GLOBAL MICROWAVE IMAGER (GMI) SPIN MECHANISM ASSEMBLY DESIGN, DEVELOPMENT, AND PERFORMANCE TEST RESULTS

Michael Kubitschek(1), Scott Woolaway(1), Larry Guy(1), Chris Dayton(1), Barry Berdanier(1), David Newell(1), Joseph Pellicciotti(2)

(1) Ball Aerospace & Technologies Corp., PO Box 1062, Boulder Colorado 80306 USA, emails: mkubitsc@ball.com, swoolawa@ball.com, lguy@ball.com, cdayton@ball.com, bberdani@ball.com, dnewell@ball.com

(2) NASA NESC GSFC 8800 Greenbelt Rd. Greenbelt, MD 20771 USA, email: Joseph.W.Pellicciotti@nasa.gov

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 changes made to the WindSat BAPTA mechanism that is currently operating on-orbit and has recently surpassed 8 years of Flight operation.

1. INTRODUCTION AND REQUIREMENTS

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 Figure 1. The SMA design has to meet a challenging set of requirements and is based on 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].

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.

Figure 1. The completed Flight 1 SMA Assembly.
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 coupling 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 Figure 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. SMA Cross-section View.](image)

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. Table 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 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

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

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
(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].

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. One of the
findings of the WindSat anomaly investigation was that
the resolver excitation signals, in particular, are
somewhat susceptible to electrical signal noise which
can occur occasionally during slipping operation
resulting in electrical drops at the SRA brush to ring
contacts under the right operational and environmental
conditions [2].

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.

Figure 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. Figures 4 and 5 show the stowed and deployed structural analysis Finite Element Models (FEM) used for the stowed and deployed stiffness determination and the first modes, respectively.

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.

3. 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 (75 million revolutions) and reliable performance over the entire life, the bearings, bellows, and lubrication are just as critical to the ultimate success of the drive. Figure 6 shows a cross-section of the SMA.

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 7. 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; $K_t = 320 \text{ oz-in/amp}$, 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 8.

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 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°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 9.

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.
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.

4. INTEGRATION EXPERIENCEE, 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 10. 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 10. SMA mounted in test fixture to prepare for acceptance test in the clean room.](image)

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 11.

5. 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 11. SMA mounted in inertial test fixture and loaded into chamber for TVAC Testing.](image)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Measured / Tested Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rotation Rate /Control</strong></td>
<td></td>
</tr>
<tr>
<td>Rate shall be 32 / - 0.3% RPM</td>
<td>32 ± 0.1% RPM</td>
</tr>
<tr>
<td>Range shall be 0 – 33 RPM</td>
<td>0 – 33 RPM</td>
</tr>
<tr>
<td><strong>Spin axis</strong></td>
<td></td>
</tr>
<tr>
<td>Align to base shall be &lt; 75 arcsec</td>
<td>&lt; 15 arcsec (RSS)</td>
</tr>
<tr>
<td>Wobble shall be &lt; 30 arcsec 3 sigma</td>
<td>&lt; 5 arcsec (RSS)</td>
</tr>
<tr>
<td><strong>Position Uncertainty</strong></td>
<td></td>
</tr>
<tr>
<td>Tach pulses/rate control position accuracy ≤ 60 arcsec</td>
<td>50 arcsec (32 tach pulses / rev)</td>
</tr>
<tr>
<td><strong>Stiffness</strong></td>
<td></td>
</tr>
<tr>
<td>First mode &gt; 50 Hz (in GMI assy)</td>
<td>60.8 Hz (GMI level test)</td>
</tr>
<tr>
<td>Deployed First Mode &gt; 6 Hz</td>
<td>&gt; 7.6 Hz (GMI deploy test)</td>
</tr>
<tr>
<td>De-spin torsion &gt; 7.6 Hz</td>
<td>&gt; 7.8 Hz (GMI deploy test)</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td></td>
</tr>
<tr>
<td>20.4 kg maximum</td>
<td>20.3 kg</td>
</tr>
<tr>
<td><strong>Torque Margin</strong></td>
<td></td>
</tr>
<tr>
<td>1.5x on knowns, 2x on variables</td>
<td>0.87 MS</td>
</tr>
<tr>
<td><strong>Operating and Non Operating Temperatures</strong></td>
<td></td>
</tr>
<tr>
<td>On-orbit Op: 0 to +50C</td>
<td>10 to 15°C Op</td>
</tr>
<tr>
<td>Survival: -35 to +55°C</td>
<td></td>
</tr>
<tr>
<td><strong>Design Life</strong></td>
<td></td>
</tr>
<tr>
<td>38 months on-orbit op + 12 months</td>
<td>BAPTA 8 yrs. on-orbit to date, SRA and SMA Bearing Life Tests Begun</td>
</tr>
<tr>
<td>I&amp;T + 2.4 months op storage (2 yr @ 10%)</td>
<td>total life reqmt 52.4 months</td>
</tr>
</tbody>
</table>
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 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.

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 all have been performing nominally for all the specified test conditions.

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

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

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].

The SRA has been configured in a vacuum and temperature controlled (TVAC) setup, see Figure 13, and has just begun 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 dwell 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.

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.

6. CONCLUSIONS AND FUTURE WORK

The SMA has now been integrated into the GMI instrument assembly, will continue through the rest of the instrument final integration, and will be completing instrument-level performance and environmental testing including vibration testing, see...
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.

7. REFERENCES


