PERFORMANCE MEASUREMENTS OF THE SUBMILLIMETER WAVE ASTRONOMY SATELLITE (SWAS) SOLAR ARRAY DEPLOYMENT SYSTEM

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Abstract

This paper discusses some unique features of the solar array deployment system used on the Submillimeter Wave Astronomy Satellite (SWAS). The mechanism system is highly optimized, incorporates no single-use components, and is fully testable in a one-"g" environment.

A single High Output Paraffin (HOP) linear actuator drives the mechanisms used to deploy and lock each wing of solar array panels. The solar arrays open slowly, requiring only enough force to overcome inefficiencies and friction. Load cells measure the force required to open the solar arrays. The system's margin is easily determined by comparing the maximum capability of the HOP actuator to the load cell readings.

The method of direct measurement of the force required to open the solar array makes this system unique. These measurements account for, but do not differentiate between sources of friction, misalignment and inefficiency.

During assembly these measurements helped simplify hinge alignment. Throughout the environmental test program, they were used to identify failures, and over time, they helped indicate any degradation of the mechanisms.

Additional performance data will be available after the solar arrays deploy in orbit. SWAS is scheduled to launch in 1995 on a Pegasus-XL launch vehicle.

Introduction

SWAS is the third mission in NASA's Small Explorer program. The spacecraft was designed and built in-house at the Goddard Space Flight Center, and the instrument (designed for the principle investigator at the Smithsonian Astrophysical Observatory) was built by Ball Aerospace. Several other institutions developed various other components for the instrument and the spacecraft.

The SWAS satellite is approximately five and a half feet tall, three feet in diameter, and weighs 625 pounds. The solar arrays, when deployed, span beyond thirteen feet and provide more than 36 square feet of area normal to the sun.

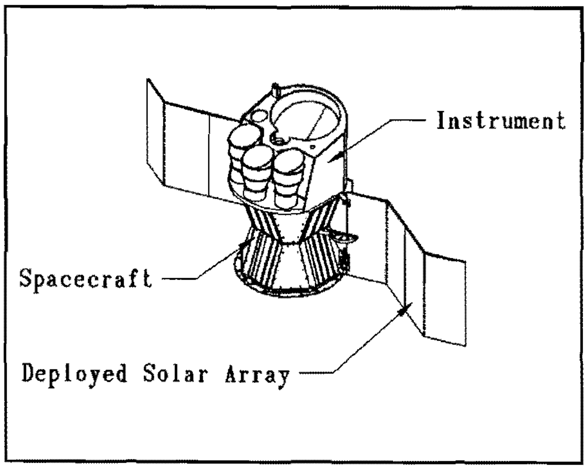

Figure 2, SWAS

All of the subsystem components are housed within the spacecraft structure; the SWAS instrument attaches to the top. The structure consists of three octagonal rings of different diameters attached by load-carrying members. Together they form an octagonal hourglass shape. The base ring attaches to the Pegasus launch vehicle, and the top ring mounts the instrument. The two solar array wings open to the sides.

SWAS is a three-axis-stabilized stellar pointing platform used to survey a variety of galactic cloud structures in the frequency range of 487 GHz to 556 GHz. Specifically, SWAS will help determine the process of star formation by measuring the abundance of water (H_2O), molecular oxygen (O_2), atomic carbon (CI), isotopic water ($H_2^{18}O$), and isotopic carbon monoxide (^{13}CO). These measurements must be taken from space due to the attenuation of their frequencies by our own atmosphere.

The instrument takes its measurements by differencing on-source and off-source readings; hours of cumulative integration time are required for each target. However, due to the thermal sensitivity of the receiver, the on- and off-source measurements must be taken quickly for a valid comparison of the data. This is accomplished by frequent transitions of the entire satellite. The sources can be as far away as three degrees, and the transitions must be completed within fifteen seconds.

The on-source observations require the spacecraft to point the instrument within a target of 57 arcseconds and with jitter less than 36 arcseconds. The solar arrays need to be rigid to achieve the structural stiffness required to meet these pointing constraints.

