, or in a few exceptional instances, because the system level requirements for GMI were different and necessitated it. But every effort was made to design the other new elements of the GMI instrument around the design of the SMA, wherever sensible, to avoid impacting the flight heritage integrity of the SMA design.

The most significant change to the SMA design was the addition of a rotary transformer, the result of an effort to avoid passing the low level excitation and return signals of the resolver across the SRA interface. If the resolver signals drop for a long enough period of time, the motor commutation can be severely affected, resulting in the loss of operational rate or position control resulting in a controlled spin-down. For this reason, the decision was made early on to alter the basic SMA configuration by adding a rotary transformer to the design. The addition of the rotary transformer added a significant amount of weight, approximately 2.0 kg, power, and some minor complexity to the control system electronics design but the trade decision was made that the added mass, power, and complexity was worth the risk mitigation that was gained by making this aspect of the design more robust.

All the other changes to the SMA design were primarily within the SRA. For instance, the SRA for BAPTA had 137 rings, whereas, for GMI the SRA needed to have 124 rings for all the GMI signals. The BAPTA SRA manufacturer acquired and combined with another supplier. Extensive time and effort was spent to recover the BAPTA SRA heritage design. That proved to be a much tougher task, as it turned out, than anyone anticipated. The basic design and production knowledge was essentially still there, but a few of the critical process details of exactly how to produce the product as desired, why it was important, and what the impacts were was lost, and had to be re-created, to meet the specification requirements of the design.

The most obvious challenge in the early SMA development was trading either adapting the drive to meet the GMI instrument interfaces and requirements, or alternatively, adapting the GMI interface (or derived requirements) so that the SMA design configuration would, or could be made to meet them without adversely affecting the functional and performance heritage of the drive or principle critical elements. One of the biggest of these challenges was converging on an instrument interface and load path for the GMI instrument that would be consistent with the load capacity and stiffness of the SMA bearings and drive configuration.

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland

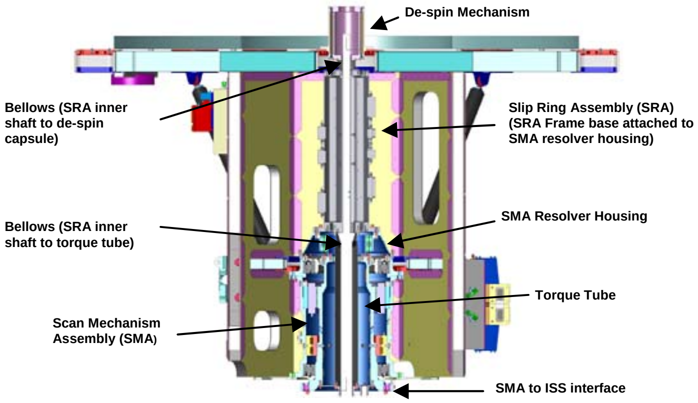

Figure 3. Cross-section of the GMI Instrument Bay Structure (IBS) with the SMA installed

Fig. 3 shows a cross-section of the primary structural elements of the SMA within the GMI instrument. A critical factor in the final configuration of the instrument architecture was the analytical determination that the GMI Instrument Bay Structure (IBS) would have to be restrained for launch in order for the SMA bearings and design to remain the same as the heritage drive. Substantial effort and care was taken in the IBS design and structural analysis to ensure that the load path from the IBS launch restraints, to the IBS structure, and transferred thru the SMA structure during launch were maintained to acceptable levels to meet adequate margins of safety with modeling and testing uncertainties.

The SMA drive design was also analyzed for adequate stiffness to meet the deployed frequency first mode requirement after the launch restraints and main reflector have deployed on orbit. Fig. 4 shows the stowed and deployed structural analysis Finite Element Models (FEM) used for the stowed and deployed stiffness determination and the first modes, respectively.

