

TWO-AXIS ANTENNA POSITIONING MECHANISM

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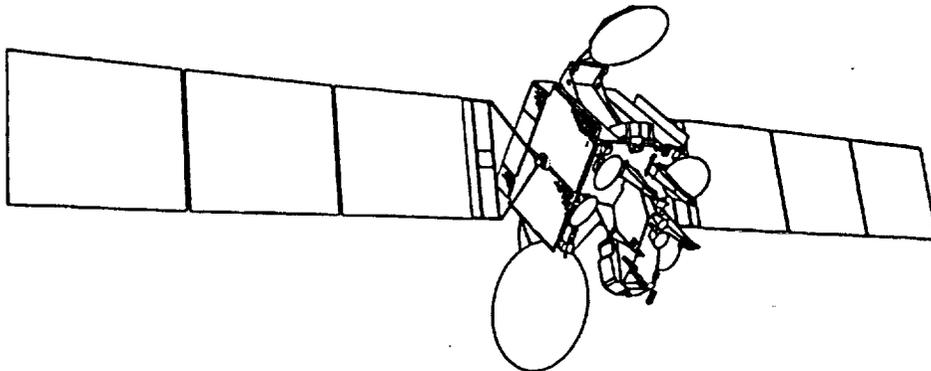
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ABSTRACT

The Two-Axis Antenna Positioning Mechanism (TAAPM) is used to position three Ku- and one C-band spot antennas on the INTELSAT VII (I-VII) spacecraft, which is a commercial telecommunications satellite purchased and operated by INTELSAT, an international consortium. The first I-VII was successfully launched on 22 October 1993 from French Guiana on an Ariane launch vehicle. All TAAPMs on the first I-VII satellite successfully completed their in-orbit functional testing.

The TAAPM was an entirely new design for Space Systems/ Loral. This paper will describe the spacecraft/ system requirements and application of the TAAPM, and present the technical findings of TAAPM qualification and protoflight testing.

**1.0 DESCRIPTION**

The TAAPM is used to position the spot antennas in two axes. The following describes the spot antenna subsystem and the TAAPM.

1.1 SUBSYSTEM DESCRIPTION

The antenna sub-system consists of (see Figure 1):

- a) Antenna: spot beam reflector, feeds, antenna structure
- b) Spot holddown
- c) TAAPM
- d) Waveguides
- e) Thermal blanketing (not shown for clarity)