Solar Arrays

The solar arrays are packaged tightly around the structure for launch. Each wing consists of two aluminum honeycomb substrate panels, the outer initially folded over the inner. Once the spacecraft separates from the launch vehicle, the arrays are deployed and locked. The implementation of stiff hinge locks helped to minimize control-structure interactions.

The dynamics requirement, and an additional requirement that the deployment mechanisms be tested on earth without the use of a "g" negation system, led to the necessity of a stiff and light-weight design. The arrays were successfully designed to achieve a stiffness goal of 2 Hz when deployed and locked.

The net solar array weight (excluding mechanisms) is 11.3 lbs. for the outer and 12.8 lbs. for the inner panel of each wing. These weights include solar cells, cover-glass, substrate, electrical harnessing, paint, adhesive, and shunt heaters. The outer hinges add an additional 0.8 lbs. to each side, and the inner hinges add 2.3 lbs. to each side.

The inner panel of each wing is opened by the force of a single High Output Paraffin, (HOP) actuator. The outer panel, coupled to the inner panel, is opened passively via cable, tensioning spring, and pulleys.

High Output Paraffin Actuators

Six HOP actuators are used on SWAS: four small actuators (nominal output = 50 lbf.) to operate the solar array launch latches, and two high force actuators (nominal output = 200 lbf.) for solar array deployment. After separation from the launch vehicle the solar arrays unlatch. Then, after waiting sufficient time to ensure the arrays are unlatched, they deploy.

HOP actuators are unique devices. They deliver a tremendous amount of force from a small package, they are reusable, and repeatable in their performance. Their design takes advantage of the high expansion rate of paraffin as it changes phases from a solid to a liquid. Redundant heaters located within a paraffin-filled cavity heat the paraffin. As the paraffin is heated it expands, applying pressure to a squeeze boot which pushes a rod out of the unit. The force of this rod is used to drive the SWAS solar array mechanisms.

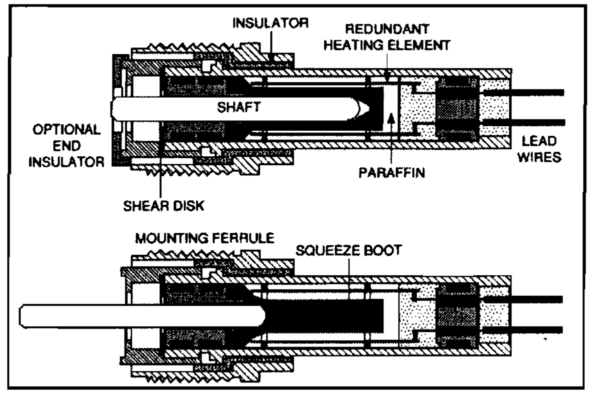

Figure 3, Starsys HOP Actuator

Immediately following the separation of the spacecraft from the launch vehicle two things happen: the solar arrays open and the attitude control system points the solar arrays at the sun. Before the arrays are pointed towards the sun, allowing the battery to charge, power consumption must be limited.

The solar arrays are deployed autonomously once in orbit; the actuators are shut off later by a command sent from the ground. Communications with the spacecraft may not be possible until after the second or third orbit. In the original design, if a problem had occurred with the deployment, the HOP actuator would continue to draw power and drain the battery.

Consequently, a modification was made to the design of the standard HOP actuator. A pair of Positive Temperature Coefficient (PTC) thermistors were wired in series with each of the heaters. The thermistors electrical resistance changes with temperature. At a specific temperature, the resistance increases sharply and turns the heater circuit into an open circuit. Essentially, the PTC thermistors are solid-state, thermally-operated electrical switches. Careful selection of thermistors with the proper properties prevented the heaters from shutting down before the full function of the actuator.

