Design of the ATMS Scan Drive Mechanism

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Abstract

The Advanced Technology Microwave Sounder (ATMS) scan drive mechanism is a torque-compensating single-axis dual-mirror gimbal assembly. The scan drive mechanism will fly as part of ATMS on both NOAA's NPOESS (National Polar-orbiting Operational Environmental Satellite System) and NASA's NPP (NPOESS Preparatory Project). The ATMS, a weather monitoring instrument under development by Goddard Space Flight Center, measures microwave energy emitted by the atmosphere which aids weather forecasting. The material covered in this paper will focus on the mechanical design of the scan drive mechanism. The topics covered include the design features of the scan drive mechanism and the methods used to minimize the transmitted torque disturbances from the scan drive mechanism to the spacecraft.

Introduction

The ATMS scan drive mechanism is a single-axis continuous-rotation gimbal that feeds microwave frequency data into the ATMS instrument. The microwave data generated by the scan drive mechanism is used to develop layered maps of the Earth’s atmosphere by measuring the temperature and humidity at different altitudes. Figure 1 shows the orientation of the scan drive mechanism and ATMS instrument in flight and a composite plot of the temperature layers showing a developing tropical storm.

![ATMS Scan Drive Mechanism and Composite Plot](image)

Figure 1. ATMS scan drive mechanism flight pattern and data from earlier generation AMSU showing a tropical storm developing in November 2005. The ATMS Scan Drive Mechanism is the 3rd generation scanner to provide atmospheric temperature and humidity data from space for weather prediction.

The ATMS scan drive mechanism is the third generation in a family of scan drives that reaches back to 1978. The ATMS scanner offers a three times improvement over the current generation AMSU scanner in number of scans per orbit. For comparison, the first generation MSU scanner rotated one scan or one revolution over 25 seconds. The AMSU second generation scanner rotates one revolution every 8

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seconds, and the ATMS scan drive mechanism rotates one revolution once every \( \frac{8}{3} \) seconds. To achieve the improved scan rate, the ATMS scan drive mechanism inserts three periods of acceleration and deceleration into each revolution as shown in Figure 2.

Figure 2. Scan Drive Mechanism Scanning Pattern: When in scanning mode, the Scan Drive Mechanism rotates at a constant velocity through the Earth scan and the Cold and Hot calibration scans. It rotates with constant acceleration or deceleration between these scans.

As with every new design, there were things done very well in the scan drive mechanism and things that could have been improved upon if time permitted. In the category of things that were done well were the packaging design, the design for manufacturability, and the disturbance torque minimization features. One of the things we wished went better was the EMI/radiated susceptibility design and in a middle category (some good, some bad) was the bearing procurement and testing.

**Scan Drive Mechanism Design**

**Packaging and Overall Design.**

The overall envelope and packaging of the scan drive is in the category of things that went well. As can be seen in Figure 3 the scan drive mechanism needed to fit in a very compact space on the ATMS instrument. The space between the two reflectors had to house two motors, two resolvers, two pairs of bearings, and a flywheel. The details of packaging the components in this space are illustrated in the Figure 4 cross section. One unique feature that aided in packaging the gimbal in this small space was the use of single-string (non-redundant) motors and resolvers. The single-string main and flywheel motors were driven by redundant wiring and electronics but by making the motors non-redundant we were able to achieve higher torque margin in a smaller package than possible with a redundant winding design of the same size. The motors were also an ironless core construction, which used a significantly thinner stator than a conventional brushless DC motor.

As shown in Figure 4, the scan drive mechanism is made up of main and compensating subassemblies. The main subassembly rotates the reflectors while the compensating subassembly limits the disturbance torque into the instrument by driving a flywheel in the opposite direction. The scan drive mechanism can be driven in both a compensated and uncompensated mode. In the uncompensated mode, the flywheel is not powered and torque compensation is eliminated.