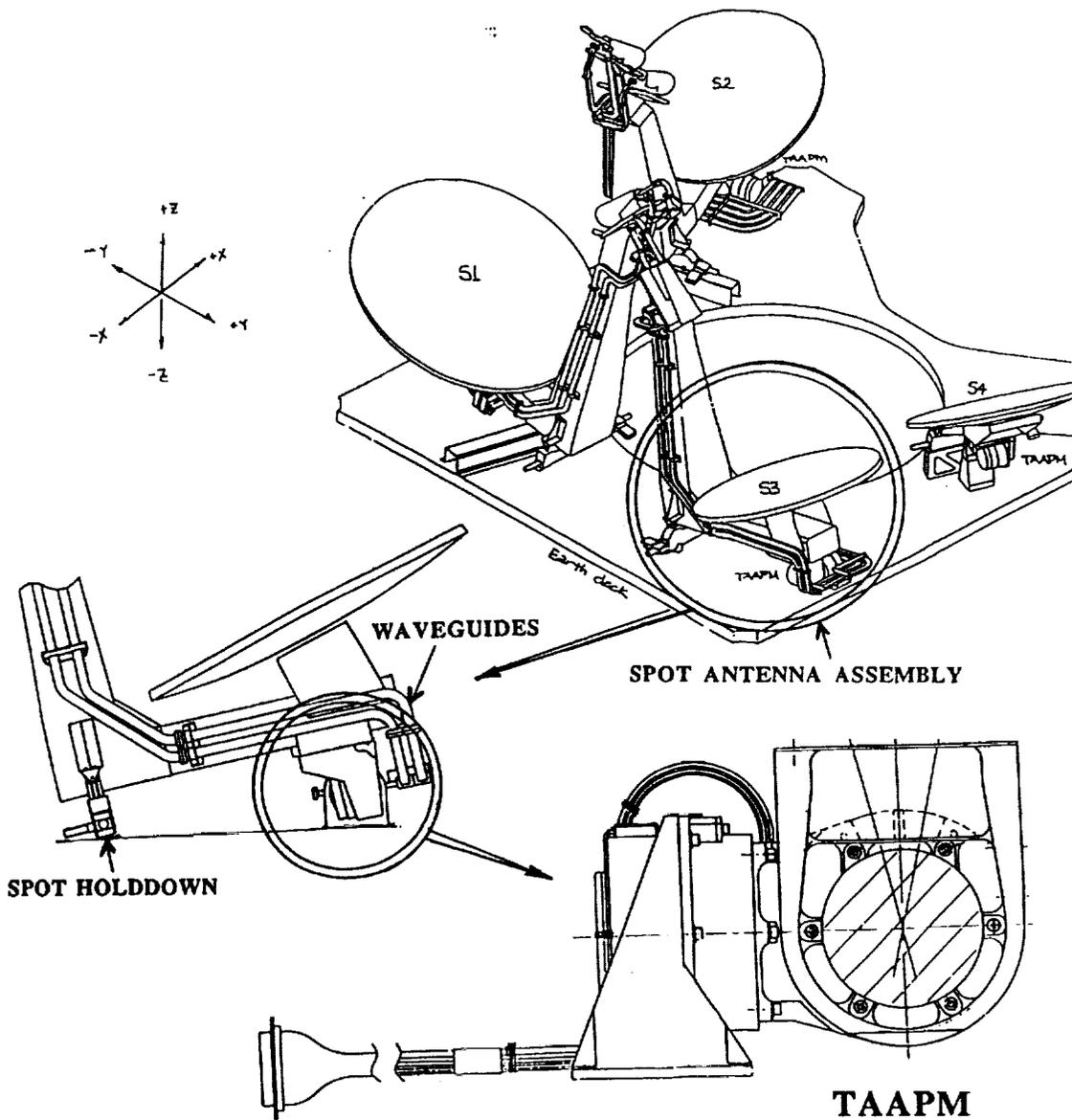


Figure 1. Spot antenna sub-system and TAAPM

During launch, the antenna is held securely in two places with the spot holddown, which absorbs the majority of the launch loads. When geosynchronous orbit has been achieved, the holddowns are released and the antenna is positioned by the TAAPM.

This configuration of TAAPM, antenna, and holddown is used during dynamic testing to verify the structural integrity of the TAAPM under simulated launch loads.

Each axis of the TAAPM is independently controlled by the Spacecraft Control Electronics (SCE) to position the antenna to point anywhere on the earth disk. The first axis (nearest the earthdeck) is the elevation actuator for antenna pitch (S1 and S3 antennas). The second axis is the azimuth actuator for antenna roll. The S2 and C-spot antennas are not aligned with spacecraft axis and therefore require conversion from pitch and roll to azimuth and elevation.

1.2 TAAPM DESCRIPTION

The TAAPM consists of two orthogonal rotary actuators and three brackets. Position telemetry is provided by redundant potentiometers in the rotary actuators.

1.3 ROTARY ACTUATOR DESCRIPTION

The rotary actuators are procured from an outside vendor and are integrated into a TAAPM assembly at Space System/ Loral. The rotary actuators are extensively tested at the vendor and at the TAAPM assembly level.

Each rotary actuator consists of a redundant three-phase 1.5-degree stepper motor, a 160:1-ratio harmonic drive gear reducer, a duplex bearing pair at the output, one coarse and two fine potentiometers. This configuration provides an output of 0.009375 degree/ step.

The fine potentiometers are coupled to the stepper motor through a 1.5:1 ratio such that each step can be resolved. The coarse potentiometer is coupled to the output to determine the cycle of the fine potentiometers so that the antenna position is given unambiguously.

2.0 SYSTEM REQUIREMENTS/ APPLICATION

The TAAPM performance requirements are derived from:

- System pointing requirements
- System pointing error budget
- Torque Margin
- Structural loads during launch
- Thermal environment on-orbit
- Modal analysis (frequency and stiffness)
- Telemetry requirements

2.1 Pointing requirements

Pointing requirements are essential to providing accurate and timely coverage for INTELSAT customers. All spot antenna TAAPMs are

commanded from the space control center at INTELSAT headquarters in Washington, D.C. Customers depend on the spacecraft's ability to give instant accurate coverage, especially in remote locations around the world. The Ku- and C-band spot antenna TAAPMs provide a significant part of that capability.

2.2 Pointing Error Budget

The pointing error budget consists of various spacecraft characteristics which include the pointing capabilities of the TAAPM. The following is a breakdown of the mechanism contributions. Unit and system level ground testing have proved the TAAPM parameters fall well within this allocation.

<u>Pointing Error Source (degrees)</u>	<u>Budget</u>	<u>Actual</u>
Fine potentiometer backlash/ hysteresis	0.005	0.002
TAAPM backlash/ hysteresis	0.028	0.026
Potentiometer voltage accuracy	0.015	0.004
Potentiometer voltage (SCE)	0.000	0.005
TOTAL	0.048	0.037

2.3 Torque Margin

The TAAPM must provide sufficient torque to move the antennas, waveguides, and thermal blanketing at any temperature within the predicted temperature extremes. The torque provided must exceed the resistances by a ratio of 3 to 1.

2.4 Structural Requirements

The structural requirements are derived from the coupled loads analysis which determined the worst-case accelerations on both the Ariane and Atlas launch vehicles. The TAAPM was designed to withstand loads greater than 1.3 times the predicted flight loads.

The protoflight and qualification TAAPMs were proof load tested to the appropriate static loads without failure. All units are vibration tested to levels which meet or exceed the launch environment. Sine vibration levels are based on the quasi-static accelerations; random vibration levels are based on acoustic noise levels measured during acoustic testing performed on the protoflight units. These tests have verified the TAAPM meets the structural requirements.