Solar Array Deployment

Once in orbit and separated from the rocket, the solar arrays unlatch and deploy. Four PTC-modified, HOP-actuated mechanisms release the arrays, two for each wing. A pair of standard thermistors bonded to the outside of each actuator measures the external case temperature. This temperature is used in the control logic to prevent deployment before the arrays unlatch and are free to move. After the arrays unlatch and an additional fifteen-minute delay expires, the deployment actuators are powered on, and the deployment begins. The entire process to unlatch and deploy the arrays takes approximately thirty minutes.

Each array opens as the actuator output rod pushes a cam shaft through a rotary cam (see Figure 4). The cam is fixed relative to the spacecraft, and the shaft to the solar array. Thus the arrays are deployed by the conversion of the linear motion of the HOP actuator to rotational motion through the cam.

The outer solar array panel is coupled to the inner via cable and pulleys. As the inner solar panel rotates 113 degrees and locks, the cable pulls the outer panel 180 degrees to its locked position. Sufficient compression of a spring used to maintain tension on the cable guarantees that the outer hinge will lock before the deployment is complete.

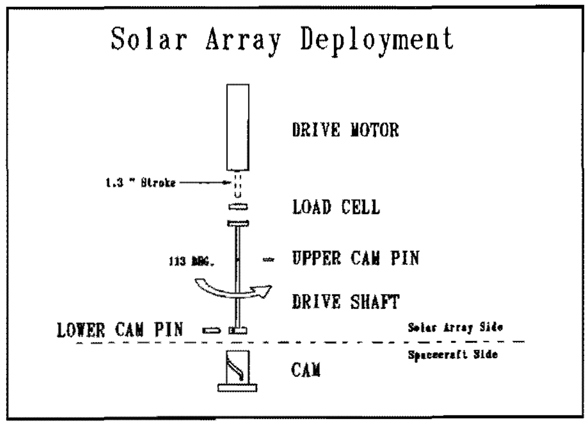

Figure 4, Mechanism Components

Maintaining enough margin to power the arrays through any "rough" spots, the actuator is required to supply just enough force to move the arrays throughout the deployment. "Rough" spots were reduced through careful material selections, part tolerancing, and hinge alignments. A load cell, located between the output rod of the actuator and the cam shaft, measures the force required throughout the deployment. The data from the load cell was useful for further reducing deployment "rough" spots by assisting the process of aligning the hinges. Measurements are recorded each time the solar arrays are deployed.

The HOP actuators open the arrays slowly. The arrays only accumulate momentum when the cable tensioning spring releases its stored energy. This event can be seen in the deployment data as sudden reductions in force (see Figures 5, 7, and 8).