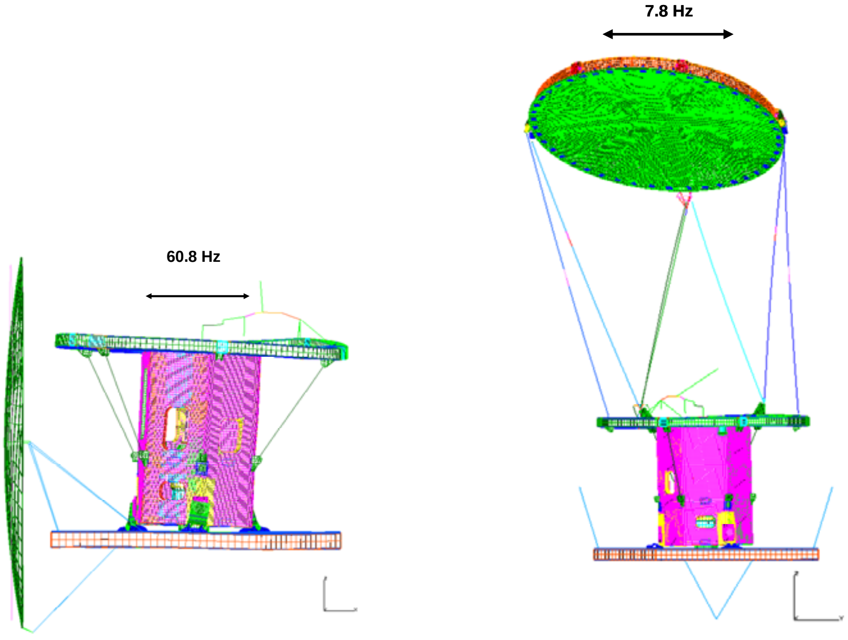

Figure 4. Finite Element (FEM) model of GMI instrument with SMA and launch restraints meets the first mode stowed frequency requirement (>50 Hz), *meets the first mode minimum deployed frequency requirement (>6 Hz) predicted on-orbit*

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland

The electronic control system architecture was adopted and leveraged from the WindSat BAPTA electronics and software to perform the speed and position control tasks for GMI. The model includes an analog controller used to control SMA rate, a control plant that includes models of the motor (transfer function with current feedback loop) and disturbance torques, and feedback sensor that models position sensor with noise and velocity calculation via position differentiation. Further detail of the control system modeling and verification testing are beyond the scope of this paper.

COMPONENT, MATERIAL, AND LUBRICATION SELECTIONS

The design-driving components for the SMA were, not surprisingly, the challenging procurements of the SRA, the resolver, rotary transformer, and the motor. However, since this design application requires such a long life (75million revolutions) and reliable performance over the entire life, the bearings, bellows, and lubrication are just as critical to the ultimate success of the drive. Fig. 5 shows a cross-section of the SMA.

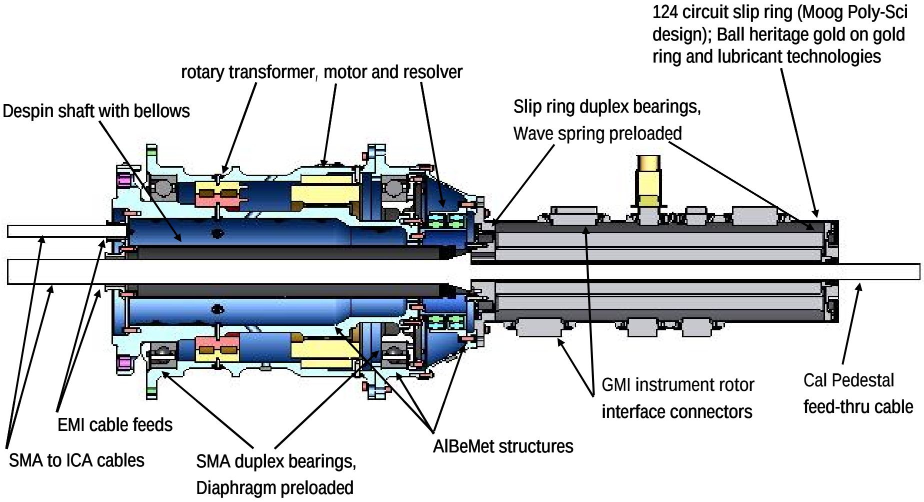

Figure 5. Cross-section of the SMA design with drive component labels

As previously mentioned, the SRA is a heritage design procured from Moog Components Group (formerly Poly-Scientific and Electro-Tech Corp.). The SRA configuration consists of an angular contact bearing pair, a gold-on-gold, double v-groove type brush to ring design with a total of 124 electrical circuits (rings) that are wet lubricated. The SRA brushes are a solid gold alloy and each brush pair rides in the hard gold over soft gold double v-groove rings. See Figure 6. This is a heritage design which dates back to DSCS II drive in 1980, and was similar to the WindSat BAPTA design with minor modifications. The PAO wet lubrication system is a BATC proprietary formulation and process [3] first demonstrated on the WindSat BAPTA SRA and will be life-tested in the GMI Life Test Unit (LTU) SRA discussed in section 5 of this paper.