2.5 Thermal Requirements

The temperatures predicted for the TAAPMs were derived from the thermal model of the spacecraft, which yielded the maximum and minimum temperatures expected during the operating lifetime. Margins have been added to the predicted temperatures to obtain test limits.

Temperature limits are:

- Operating: -50°C to +80°C
- Non-Operating: -60°C to +85°C

2.6 Frequency/ Stiffness Requirements

To avoid dynamic coupling with the spacecraft control system during launch, a structural frequency goal of 50 Hz was established. This frequency was used to design the TAAPM brackets for sufficient stiffness, and to obtain minimum axial, radial and moment stiffnesses of the rotary actuator, which governs overall TAAPM stiffness.

Dynamics testing performed on the first three flight sets has demonstrated that the antenna/ holddown/ TAAPM system has a primary mode between 50 and 55 Hz. This mode is primarily due to the antenna structure and holddown, independent of the TAAPM. The structural model predicted 51 Hz, giving good correlation to test results.

2.7 Telemetry

Position telemetry is provided by the output of the redundant fine potentiometers, which vary from 0 to 5 volts, repeating every 150 steps. The cycle number of the fine potentiometer is determined by the coarse potentiometer which spans the whole range (~26°) in less than 5 volts. The voltage/ angle calibration is performed during final functional testing performed at the TAAPM level. Temperature telemetry is provided by thermistors.

3.0 TESTING

The overall test program consists of qualification, protoflight, and flight acceptance testing. Qualification testing was the most extensive, including testing for stiffness, strength, detent torque, running torque, and stall torque to verify structural models and to confirm vendor data taken at the rotary actuator level. Due to schedule constraints, the protoflight units were required before the qualification unit could be fully tested. As a result, the protoflight units underwent extensive testing, approximately equivalent to qualification. The data gathered during protoflight testing was evaluated to determine which tests were appropriate for the acceptance units.

3.1 TEST METHODS

To characterize TAAPM performance, unique test methods were required. These test methods allowed testing to be performed in two axes without reconfiguring.

3.1.1 Tiltsensor

To accurately meet the TAAPM pointing requirements, a precise calibration of potentiometer voltage to angle is required. Several alternatives were investigated: optical encoders, laser interferometers, and tiltsensors. The tiltsensor was chosen for the following reasons:

- The ability to accurately (<.005°) measure angles in two axes with one unit
- Alternatives could not be used under thermal-vacuum conditions without costly modifications
- Low technical skill level required to use (no alignments)
- Lowest cost

The tiltsensor is an electrolytic device that uses a conductive fluid contained in a glass tube similar to a bubble level. The tiltsensor used for testing TAAPMs is a biaxial device: one unit contains two independent, orthogonal tubes. When the tube is tilted the bubble movement causes a resistance change that changes a voltage output which is read by a processor. The output voltage of the processor is correlated to an independent angle measurement device (such as a laser interferometer) to obtain a voltage vs. angle calibration of the unit (in the form of a data file, a.k.a. conversion file). In use (after calibration), the processor voltages are translated into angular data through the conversion file.

The accuracy of the tiltsensor is primarily affected by two variables: temperature and settling time.

TEMPERATURE: Since the tiltsensor consists of liquid metal that has a high coefficient of thermal expansion, the temperature must be tightly controlled to achieve consistent results. To maximize accuracy at ambient conditions, the temperature must be controlled within 26.00 ± 0.005 °C. To achieve temperature control, a heating/ cooling system utilizing a thermo-electric device (Peltier effect) was added to the tiltsensor.

Tests performed on the first four TAAPMs under thermal-vacuum conditions indicated that the temperature could not be controlled well enough to consistently obtain meaningful data. Also, exposure to temperature permanently damaged several tiltsensors.

At this point, it was decided to eliminate the use of tiltsensors under thermal-vacuum conditions. This decision was partially validated by comparing the step count vs. potentiometer voltages at ambient and temperature conditions: the differences were insignificant. Also, ambient and thermal-vacuum data taken with one particularly robust tiltsensor indicated no significant angular differences under temperature.

SETTLING TIME: When the tiltsensor is tilted, the liquid metal moves to become level. The momentum of the liquid particles causes "sloshing" about the true-level position. Eventually, the damping of the liquid allows equilibrium near the true-level position. The amount of time required to obtain measurements within a certain error band is called the tiltsensor "settling time".

An experiment was performed using a TAAPM, a laser (to measure angle precisely) and a tiltsensor set at various settling times. The results indicate that:

- Optimum settling time was unique to each unit
- Units possessed repeatable error that was location dependent
- Settling time was sufficient at approximately 2.5 seconds/step.

The location-dependent error was determined to be related to the tiltsensor hysteresis. This error is caused by slight imperfections in the glass tube or electrodes, which react to the surface tension of the liquid. The tiltsensor hysteresis has been fairly repeatable to less than 0.03 degree. This number is greater than the accuracy required of the measurement, which is 0.005 degree. However, the tiltsensor hysteresis only effects the data when comparing data from two different directions. The tiltsensor has shown to be repeatable when coming consistently from the same direction.