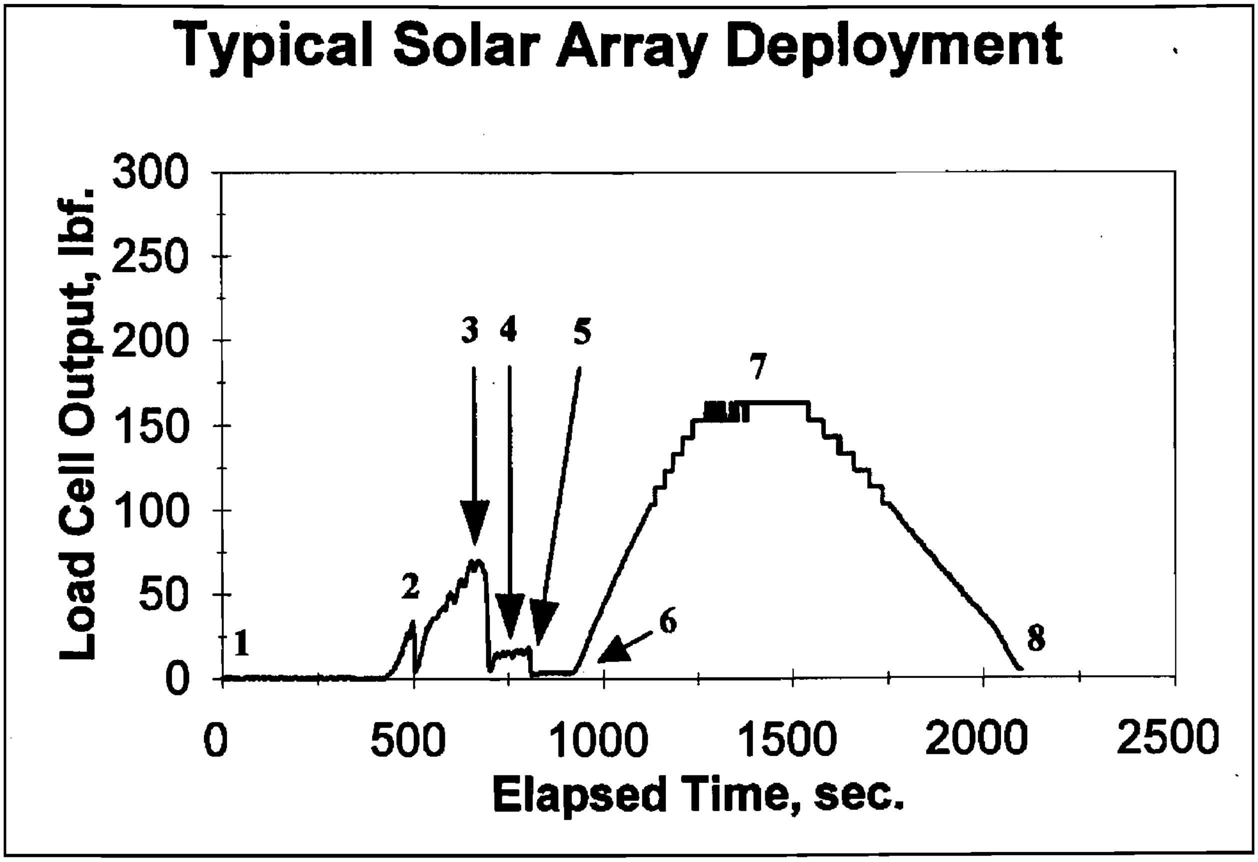

Figure 5, Typical Solar Array Deployment

A typical plot of force versus time is shown in Figure 5. This is the time history of force recorded from the solar array deployment prior to the spacecraft environmental testing. Several interesting points are labeled on the graph:

1) The deployment actuator is powered on.

2) Force builds and is released upon the first motion of the solar panels.

3) The highest force during the deployment occurs as the outer panel cable reaches the tangent point with one of the cable guides. The stored energy in the cable tensioning spring is released, and the solar arrays swing to a position near complete deployment; this is the vertical drop between points 3 and 4.

4) The solar array opens the remaining few degrees, and the outer hinge locks engage.

5) The inner hinge locks just prior to position 5, and deployment is complete.

6) The actuator hits hard stop at its full stroke of 1.3 inches.

7) The PTCs turn the heaters off, and actuator begins to cool. Note that the data resolution is poor here. This is due to a data format error effecting forces greater than 100 lbf.

8) The data acquisition system is terminated.

The data can also be plotted as output force versus hinge angle. This has proved useful to pinpoint misalignments, points of high friction, or other factors inhibiting performance. This was extremely valuable throughout the assembly and alignment, integration, and testing phases. In-flight performance data will be stored on the spacecraft and sent via telemetry to the ground. A comparison of the test data to the actual flight performance will be an interesting topic for another paper.

If a blockage anywhere in the mechanism system prevents the HOP actuator from movement, the actuator will continue to heat, increase its internal pressure, and apply more force. If the blockage is not overcome, and the PTC does not shut off the power, the shear disk will fail. A shear disk failure allows the paraffin cavity to safely expand its volume. The expanded volume allows the paraffin to continue to heat without endangering the structural integrity of the actuator case.

