THE STRETCHED LENS ARRAY'S TESTING AND MISSION SUCCESS IN HARSH ENVIRONMENTS

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ABSTRACT

The hazards of space are real and life-threatening to satellites and mission hardware. The solar array is exposed to the harshest environment of all spacecraft components. Micrometeoroid bombardment, radiation degradation, electrostatic discharge, and temperature extremes are a few of the elements that a solar array must withstand to provide reliable and continuous power to space systems. This paper will describe the testing and mission success of the Stretched Lens Array (SLA) in harsh environments. It will examine various missions that can cause complications for standard arrays and demonstrate the ability of the SLA to fully operate in all extreme situations.

1. INTRODUCTION

The hazards of space are real and life-threatening to satellites and mission hardware. The solar array is exposed to the harshest environment of all spacecraft components. Micrometeoroid bombardment, radiation degradation, electrostatic discharge, and temperature extremes are a few of the elements that a solar array must withstand to provide reliable and continuous power to space systems. This paper will describe the testing and mission success of the Stretched Lens Array (SLA) in harsh environments. It will examine various missions that can cause complications for standard arrays and demonstrate the ability of the SLA to fully operate in all extreme situations.

Solar array power levels will continue to increase as lunar bases, solar electric propulsion missions, and higher power communication satellites are developed. As power levels continue to increase more durable arrays that can operate in high voltage operations must be incorporated. The SLA is especially well suited for high voltage operations, electric propulsion missions, and operation in high radiation environments such as the Van Allen belts or in those found around Jupiter. Current and future testing efforts have been described to show the SLA's survivability in any orbit. The status and results of these programs will be presented showing the SLA is ready for flight missions with array sizes from 1 to 100 kW at substantial cost savings. The SLA is a reliable solution to the solar array power needs of today and tomorrow especially in harsh environments.

2. SLA's BACKGROUND

The SLA is a refractive photovoltaic concentrator (Fig. 1), developed by ENTECH, Inc., that converts solar energy into useful electricity with an efficiency >27%. SLA's unique, lightweight, and efficient design leads to outstanding performance ratings as shown below [1]:

- Areal Power Density: > 300 W/m^2 due to High-Performance Lenses and Cells
- Specific Power: > 300 W/kg for a 100 kW Solar Array on ATK's SquareRigger Platform
- Stowed Power: > 80 kW/m^3 for a 100 kW Solar Array also with ATK's SquareRigger Platform
- Scalable Array Power Capacity: 4 kW to 100's of kW's
- Super-Insulated Small Cell Circuit: High-Voltage (up to 600 V) Operation
- Super-Shielded Small Cell Circuit: Excellent Radiation Hardness at Low Mass
- 85% Cell Area Savings: Up to 75% Savings in Array $/W Versus One-Sun Array
- Modularity & Mass-Producibility at MW's per Year Using Existing Processes and Capacities

The end-of-life specific power and areal power density is 3-4X greater than a planar array. The SLA's attributes

Figure 1. Stretched Lens Array in sunlight

match the critical requirements needed for radiation-hard NASA Exploration missions including spiral-up Solar Electric Propulsion (SEP) missions, earth resources survey, radar observations, etc. SLA's small cell size which is 85% smaller than planar high-efficiency arrays, allows shielding and insulation to be added without detrimental mass effects. In the SLA, the entire cell and cell edges are fully encapsulated providing a sealed environment preventing the most common failure mechanism of arcing. The module shown in Fig. 2 is the latest version of the design. This design leads to a specific power exceeding 300 W/kg at voltages exceeding 300 V.

Figure 2. Full scale SLASR panel

SLA is an evolutionary development based on the successful SCARLET array flown on Deep Space 1, which itself was based on the Mini-Dome Lens array flown on PASP-Plus [2]. This mini-dome lens array performed extremely well throughout a year-long mission in a high-radiation, 70-degree inclination, 363 km by 2,550 km elliptical orbit, validating both the high performance and radiation hardness of the refractive concentrator approach [3]. The SCARLET array performed flawlessly and within 2% of its projected performance over the entire Deep Space 1 mission validating the use of solar-powered ion propulsion for extended space missions. Both missions can be seen in Fig. 3.