3.1.2 Inertia:

There are three loads the TAAPM must drive: the bending resistance of the flexible waveguide, the resistance of thermal blankets, and the inertial load induced by the mass of the antenna. To correctly simulate loads, testing was performed with waveguide simulators and an inertia simulator. Thermal blanket resistances were determined to be insignificant and were not simulated.

To simulate inertia without inducing gravity effects for a two-axis unit is not straightforward. To obtain the correct inertia, a lumped mass is used with a moment-arm. It is desirable to minimize the required weight of the lumped mass to minimize the reaction force on the unit, which is not present in zero g. However, due to limited volume available in vacuum chambers, a large mass with a small moment-arm was necessary. This required that the mass be off-loaded with a three dimensional off-loader (see Figure 2).

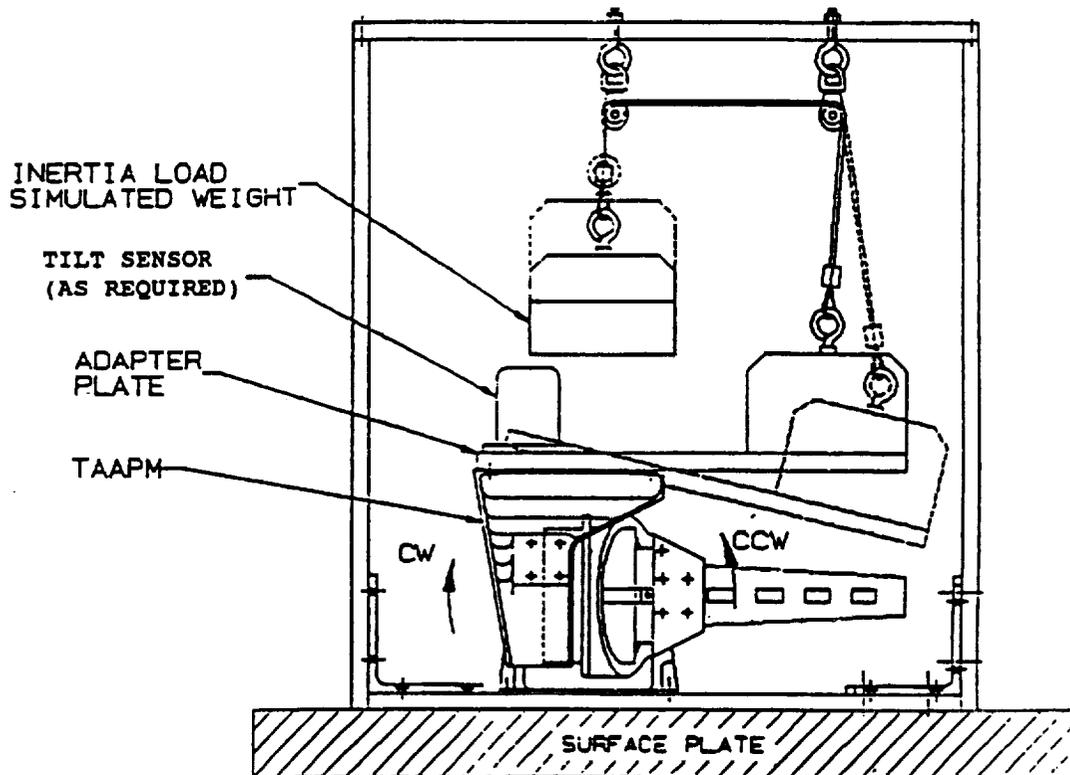


Figure 2. TAAPM Inertia Load Test Setup

Testing performed on the first four units showed much higher hysteresis (friction) than expected. The test set-up was evaluated, and as often is the case, the test fixturing was the culprit. The inertia simulator off-loader was fabricated using commonly available sleeve pulleys. When the pulleys were changed to high quality ball bearings the friction dropped nearly 80%, to levels which were acceptable.

Even with the modification mentioned above, there were consistent differences in measured torque according to direction of travel. Tests performed without inertia simulators showed no directional bias, indicating that the raising and lowering of the weight was affecting the measured data.

The approximate magnitude of the inertially induced torque (in zero g) was calculated, and was very small, less than 0.1 N·m. Since the inertia simulator was clouding the data, and the inertia effect in-orbit is very small, the use of inertia simulators has been abandoned.

3.1.3 Torque Margin

The torque margin¹ of the TAAPM is required to be greater than 3.0 for any operating condition. Measuring the torque margin (torque output/resistance torque) of a single-axis rotational device is simple to do with a torque transducer; however, with a two-axis device a direct torque measurement is not possible.

An indirect method of determining the torque margin was developed: for each rotary actuator, the torque versus voltage relationship was measured (see Figure 3). During testing, the minimum voltage required to drive the load without skipping steps was determined (threshold voltage). Using the torque vs voltage plot, the torque corresponding to the threshold voltage is determined; this torque is compared to the torque available at the nominal operating voltage, derated to correspond to spacecraft end-of-life voltage (23V). The ratio of the torque at 23V to the torque at the threshold voltage is the torque margin.