The shear disks are calibrated and the pressure required to break them is well known. The PTC thermistors are designed to turn off power to the heaters at a certain temperature. However, if the actuator rod has not extended beyond 70% of its stroke, the paraffin will not be able to reach the temperature required for the PTC to shut the heaters off. Consequently, the shear disk will fail, thus limiting the maximum force to this point. The shear disks used on the SWAS HOP actuators are set for 300 lbf. Beyond 70% stroke, the paraffin does have sufficient volume to expand and heat such

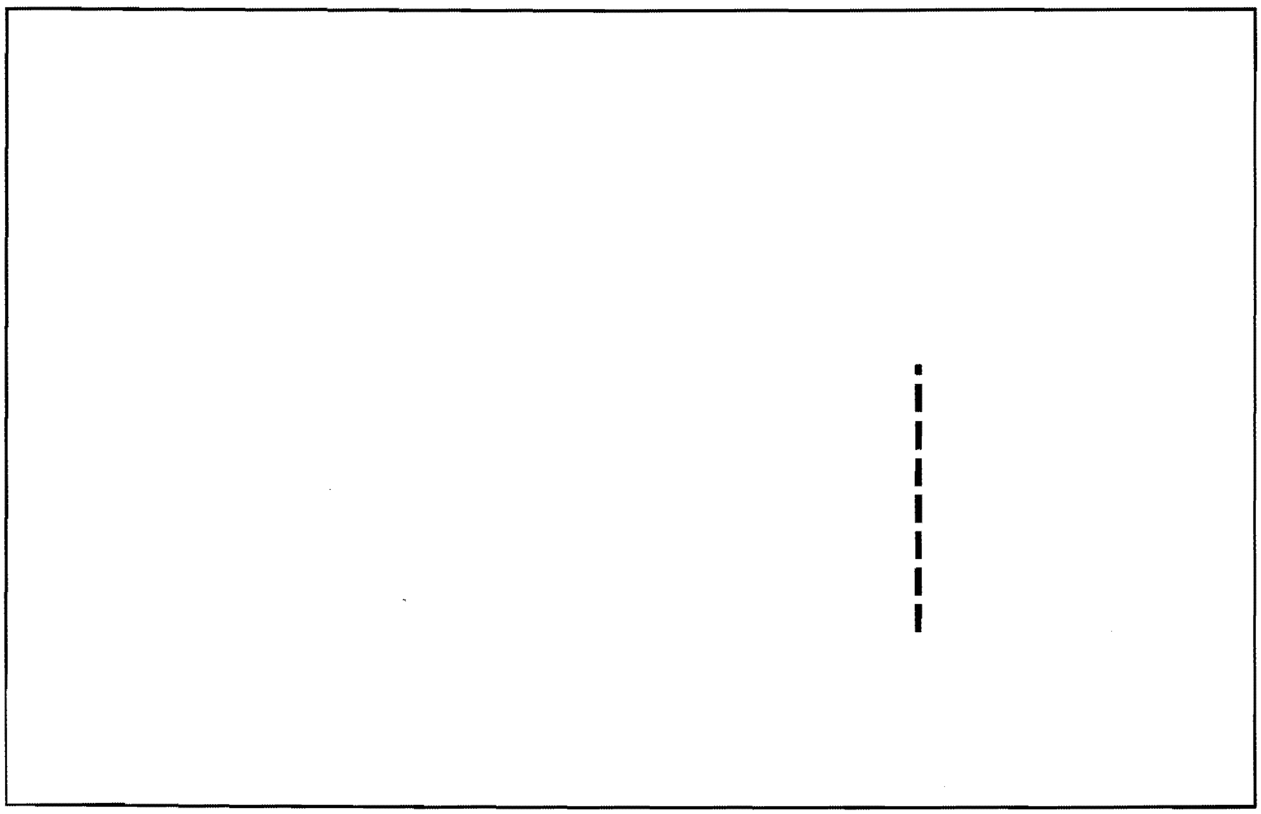

Figure 6, PTC HOP Actuator Capability

that the PTC thermistors will shut the heaters off before the shear disk ruptures. Therefore, the maximum force is limited by the PTC only for the last 30% of the stroke.