The primary drive and control components; motor, resolver, and rotary transformer were all procured from Axsys Technologies, now owned by General Dynamics AIS. The motor is an external rotor 3-phase brushless DC torque motor with a skewed and redundant winding design. The motor design parameters; Kt = 320 oz-in/amp, cogging torque = 13 in-oz, peak torque = 639 oz-in (at 1.71 amps max. current), air gap=0.023 in, and weight = 7.02 lbs near identical to the heritage motor used on WindSat BAPTA. See Figure 7.

The resolver and rotary transformer were procured as matched sets with redundant units mounted on common hub and sleeve designs. The resolver design is the BAPTA heritage 2-speed (1x/64x) resolver

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland

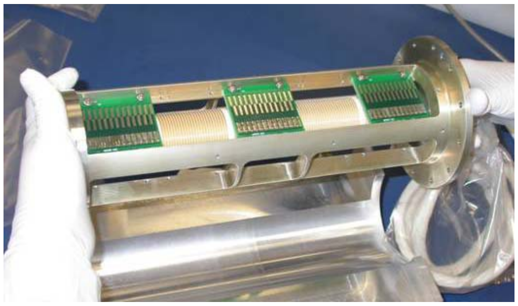

Figure 6. Slip Ring Assembly (SRA) showing double gold brush pairs, double v-groove gold rings

used for commutation and position feedback. The combined resolver/rotary transformer set was specified to have a reduced 30 arcsec minimum accuracy (at room temperature) and a 6 arcsec maximum electrical zero shift over temperature (+/- 20^{o}C), and a rotary transformer weight = 3.9 lbs. The resolver mounting alignment requirement = 0.0005 in, air gap = 0.016 in, and resolver weight = 1.52 lbs were all heritage designs too. See Figure 8.

Figure 7. BAPTA 3-Phase DC torque motor

Figure 8. BAPTA 2-speed Resolver (1x/64x)

It is probably becoming clear that 'Flight Heritage Design' does not always mean it is truly 'flight' heritage. There is no such thing as 100% heritage based design; materials are altered, processes change, suppliers change, and requirements, or specific applications change loads, environments, or other critical conditions that may affect the design performance in sometimes dramatic ways.

The main SMA drive consists of a pair of preloaded angular contact bearings separated axially on an AlBeMet^{TM} (Aluminum Beryllium Alloy Material) shaft and housing. The bearings are ABEC 7 (ABEC 5 balls), 52100 steel bearings procured from NSK Corp. (formerly manufactured by RHP, England) and is a heritage component except for a manufacturing change by the new vendor to improve the inner raceway curvature and dam height. These changes were modeled in the structural analysis and taken into account in the lubrication analysis that still shows a slightly positive margin of safety (MS = 0.02) at End of Life (EOL) for the number of stress crossings and with the mean Hertzian contact stress of the 110 lb. preloaded bearings, which is acceptable. The bearings are precisely preloaded and 'snubbed' by means of a titanium diaphragm and snubber. Several axial deflection vs. force measurements were taken during assembly to confirm the correct preload and snubber gap were achieved in the assembly. The lubrication for the SMA main drive bearings is a Nye Synthetic Oil with Rheolube grease and is heritage BATC tribology elements [4].

The SMA primary structural housings and inner shaft elements were fabricated out of AlBeMet^{TM} which contains 62% Beryllium and 38% Aluminum and was chosen because of the material properties; mainly for high specific stiffness and heat conduction, compared to other more common aerospace structural materials. However, because of the Beryllium content in this alloy, it does require special handling to prevent human exposure to any particles that could be generated from the parts.

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland

Finally, it should be mentioned here that a despin shaft with bellows coupling is used to provide the mechanical ‘despin’ interface to the stationary upper instrument structure, calibration assembly, and to account for any minor misalignments between the bearing pair in the SMA main drive and the bearing pair in the SRA. There is also another preloaded angular contact pair that supports the Calibration Pedestal and the upper IBS structure, this bearing configuration is referred to as the Despin Mechanism in the GMI instrument. Those bearings are being life-tested as well but the design of that mechanism is not included or mentioned further in the discussions in this paper but similar issues and constraints apply. The bellows life test was a significant effort at Tara BelFab.