Example: Torque Margin = $\frac{26 \text{ N}\cdot\text{m (at 23V, end-of-life)}}{2.8 \text{ N}\cdot\text{m (at ~11V, threshold)}} = 9.2$

3.2 TEST RESULTS

3.2.1 Potentiometers

ROTARY ACTUATOR TESTS

During rotary actuator level testing, two significant potentiometer anomalies were revealed. The first was a coarse potentiometer voltage shift

¹ Torque margin is a misnomer. In this case, the torque margin is defined to be a ratio of available torque to resistance torque, which is not the same as "margin".

at neutral position (center of travel). The second pertained to voltage dropouts seen after random vibration testing.

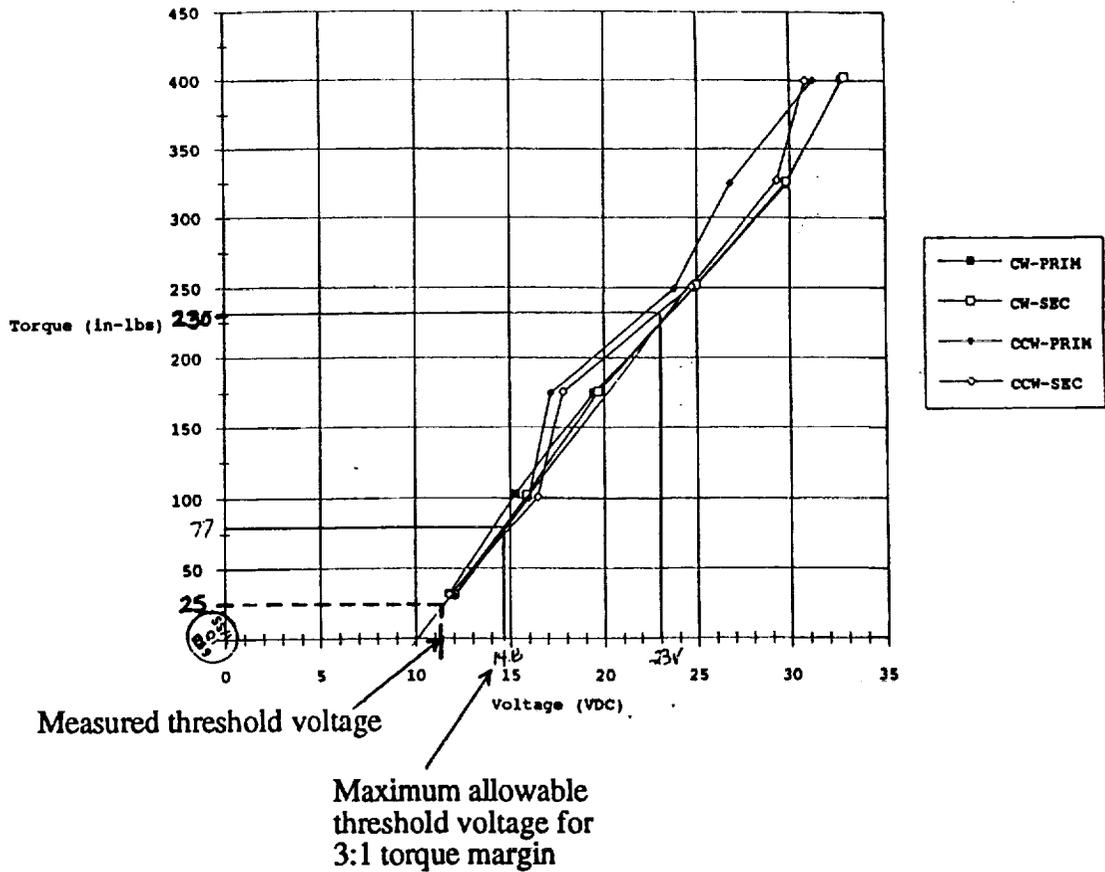


Figure 3. Rotary Actuator Torque versus Voltage Curve

Coarse potentiometer voltage shift

The rotary actuator is "calibrated" during assembly to obtain a potentiometer voltage corresponding to the neutral position. The test specification required the coarse potentiometer voltage to be 2.5 ± 0.025 VDC at neutral. During testing, the coarse potentiometer voltage varied from the calibrated neutral position as much as 0.046 VDC.

An extensive design and statistical data analysis was performed, as well as a physical inspection and some investigative testing. The following possible sources for the coarse potentiometer voltage variations were considered:

- shaft to front housing interface
- shaft to coupler interface
- coupler to potentiometer shaft interface
- mechanism internal to potentiometer
- potentiometer housing to motor housing interface

- motor housing to retainer interface
- harmonic drive hysteresis
- fine potentiometer gear mesh
- harmonic drive flexcup to front housing interface
- external equipment error

The analysis pinpointed the source to the potentiometer coupler to shaft interface, which allowed the greatest amount of relative motion. Because this interface was difficult to redesign, the voltage tolerance requirement was revisited.

One revolution of the fine potentiometer is equivalent to a 0.21 VDC change in the coarse potentiometer voltage. The neutral position coarse potentiometer tolerance was opened to ± 0.100 VDC, which still accurately determines the fine potentiometer revolution and provides an acceptable test limit that all actuators can meet.