Weight was another key requirement that went well. The weight and other requirements for the scan drive mechanism are given in Table 1. To achieve the required weight, the reflectors and the main and compensating subassembly housings were made of beryllium. The reflector material selection was important for weight as well as inertia. The spherical shrouds around each reflector were made of 6061-T6
aluminum. Other materials were considered for the shrouds but aluminum was selected for both for weight and manufacturability.

Figure 3. The Scan Drive Mechanism mounted on the ATMS instrument illustrates the packaging challenge of this design. Two motors, two resolvers, two pairs of bearings, and a flywheel must fit in the center section between the two spherical shrouds.

**Design for Manufacturability.**
The scan drive mechanism design not only met very tight packaging goals and weight requirement but was created as a modular assembly that allowed assembly, disassembly (when required), and test as subassemblies. This approach provided schedule and work load flexibility during assembly and test. The modular design of the scan drive mechanism can be seen in Figure 5 where the main motor subassembly and compensation flywheel subassembly are on the work bench together. The subassembly approach also allowed for the separate balancing of the main assembly with the reflectors and the compensating assembly with the flywheel.

Fabrication of the spherical shrouds and a repeatable method of assembling and disassembling the shroud halves with the scan drive mechanism was another important manufacturing challenge. The shrouds attach to rings that have floating nut plates and locating pins for repeatable reattachment of the shrouds. The shrouds are split along a horizontal seam to allow removal of the upper shroud half during reflector alignment verification (see Figure 6). The shrouds are rough machined out of one piece of aluminum and then split along the horizontal seam. The spherical shape of shrouds provided a maximum view factor for each reflector and covered the warm calibration source inside the ATMS during earth scan.
Figure 4. Cross Section of the Scan Drive Mechanism illustrates compact packaging and materials selection used to meet weight and envelope requirements

Reflector Alignment
The reflectors mounted to the main shaft with titanium spiders that allowed axial and rotational alignment. The spiders attached to the shaft using tapered square holes to ensure repeatability of position during successive assembly and disassembly operations. In order to meet the required alignment, as shown in Table 1, there were shims between the spider and the reflector. The shims were pre-machined in thickness increments of 0.01 mm (0.0005 in). This shim kit allowed for rapid alignment of each reflector to the spin axis on a coordinate measuring machine (CMM). The CMM was used to define the true angle of the reflector relative to the spin axis by defining multiple planes whose normal vectors defined a cone. The upper half of the split shroud was removed during alignment to allow full access across the entire reflector.

Radiated Susceptibility
The cable harnessing and EMI design on the scan drive mechanism were things that fell into the category of things-not-done-so-well. Cabling is often one of the last features considered by mechanical designers and the scan drive mechanism was no different. The scan drive mechanism has two harnesses with connectors that extend a short distance out of the gimbal. Inside the gimbal the harness travels on the surface of the gimbal housing inside a cable tray. The harness was originally sheathed with braided shielding and the surfaces of the cable tray and gimbal housing were coated for conductivity. Despite these seemingly normal precautions, the scan drive mechanism dramatically failed the first radiated susceptibility test. Instead of providing a required 60 dB of attenuation in the 1 to 4 GHz frequency range, the scan drive mechanism harness and shielding were effectively acting like an antenna.
Table 1. Requirements and capability for the ATMS Scan Drive Mechanism – to achieve a 3x increase in the scan rate, the single-axis SDM is accelerated and decelerated between measurement and calibration scans

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
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<tbody>
<tr>
<td>Scan profile period</td>
<td>8/3 seconds</td>
</tr>
<tr>
<td>Reflector to Scan Axis misalignment</td>
<td>&lt;10mdeg</td>
</tr>
<tr>
<td>Earth View Sector Control Accuracy</td>
<td>+/- 35mdeg</td>
</tr>
<tr>
<td>Disturbance torque into spacecraft</td>
<td>&lt;0.003 N-m between 0.01 and 1.0 Hz</td>
</tr>
<tr>
<td></td>
<td>&lt;0.1 N-m above 33 Hz</td>
</tr>
<tr>
<td>Torque capability</td>
<td>function under 3X worst case drag</td>
</tr>
<tr>
<td>Life (continuous service)</td>
<td>11 years</td>
</tr>
<tr>
<td>Mass</td>
<td>&lt;10.9Kg</td>
</tr>
<tr>
<td>Average Power</td>
<td>&lt;13W</td>
</tr>
</tbody>
</table>