The 70/30% point is approximate. The exact point varies with the initial conditions. Since the PTC thermistors are electrically resistive elements, they generate heat; therefore, their temperature is always slightly greater than the average temperature of the paraffin. The temperature difference between the PTC and the paraffin increases with the amount of time the unit is powered. Since the heaters are switched off based upon the PTC temperature, rather than the paraffin temperature, a lower starting temperature results in an earlier heater shutdown. This equates to a lower pressure and, therefore, a lower maximum actuator force. This is indicated by the dashed lines in Figure 6. The line A-B indicates a lower starting temperature than the line A'-B'.

The vertical line at a stroke of 1.0 inches (in Figure 6) indicates full solar array deployment. The SWAS deployment HOP actuators have a full stroke of 1.3 inches; the last 0.3 inches is not used. So, the array deployment is nearly complete after the first 70% of the stroke. Only at the very end of the deployment is the actuator capability reduced at low starting temperatures.

The actuators used on SWAS have been qualified for starting temperatures above -60 degrees Celsius, and tested on the spacecraft as low as -45 degrees, and as hot as +60 degrees Celsius.

Performance Measurements

To prevent the actuator squeeze boot from turning inside-out, the actuator rod must hit a hard stop at its full stroke. When the actuator reaches this point the paraffin continues to heat until the PTC shuts off the heaters. (This is the point labeled B, or B', in Figure 6.) The health of the actuator and the PTC can be monitored by this data point over time. A problem with the PTC or a chemical breakdown of the paraffin itself would show up as a reduced force at this point.

Remember, only for the last 30% of the actuator stroke is the force limited by the PTC; the first 70% is limited by the shear disk. The solar arrays are completely open and locked at a stroke of one inch, which represents 76% of the actuator's full stroke. The system performance is evaluated based upon the load cell measurements. Since the arrays move when just enough force is applied, system inefficiencies and friction are measured by the load cell throughout the array deployment. Margin is then computed by comparing the load cell data to the shear disk rupture force, or the PTC limited force for the last few degrees of the deployment.

The margin is easily viewed when the data is plotted on a graph. Figures 7 and 8 show actual data obtained from solar array deployments throughout the spacecraft environmental test program. Deployments were performed prior to testing, after acoustics tests, after vibration tests, during the cold and hot thermal vacuum tests, and after thermal vacuum testing. The highest forces recorded occurred during the cold thermal vacuum deployment test; this was the expected result.