3. SOLAR ARRAY ANOMALIES

Reliable power delivery over the mission life is critical to all satellites; therefore solar arrays are one of the most vital links to satellite mission success. However, in the last ten years Airclaims has documented 118 satellite solar array anomalies, 12 resulting in total satellite failure, making solar array reliability a serious issue. Failures can not always be traced back to an exact cause but two of the top failure mechanisms for solar arrays include electrostatic discharge and radiation

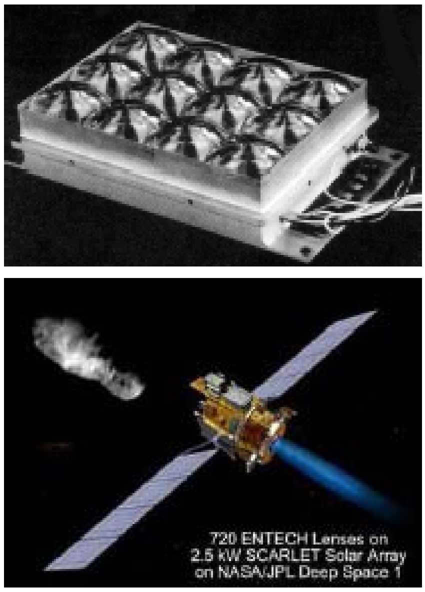

Figure 3. Top photo is the PASP+ module, bottom photo is the SCARLET Deep Space 1 array

degradation. Both lead to a significant loss of power causing a shortened satellite lifetime. The SLA is inherently designed to protect against such issues.

A statistical analysis of satellite anomalies performed with the use of Airclaims's Ascend SpaceTrak database [4] determined that the GEO environment is especially dangerous for solar arrays. Spacecraft charging in geosynchronous orbit is a reality that can be destructive and thus negatively affect the satellite industry as a whole. Fig. 4 shows that the number of satellite anomalies in GEO is significantly greater than any other orbit for the last ten years. In the last ten years only 25% of satellite launches went to GEO. However, 41% of all anomalies and failures occurred in GEO including 71% of all solar array anomalies. The majority of these anomalies can be traced to electrostatic discharges that often occur when the satellite emerges from an eclipse period into a solar storm. Yet over the last decade, no effective solution for this problem has been implemented.

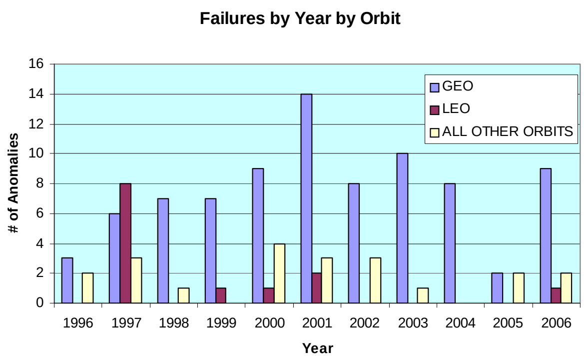

Figure 4. Solar array anomalies by year and orbit

Solar array anomalies show the classic infant mortality trend as depicted in Fig. 5. Infant mortality generally indicates that the design is poor and/or there are defects in construction. This observation raises fundamental questions about solar array designs, construction, and testing prior to launch. It has also been determined from the SpaceTrak data base that no single manufacturer is having all the problems. These failures are a worldwide phenomenon; therefore, defects in construction are an unlikely cause. However, new solar array designs are usually not considered due to the conservative belief that flight heritage is the best proof of performance.

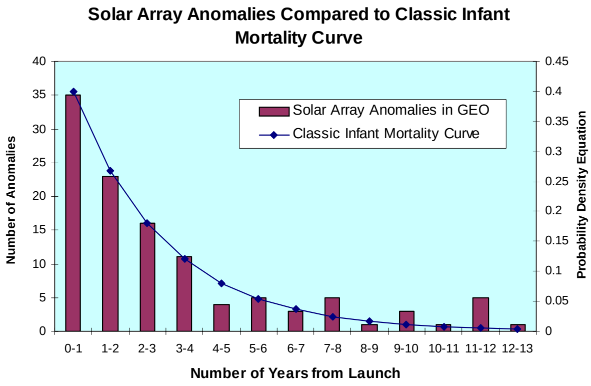

Figure 5. Infant mortality trend with respect to solar array anomalies

4. RADIATION

Solar array power loss by radiation degradation is an anomaly that occurs frequently in space. This is especially common in the high radiation environment of MEO. For SEP missions to become practical the arrays must be able to spiral out through the Van Allen Belts with minimal degradation. Radiation shielding can be increased with little impact on SLA's mass, hence providing a "super shielded" system for operation in high radiation environments such as the heart of the Van Allen belts or in those found around Jupiter. To understand and compare the various radiation environments for these orbits, simulations have been run using The European Space Environment Information System (SPENVIS) and the data has been graphed. The natural radiation environment in space is defined by existing models, such as AE-8 for trapped electrons and AP-8 for trapped protons in Earth's radiation belts, and JPL models for solar protons. SPENVIS incorporates these models in an online analysis program package. The SPENVIS model provides the 1 MeV equivalent electron radiation doses for given orbits and durations. Losses in maximum power (Pmax), short circuit current (Isc) and open circuit voltage (Voc) are calculated as a function of protective layer thickness. This information, in conjunction with a standardized chart of power degradation of solar cells with electron fluence, permits calculation of the power degradation of the solar cell as a function of cover glass thickness as shown in Fig. 6 for a high radiation orbit of 5000 km with a 28 degree inclination angle.