There were numerous causes for the radiated susceptibility failure:
1. The beryllium housing halves and cable tray were attached with fasteners spaced too far apart and there were no provisions for EMI gaskets (the gaps were radiation sources).
2. There were no provisions for terminating the harness shield to the cable tray or to the entry into beryllium housing necessary to make a continuous Faraday cage.
3. The beryllium housing mesh air vent was installed with non conductive RTV – an ungrounded air vent can propagate RF energy.
4. The harness inner shield was tied to the outer shield inside the connector backshells - both shields terminated at one end can act as an RF antenna.
5. Motor and resolver harnesses were routed together providing coupling paths inside the harness.

Unfortunately these shortcomings were not uncovered until late in the testing program and schedule did not permit major design changes to fully correct the problem.

The fixes as shown in Figure 7 consisted of caulking the cable tray and housing halves with silver-filled epoxy, using silver-filled epoxy to ground the vent screen, and wrapping the harnesses with copper foil over the braided shielding. These fixes fell short of the required 60-dB attenuation, but fortunately the requirement was lowered to 40-dB attenuation and the reworked scan drive mechanism passed the radiated susceptibility test. The painful lesson from this experience is that every wire harness and EMI task is not necessarily similar to the last design and a quick discussion with a subject area expert can save weeks of time.
Figure 5. Torque compensation flywheel. The torque into spacecraft due to accelerating and decelerating the reflectors is compensated for by active control of the counter rotating flywheel. The flywheel inertia is lower than the inertia of the rotating reflectors so the flywheel is accelerated at the inertia ratio times the changing rotation rate of the main rotating assembly.

Figure 6. Upper half of Scan Drive Mechanism shroud is removed to verify alignment of reflectors and rotation center before and after each environment.
Gimbal Bearing Handling
The manufacturing handling of the gimbal bearings was good news, bad news story. On the plus side, bearing torque characterization tests were implemented as part of the manufacturing plan to detect torque irregularities. On the down side, the bearings did not have sufficient cleanliness controls. The bearings in the scan drive mechanism were designed for a life of 130 million revolutions for the reflector shaft bearings and 230 million revolutions for the flywheel bearings. Cleanliness of the bearings and lubricant was absolutely essential to achieve bearing life and smooth torque performance. Fortunately, we had a bearing torque test after the bearings were installed in the gimbal and on the third scan drive mechanism we found a noisy torque trace on a flywheel bearing duplex pair and on closer inspection we found debris in the bearing. The most likely sources of debris were:

1. Metallic debris was found and was most likely from tooling used for torque testing at the supplier. Inspection of the supplier tooling found metallic debris in threaded holes on the tooling.
2. White fibers were found and were most likely from cleanroom wipes or hair bouffants.

Although disassembly and replacement of the bearing was a painful schedule hit, the bearing contamination was caught before entering acceptance test. None of the other gimbal bearings ever showed erratic torque performance and a recommended cleanliness program was implemented by our bearing supplier to eliminate future contamination. Figure 8 shows our bearing torque set-up and samples of the debris found in the bearing.

![Image](image_url)

**Figure 7.** During radiated susceptibility testing in the 1 to 4 giga-Hertz frequency range, the scan drive mechanism harnessing acted as an antenna causing interference with the ATMS receivers. Various fixes were implemented to reduce the interference but adding the right EMI features earlier in the design process would have worked better.
Figure 8. Contamination was found in the flywheel bearing of flight unit 3. The in-situ bearing torque test was invaluable at identifying bearing problems during the assembly of the gimbal. Fortunately disassembly features were built into the design of the scan drive mechanism.