INTEGRATION EXPERIENCE, TEST SETUPS, AND TEST PLANNING

The SMA drive successfully completed performance and environmental (thermal vacuum and EMI) acceptance testing in Nov. 2010, and met all of the sub-system requirements that were to be verified via test. The objective of this testing was risk reduction for verifying the critical functional and performance requirements early in the integration and test program, so that any issues found in the SMA integration with the electronics, performance or environmental testing could be addressed at the sub-system level, months before the SMA is integrated into the GMI instrument.

The test setups for performing the acceptance testing are briefly described here. The electronics integration, commutation offsets, initial spin testing, and baseline performance tests were all run in the clean room with the SMA mounted within the Inertial Test Fixture (ITF), See Figure 9. The completed SMA is seen within the test fixture along with the circular instrument mass and inertia simulator plate mounted on the SMA. The square shaped torque tube plates around the SRA above the SMA are seen and are used to interface with the optical encoder, torque transducer, and brake during the torque margin and rate testing.

Figure 9. SMA mounted in test fixture to prepare for acceptance test in the clean room.

Once the ambient testing was successfully completed, the test setup was loaded into the Thermal Vacuum (TVAC) chamber and the article under test was taken thru one complete survival thermal cycle with 4 hour minimum dwells at each temperature extreme. Then all the acceptance tests were repeated in the TVAC at the operating temperature extremes, see Figure 10.

PERFORMANCE TEST RESULTS

The results of the acceptance testing of the SMA, including: measured rate control, position accuracy, pointing alignment, wobble, and power dissipation over operating temperature ranges in vacuum is summarized in Table 2.

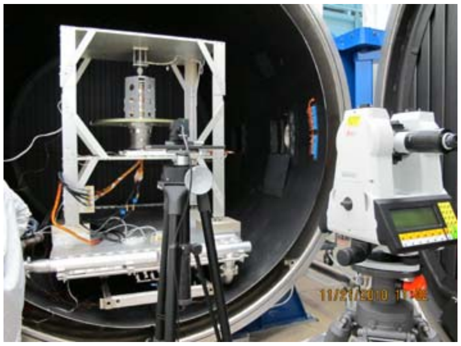

Figure 10. SMA mounted in inertial test fixture and loaded into chamber for TVAC Testing

The SMA torque margin was only tested in the cleanroom at ambient temperature but the drive current was monitored over temperature during operation. The torque margin can be calculated by knowing the motor constant Kt (which is essentially constant over temperature) and measuring the current at the operating temperature extremes. Then the change in current is due entirely to the change in bearing and SRA drag torque or the drive, within the measurement uncertainty of the torque transducer.

Table 2. SMA Tested Performance vs. Requirements

Requirement	Measured / Tested Performance
Rotation Rate /Control Rate shall be 32 + / - 0.3% RPM Range shall be 0 – 33 RPM	32 ± 0.1% RPM 0 – 33 RPM
Spin axis Align to base shall be < 75 arcsec Wobble shall be < 30 arcsec 3 sigma	< 15 arcsec (RSS) < 5 arcsec (RSS)
Position Uncertainty Tach pulses/rate control position accuracy ≤ 60 arcsec	50 arcsec (32 tach pulses / rev)
Stiffness First mode > 50 Hz (in GMI assy) Deployed First Mode > 6 Hz De-spin torsion > 7.6 Hz	60.8 Hz (GMI level test) > 7.6 Hz (GMI deploy test) > 7.8 Hz (GMI deploy test)
Mass 20.4 kg maximum	20.3 kg
Torque Margin 1.5x on known's, 2x on variables	0.87 MS
Operating and Non Operating Temperatures On-orbit Op: 0 to +50C Survival: -35 to +55C	10 to 15C Op
Design Life 38 months on-orbit op + 12 months I&T + 2.4 months op storage (2 yr @ 10%); total life reqmt 52.4 months	BAPTA 8 yrs. on-orbit to date, SRA and SMA Bearing Life Tests Begun

The rate control was measured independently with an optical encoder and compared to the tachometer/ resolver feedback data. In this way, we measured and compared the rate control of the drive as commanded and the resultant rate, by performing an interpolation between any 2 points in the sample

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland

data set, and calculating the error between the encoder and the resolver information for rate and position. The rate control and position knowledge of the drive was very good and well within the specified required accuracy. See Table 2 for SMA test results.