Voltage dropouts

After three axes of random vibration, the qualification rotary actuator exhibited coarse potentiometer voltage dropouts (seen on strip chart recordings). The dropouts were attributed to the dithering between the potentiometer wiper and element caused by the shaft to coupler interface movement during vibration testing. It is believed that the dropouts are a discontinuity caused by debris generated during the vibration dithering. These dropouts were diminished and eventually "wiped" away with subsequent operation of the rotary actuator.

The vibration levels were re-evaluated and lowered based on recently acquired spacecraft test data. Subsequent testing at the lower levels was successfully completed without any dropouts.

TAAPM TESTS

At TAAPM-level testing, potentiometer voltage dropouts resurfaced. There were dropouts noted after vibration as well as during cold thermal-vacuum testing. In both cases, the dropouts were eliminated by continued operation of the TAAPM through the regions affected.

During vibration in the antenna subsystem configuration, the coarse potentiometer receives the worst loading since it is tied to the output of the TAAPM while the fine potentiometers are geared to the motor input and see less "free play".

After vibration testing, the TAAPM goes through non-operational and operational thermal cycles to simulate the space environment. During operational testing, the potentiometers are monitored by a strip chart recorder. Dropouts were seen on these strip charts and detected by test software problems due to inconsistent voltage readings. The worst dropouts were seen during the qualification life testing at cold temperature.

A combination of vibration exposure and difference in the coefficient of thermal expansion between debris and/or the materials of the potentiometers appears to cause the dropouts. At cold temperature there seems to be a greater mismatch. Once the TAAPM is returned to ambient or hot temperatures, the dropouts disappear.

3.2.2 Resolution Step Size/ Repeatability

Step size is defined as the angular movement of one step. Repeatability is the angular difference between two measurements of the same step location. The rotary actuator step size varies cyclically throughout the range of motion due to the design of the harmonic drive (see Figure 4). The rotary actuator vendor maximizes the accuracy of the step size by positioning the harmonic drive to have the range of motion in the best area of the harmonic drive accuracy curve.

For on-orbit pointing, the angular repeatability of the step position over the range of motion is more important than the size of each individual step. Test results indicate very good repeatability, typically less than the magnitude of one step (~0.010 degree).

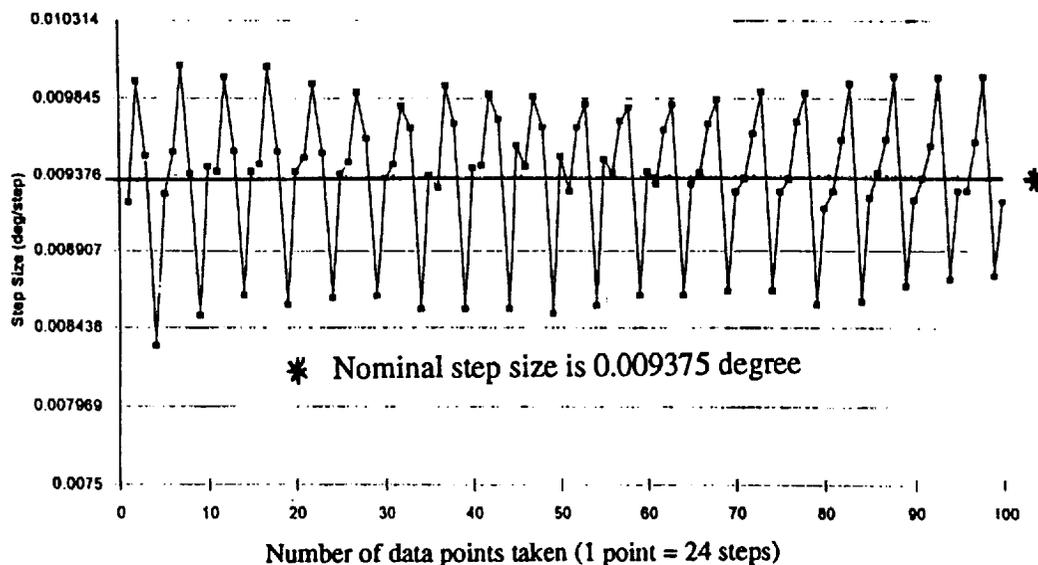


Figure 4. Typical cyclic step size variation over Rotary Actuator range of motion

3.2.3 Hysteresis

TAAPM hysteresis is measured as the total difference in step readings when approaching a given position from opposing directions. Tiltensor hysteresis made quantifying actual mechanism hysteresis very difficult (see paragraph 3.1.1 Tiltensor). The TAAPM hysteresis is primarily comprised of the harmonic drive flexibility, potentiometer and waveguide effects.

Although the harmonic drive design offers essentially zero backlash, a disadvantage arises in positional hysteresis. The flex spline of the harmonic drive acts as a spring and tends to wind up when driven into a stop. This wind up causes a step versus position error. Since antenna positioning is estimated by step counting, whenever a stop is hit, this error must be taken into account. Tests show this error to be ~ 0.026 degree. Potentiometer error is ~ 0.002 degree, while the waveguide hysteresis is ~ 0.01 degree.

3.2.4 Vibration

The antenna subsystem, consisting of antenna, holddown and TAAPM has a resonance near 50 Hz. To obtain realistic vibration loads, the TAAPM is vibration tested using an antenna simulator and a flight holddown.