**Disturbance Torque Reduction.**
Torque reduction was an aspect of the scan drive mechanism that went well. The level of torque disturbance allowed by the scan drive mechanism as shown in the Table 1 is less than 0.027 in-lb (0.003 N-m) across the 0.01 to 1.0 Hertz frequency range. To achieve this level of quiet operation, a number of disturbance reduction techniques were required. The first was to use a counter-rotating flywheel to compensate for the torque disturbance caused by accelerating and decelerating the reflectors three times each scan rotation. Other techniques used to achieve quiet operation included accurate balancing both the main antenna rotation assembly as well as the flywheel, and careful selection of parts including low run-out bearings and low cogging motors for both main and flywheel assemblies.

One of the primary reasons for designing the scan drive mechanism as two subassemblies was to allow access for balancing the main reflector rotation subassembly and flywheel compensation subassembly. In Figure 5, radial and axial threaded holes for balance weights can be seen on the flywheel subassembly. The balance weight holes were filled with set screws as required to achieve a 80,935 g-mm² (4.4 oz-in²) dynamic balance and 216 g-mm (0.3 oz-in) static balance. Figure 9 illustrates the features on each reflector shroud that allowed balancing of the main shaft and reflector subassembly. The main subassembly was difficult to balance due to the cutout in the shroud for reflector viewing. The cutout was balanced by placing a tungsten weight on the hole side of the reflector assembly. Several other smaller masses were added around the shrouds to account for other inconsistencies in geometry. The main subassembly was balanced to the same level as the flywheel subassembly.
Figure 9. To minimize uncompensated torque disturbances, balancing features inside each shroud allowed dynamic and static balancing of the rotating main assembly.

One of the unique features of the scan drive mechanism was the counter-rotating flywheel used to minimize the torque generated by accelerating and decelerating the reflector each scan cycle. The scan drive mechanism acceleration/deceleration pattern (Figure 2) shortened the scan period and increased overall gap coverage but generated undesirable torque disturbances. The counter-rotating flywheel cancelled 92% of the torque from the reflector acceleration profile. The success of this approach is shown in Figure 10 where the scan drive mechanism was run both with and without the flywheel compensation.

Pointing Performance
The final link in the scan drive performance was the earth scan pointing. Pointing performance success was a combination of mechanical alignment and motor and resolver selection. As noted the brushless DC motor was a low-cogging ironless-core design which resulted in very low torque ripple. The main motor and reflector assemble position was controlled by a 64-speed and single-speed brushless resolver. The resulting pointing performance is shown in Figure 11.
Figure 10. Reaction torque cancellation is successful with the compensation flywheel motor on. The Scan Drive Mechanism can operate in reduced mode (greater torque disturbance) using only the main motor.

Figure 11. The Scan Drive Mechanism meets the ultimate test of pointing accuracy for earth scan as well as during hot and cold calibration. Acceleration/deceleration periods offer the ability to provide more earth scans per orbit.
Acknowledgements

Every successful major project results from the combined efforts of many people. It is with great regret we don’t have the space to list all of the many people who contributed time, effort, and talent to the ATMS Scan Drive program. None-the-less, most of those who participated in the Scan Drive program would agree that the following people were key to the success of the mechanism part of the program. Goddard Space Flight Center: Sergey Krimchansky, Robert Lambeck, Rick Schnurr; Northrop Grumman Electronic Systems: Dennis Lord, Terry O’Brien; Lockheed Martin: Ed Boesiger, Caesar Ching, Jeff Fisher, Patrick Herbert, Stu Loewenthal, A.J. Maher, Larry McGovern, Gordon Smith, Nic Mercer and Julie Price.

References

2) AMSU temperature plots: http://pm-esip.msfc.nasa.gov/amsu/