The current was monitored during GMI instrument level before and after environmental tests including vibration, acoustics, EMC/EMI, and TVAC testing. Figure 11 below shows a summary of the SMA motor current monitoring and trending during GMI instrument level testing. Characteristics to note are that the motor current is higher during ambient environment testing due to the air drag on the main reflector and reflector deployment assembly in the cleanroom. The motor current measurements also show that the bearing drag torque in vacuum is higher at cold temperature as expected and predicted. The variation in motor current at cold is due to cycling of the SMA operation heaters at or near cold operating temperature.

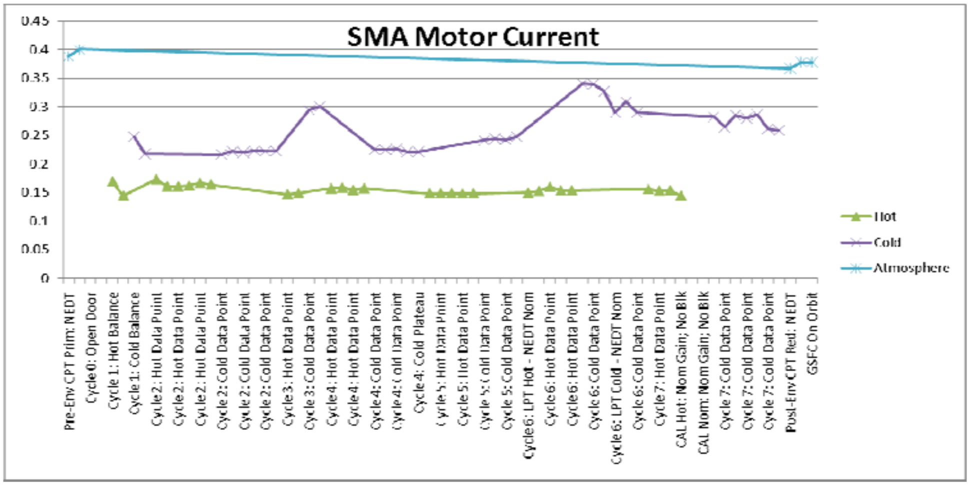

Figure 11. Summary of SMA motor current monitoring and trending thru GMI environmental test

Additionally, the SMA bearings and Slipring Assembly (SRA) have each begun a life-test program. The SMA bearings (3 preloaded bearing pairs) began testing Dec. 2010, see Figure 12. To date, the bearings have completed a survival temperature cycle, followed by 30 days of ambient operation, then 8 operational temperature cycles (1 day each at operating temperature extremes each cycle), 60 days back at ambient, and 30 days at each temperature extreme, all under vacuum and rotating at 32 rpm. That is just over 3.5 million revolutions or 3.4% of the total 104 million cycles (1.25x Flight Model total life) test objective. The test articles and test setups were all performing nominally for all the specified test conditions as initially planned.

Figure 12. SMA main bearings Life Test setup and preloaded bearing capsules (3 pairs)

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland

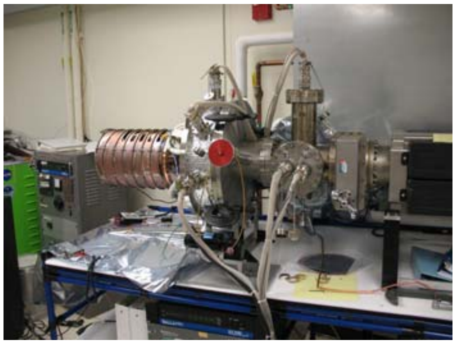

Figure 13. SRA life test Setup with the SRA Life-Test Unit (LTU) inside a small chamber ready for TVAC test

The SRA was configured in a vacuum and temperature controlled (TVAC) setup, see Figure 13, and began a life test in May 2011. This SRA assembly will also see one month of ambient operation, then one survival temperature cycle with 8 hour minimum dwells at the temperature extremes, followed by 8 thermal cycles to the operating temperature extremes (1 day dwell duration at each extreme) while rotating, and then 1 month at each temperature extreme before returning to 60 days running at ambient temperature before repeating.