Sine vibration testing attempts to simulate quasi-static launch loads. The quasi-static loads (for example 10.0 g lateral) are basically achieved in the low frequency region of the vibration test, near 20 Hz. Above 20 Hz, the sine input excites resonances, which are not necessarily part of the launch environment being simulated. To address this shortcoming of the test, the input can be limited such that the flight expected loads are not exceeded.

During the TAAPM vibration testing curious behavior occurred while limiting the input. The system resonance was so abrupt that the input could not be controlled. This behavior was characterized as being very non-linear: the resonance did not normally drop off with increasing frequency, but dropped off abruptly, as shown in Figure 5. This type of behavior is associated with the dynamic behavior of mechanical gaps or dead-bands.

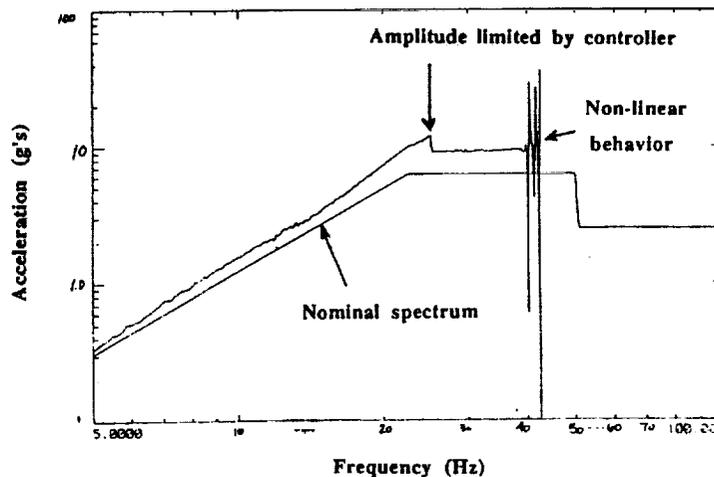


Figure 5. Spot Antenna Feed Response During Sine Vibration

The design of the holddown was thoroughly evaluated: there were several areas which contained excess free-play (slop). The design was

revised to eliminate the free-play, and vibration testing was repeated without further anomaly. The system still has a 50 Hz resonance; however, the magnitude of amplification is greatly reduced.

As a result of testing in the "subsystem" configuration, this design oversight was able to be corrected early in the test program, before the components were integrated to the spacecraft. The interactions of various elements of a system can not always be predicted, which necessitates a thorough system/subsystem test plan.

3.2.5 Torque margin

Torque margin was highest at cold temperatures. Even though the waveguide stiffness and internal frictions increase with cold temperature, the motor develops more torque due to the decrease in winding resistance and resulting increase in current.

Duty cycle has a pronounced effect on output torque of the unit: full rated torque can only be developed at 100% duty cycle. The TAAPM is normally operated at 57% duty cycle for power and thermal reasons. Full torque is not realized at 57% duty cycle because the motor reverts to detent torque during the 43% off portion of the pulse. The result is that above a certain voltage, torque does not linearly increase with increasing voltage. This result is shown in Figure 6.