The ability to measure margin directly

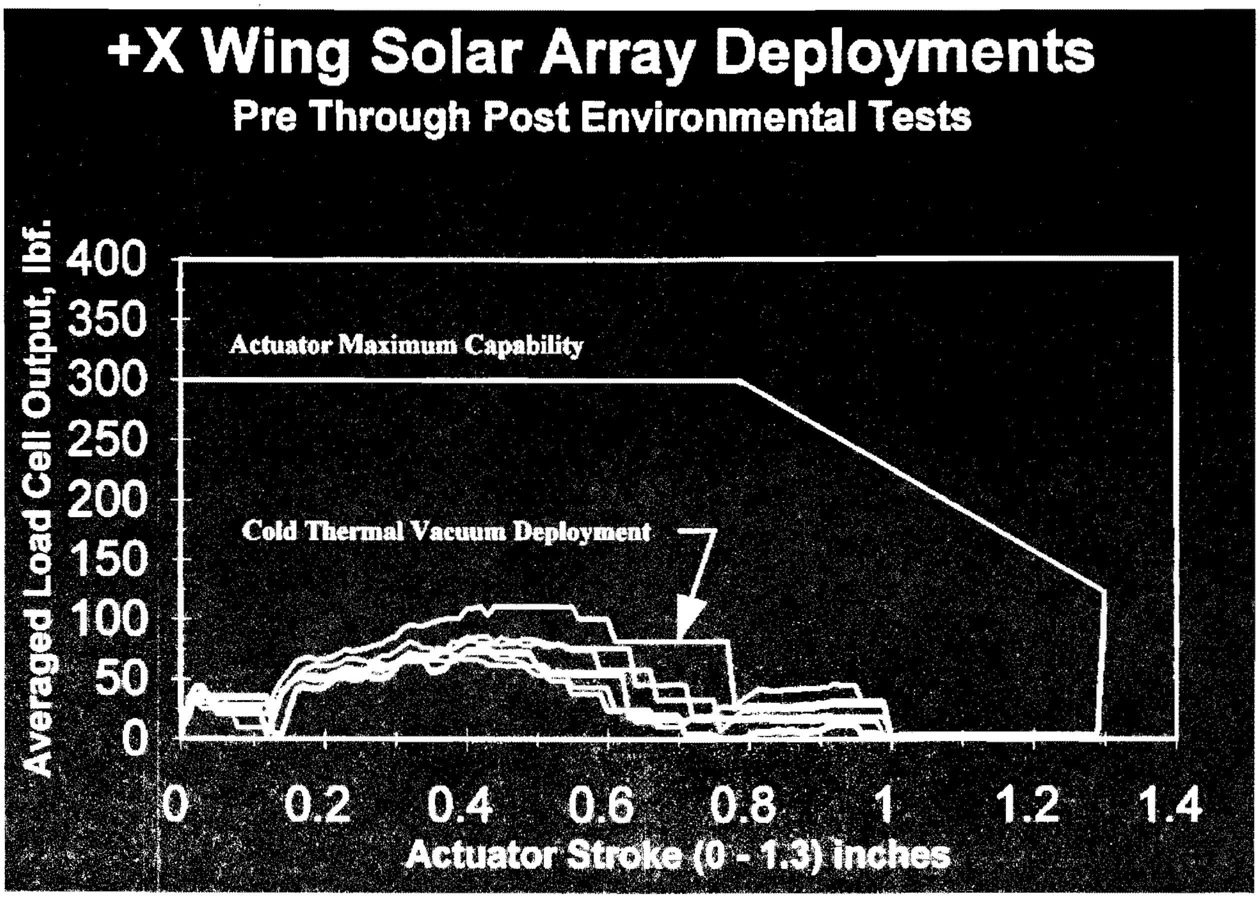

Figure 7, Composite Solar Array Deployments (+X Wing)

makes this system unique. Nowhere does this system differentiate between sources of friction, misalignments or inefficiency, nor does this system overlook these or any other critical elements.

The ability to pinpoint "sticky spots" in the hinges is achieved by comparing high force points with the angular position of the hinges. If a force spike occurs at a particular angle, a misalignment or other problem can be more readily diagnosed and repaired.

Measurements were taken each time the solar arrays were deployed. They are typically deployed before and after any event that could disrupt the solar arrays or their mechanisms, such as destructive tests like vibration testing. Over the life of the mechanisms, these measurements have been used to determine if any long term degradation has occurred.

Conclusions

The entire design of this system was approached from a unique direction. A light-weight, slow-moving system posed some challenging demands on the design of the solar arrays and mechanisms. The system is low mass and stiff, yet robust enough to fully test on earth, and uses only reusable components. Therefore, the system that was tested will be the system flown.