However, during the first cycle cold it was discovered that the dewar/chamber being used to chill the SRA assembly was not functioning properly and could not achieve the cold survival temperature, or remain stable enough to meet requirements at the cold operating temperature for the duration of the test. So the decision was made to purchase another chiller for the chamber with more cooling capacity to meet the requirements with adequate margin for desired stability at both cold survival and operating temperatures. The new chiller has been installed and the SRA assembly has been taken cold and successfully completed the first cold survival cycle and 7 cold operating cycles to date.

The temperature profile and durations were designed to give roughly 80% of the revolutions at the on-orbit predicted temperature (essentially room temperature, in this case), 10% of the cycles at hot operating, and 10% of the cycles at cold operating by the EOL of the Life Test. It was also found to be very important to monitor and control the temperature gradient across the bearings and rotating to spinning elements in both the bearings and SRA life test units under test. The Life Tests are expected to run continuously for the next 5 years and accumulate approximately 104 million cycles or revolutions on each test article. It is possible that the Life Test may be extended beyond the projected life if the life test is successfully completed, in order to gain qualified Life Test data for similar longer life missions.

In October, 2011 the SMA bearing life test was briefly stopped for a few weeks due to an apparent increase in bearing torque of one of the bearing pairs. After further investigation it was found that the strain gage use to measure the bearing pair torque external to the housing was found to have become misaligned and broken, giving a falsely high torque reading, Figure 14 below. The decision was made to break vacuum, rework GSE setup, replace the strain gage, and restart the test. The Life-Test was restarted in late November, 2011 and has been running without incident since then.

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland

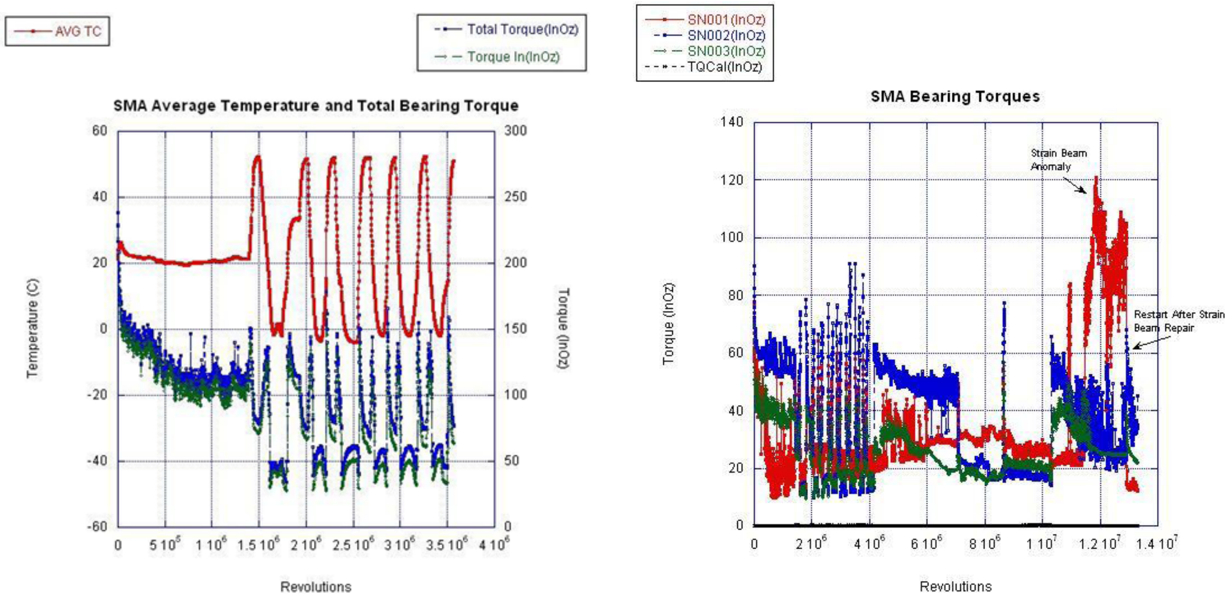

Figure 14. SMA main bearings life test temperature, bearing torque baseline over temperature, and total number of revolutions just prior to torque rise latter attributed to GSE strain gage

Figure 14 shows the average bearing temperature, total bearing torque, and torque measured going into the life test assembly over the revolutions completed to date [5], as well, as the faulty torque readings later concluded to have originated from a misaligned bracket and broken GSE strain gage in the SMA bearing life test setup.