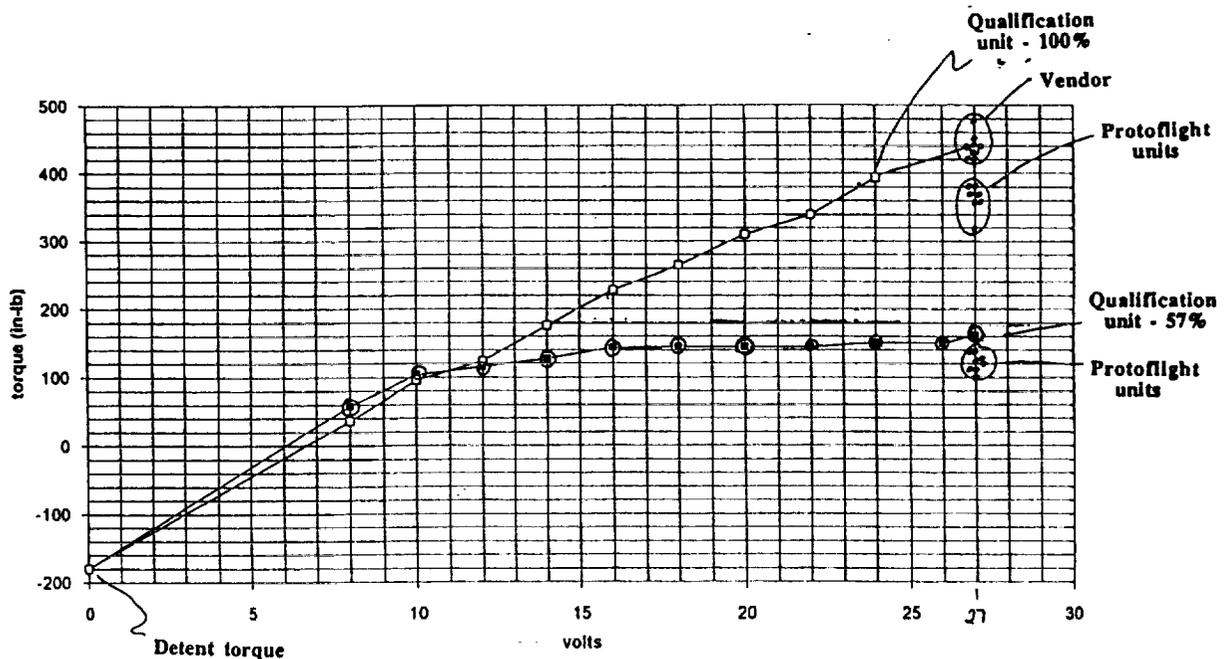


Figure 6. Torque versus Voltage at 57 % and 100% duty cycle

3.3 SPACECRAFT TESTING ISSUES

At system level, antenna pointing, TAAPM range of motion and torque margin are verified at ambient and worst-case thermal-vacuum conditions. In order to verify the spot antenna/ TAAPM performance, an off-loader is required to react the large gravity moments induced by the antenna. Since the center of gravity of the spot antenna is not located on the structure but at a point in space (see Figure 7), an off-loader was difficult to design. On the S2 spot antenna, off-loader design was compounded by the requirement for movement at an odd angle to the gravity vector.

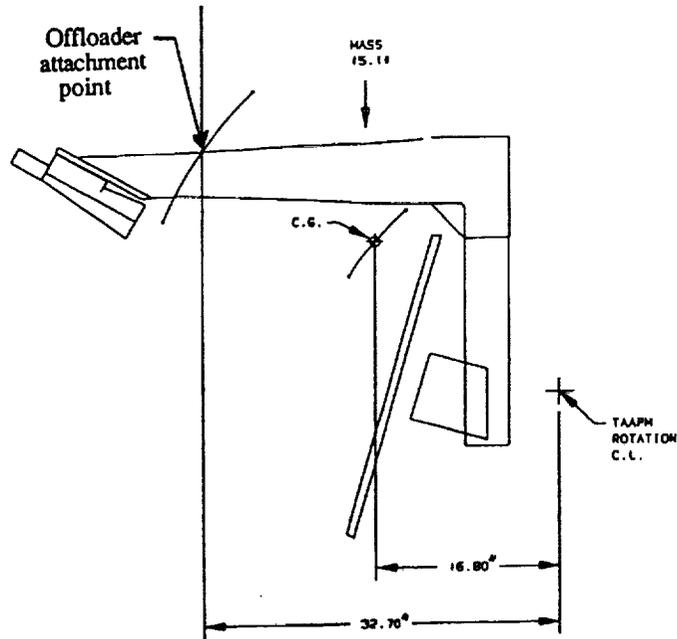


Figure 7. Location of center of gravity (c.g.) on spot antenna assembly

3.3.1 Two off-loader designs

Two different off-loaders were required for system level testing: one for the Compact Antenna Test Range (CATR) testing where pointing telemetry and RF antenna pattern are correlated, and one for the spacecraft thermal-vacuum test where TAAPM range of motion and torque margin are verified at temperature extremes.

The CATR off-loader utilized a calibrated constant force spring assembly while the spacecraft thermal-vacuum off-loader consisted of a pulley and counterweight system. The CATR off-loader proved to be a better design.

3.3.2 Effects of the off-loader on spacecraft thermal-vacuum test results

The primary factor that adversely affected the range of motion and torque margin during spacecraft thermal-vacuum testing was hysteresis due to gravity torques and friction in the pulley system. With this system, the uncompensated gravity torques vary throughout the TAAPM range of motion, and with the addition of friction in the pulleys, it was very difficult to determine an accurate torque margin. The friction was of significant magnitude to prohibit TAAPM motion. Since off-loader effects obscure the data, it was decided to use unit-level data to prove design torque margin.

4.0 ON-ORBIT OPERATION/ CONCLUSION

On-orbit range of motion tests were successfully completed on all spot antennas during the period of 31 October thru 2 November 1993. The on-orbit test results were very consistent with the unit and spacecraft ground-level testing at Space Systems/ Loral.

4.1 On orbit test results

During these tests, all TAAPM potentiometers were continuously monitored. The following observations were made:

1. During the range of motion tests, the S2 spot antenna coarse potentiometer exhibited "glitches" or dropouts in the location of the stowed/ launch configuration; this same location was anomalous during ground testing.
2. On-orbit data was taken at specific positions through the range of motion, at zero and near the TAAPM stops (approximately 1000 to 1300 steps from the zero position). In general, the on-orbit telemetry agreed with the final spacecraft (prior to launch) test data to within 1 step.

4.2 Conclusion

The most significant "lesson learned" during the TAAPM test program was that subsystem application must be seriously considered in developing test methods and setups for unit-level qualification. Although the TAAPM could easily meet unit requirements, unexpected problems arose during subsystem (flight configuration) testing.

Secondly, proper design of equipment used during ground testing is fundamentally important for obtaining meaningful test results on flight hardware. As evidenced by this paper, subsystem configuration and test setups proved to make TAAPM testing much more challenging than anticipated.