Direct measurements have eliminated the possibility of overlooking contributing

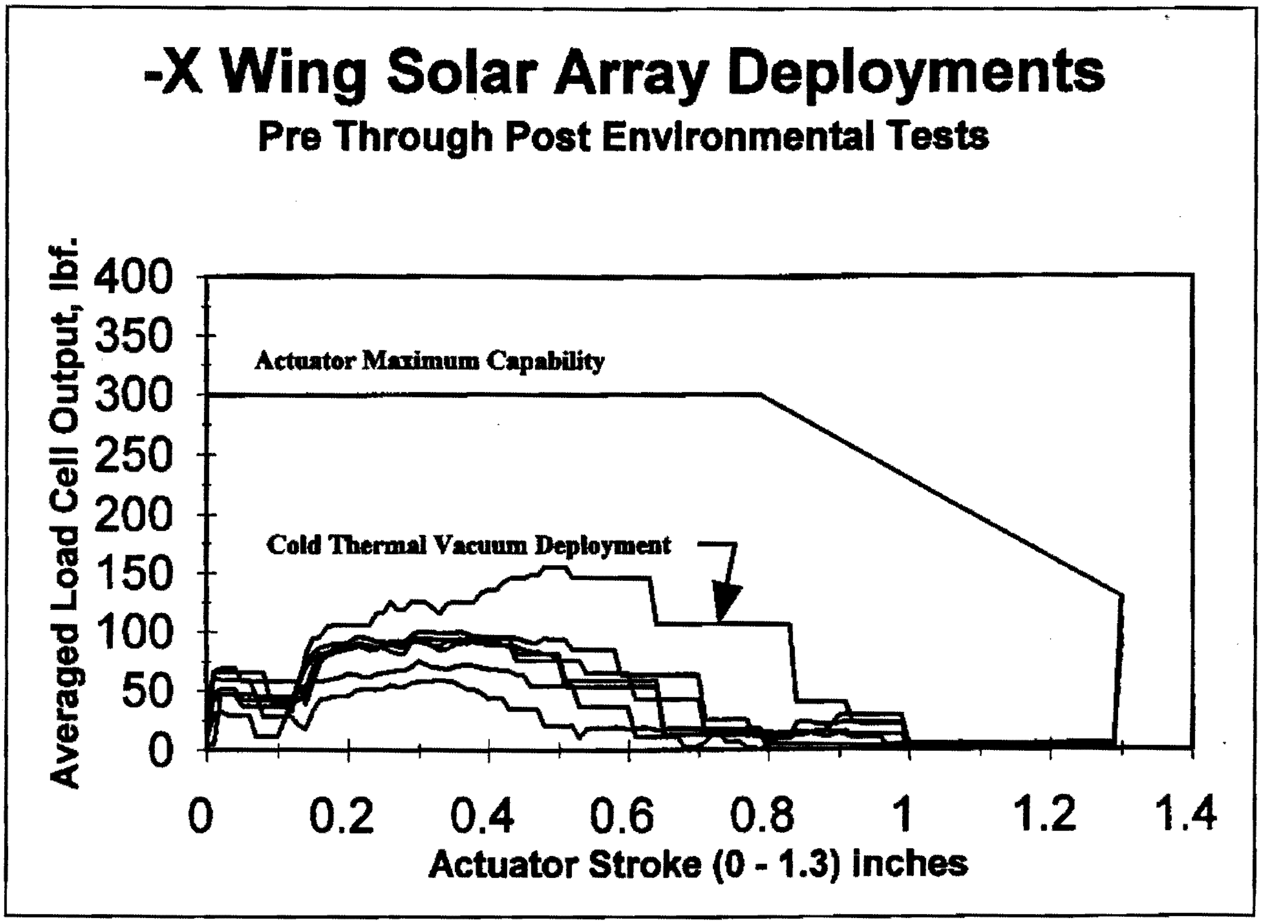

Figure 8, Composite Solar Array Deployments (-X Wing)

variables in margin calculations, thereby increasing reliability in the margin. The measurements have simplified the process of hinge alignment, and given valuable insight to the health of the mechanisms. Also, the total system cost has been reduced by eliminating the necessity of complex analysis and modeling.

Author Biography:

Gary Sneiderman has his undergraduate degree in mechanical engineering from Tulane University, and is currently completing a masters degree in space systems from George Washington University. He has been employed for seven years at NASA's Goddard Space Fight Center. Most of that time has been spent working as the lead mechanical engineer on SWAS. He has been responsible for the mechanical aspects of the spacecraft since the conception of the design.