Table 3. GMI Instrument and SMA vibration test and design analysis for launch environments

Random Vibration

Frequency (HZ)	ASD Level (g^2/Hz)	
	Qualification	Acceptance
20	0.010	0.010
20-50	+2.83 dB/Oct	+0.56 dB/Oct
50-800	0.024	0.012
800-2000	-2.83 dB/Oct	-0.56 dB/Oct
2000	0.010	0.010
Overall	6.0 G_{rms}	4.7 G_{rms}

Sine Vibration

Frequency	Limit Level	Protoflight/ Qualification Testing	Acceptance Testing
5-50 Hz	4.8g	6g	4.8g

Design Limit Loads

GMI Axis	Launch Vehicle Direction	Design Limit Loads (g)
X	Axial	10.0
Y	Lateral	8.0
Z	Lateral	8.0

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland

CONCLUSIONS AND FUTURE WORK

The SMA was integrated into the GMI instrument assembly, continued through the rest of the instrument final integration, and successfully completed all instrument-level performance and environmental testing including vibration testing, see Figure 15, to levels outlined in Table 3 above, at the end of January 2012.

The GMI instrument level vibration testing verified the stowed 1st mode frequency requirement. The SMA deployed stiffness was also measured and verified during the GMI Instrument level test program in the final flight configuration with the main reflector and Reflector Deployment Assembly (RDA) installed and deployed on the IBS, see Figure 16.

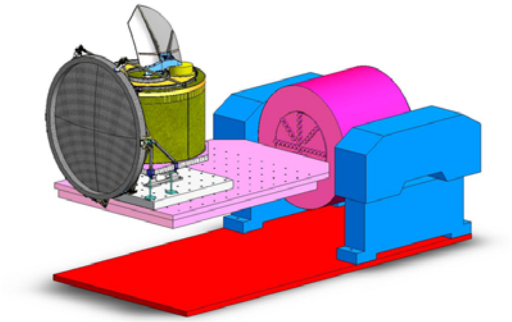

Figure 15. GMI Instrument during vibration testing on vibration test table in stowed configuration

The GMI instrument will also successfully completed a static and dynamic spin balance measurement and balancing program both in the cleanroom and in vacuum, to separate and eliminate the effects of air drag on the spin balance results. There has been extensive work done in this area and this subject alone is worthy of another paper in itself [6]. The GMI instrument was successfully completed, delivered to Goddard Space Flight Center in integrated onto the GPM spacecraft in early March, 2012.

Finally, the SMA Bearing and SRA Life Tests will continue for the next 4-5 years and updated status reports will be completed at least once a year until the completion of the tests, assuming the test data remains nominal until the tests are complete.

Figure 16. GMI Instrument during initial SMA Spin testing in Cleanroom with the reflector deployed

---

A special thanks to Sergey Krimchansky** of GSFC for his input over-seeing the technical work on GMI and for his support in writing these technical papers.

References

1. Newell, D., Rait, G., Ta, T., Berdanier, B., Draper, D., Kubitschek, M., Krimchansky, S. "GPM Microwave Imager Design, Predicted Performance and Status", *Proceedings of the 2010 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* Publication Date: July 25, 2010
2. Koss, S., Woolaway, S. "Lessons Learned From the WindSat BAPTA Design and On-Orbit Anomalies", *Proceedings of 38th NASA Aerospace Mechanisms Symposium*, Langley Research Center, May 2006.
3. Pierre, W. "GMI Spin Mechanism Structural Analysis", *BATC Internal SER Report No. 2307821B*, Ball Aerospace and Technologies Corp., Nov. 2008.
4. Dayton, C. "Slipring and SMA Bearing Lubrication Analysis", *BATC Internal SER Report No. 2242913D & 2241045D*, Ball Aerospace and Technologies Corp., Oct. 2008.
5. Hoffman, C. "Status of the GPM/GMI Bearing Life Test", *541/Materials Engineering Branch Memorandum No. MEB-2011-025*, Ball Aerospace and Technologies Corp., Apr. 2011.
6. Ayari, L. "GMI Rotating Mass Balance Uncertainty", *BATC Internal SER Report No. 2324813A*, Ball Aerospace and Technologies Corp., Jun. 2009.

---

*Ball Aerospace & Technologies Corp., Boulder, Colorado
**NASA NESC Goddard Space Flight Center, Greenbelt, Maryland