Next the mass of the cover glass material must be considered to allow calculation of the end-of-life (EOL) specific power for the array. The peak EOL specific power values for each time period have been obtained for both the SLA and a planar array as shown in Fig. 7. This assumes a beginning of life areal power density of 300 W/m^2 which is comparable to today's SLA. Note that SLA offers more than a 3X advantage over the planar array for 1 year on the time scale, and a 4X advantage over planar for 10 years on the time scale, for this example case (5,000 km altitude, 28 degree inclination, circular orbit). SLA's advantage over planar is apparent especially in high radiation missions. Fig. 8 shows the SLA advantage over a planar array by displaying the areal power density variation for the heaviest SLA analyzed versus the lightest one-sun array analyzed. It is important to note that the heaviest SLA is 14% lighter than the lightest one-sun array, thus the remaining power advantage of SLA is spectacular. SLA's advantage over planar will grow even larger for higher radiation missions.

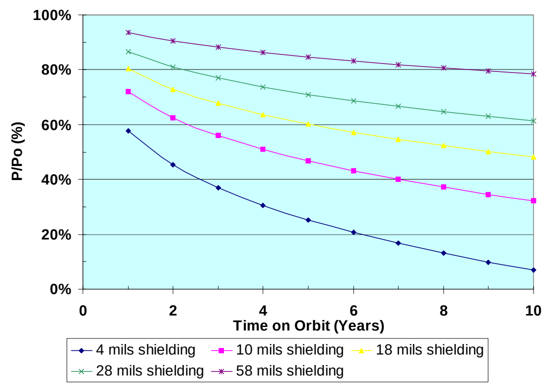

Figure 6. SLA performance in high radiation orbit

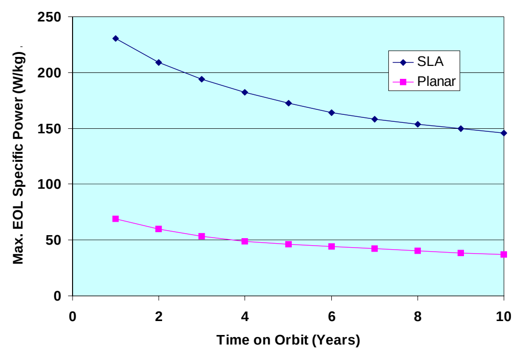

Figure 7. EOL specific power with optimal shielding

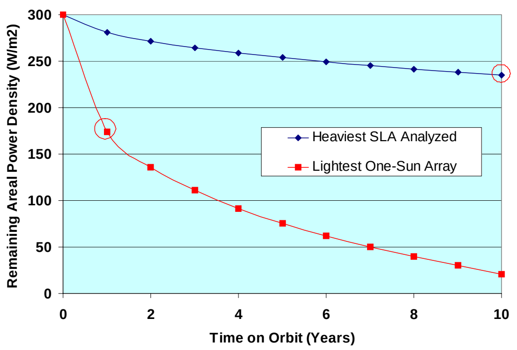

Figure 8. SLA/planar areal power density comparison

5. HIGH VOLTAGE OPERATION

Another recurring obstacle to reliable power in space is electrostatic discharge seen most commonly in high voltage operations such as high power systems or SEP. The SLA can be specifically optimized for SEP by the ability to direct-drive Hall-effect thrusters. This technology designed by NASA Glenn can minimize the inefficiency, mass, cost and complexity of the power management and distribution interface between the solar array and electric thruster [5]. The initial drawback is that the solar array must be able to operate at the voltage level needed to drive the electric thruster. This voltage is much higher than the present operation voltage of space solar arrays of 100 V. Serious discharge, arcing, and ground-fault problems have occurred on orbit with even the present operating voltage. SLA overcomes this challenge by fully encapsulating the entire cell circuit to create a sealed environment. This can be accomplished without a huge mass penalty due to the 8X concentration and fewer cells needed to provide the same amount of power. The SLA's inherent design also protects against electrostatic discharge. The lens is several inches away from the cells and substrate and arcing cannot occur across that distance. This solves the problems associated with corona discharge in long term missions. Other array designs do not guard against this potential failure mechanism.

Furthermore, array segments are under test for corona breakdown that can become a critical issue for long term, high voltage missions. The SLA design is suited for high voltage operation because the entire cell and cell edges are fully encapsulated by a cover glass that overhangs the perimeter and the silicone adhesive covers the cell edges, Thus it provides a sealed environment which limits the possibility of electrostatic discharge. ENTECH has fabricated and tested a number of such single-cell SLA receiver samples (Fig. 9) at very high voltage levels (2,250 to 4,500 V) in an underwater hi-pot test for very long periods of time. Auburn University has conducted similar tests in vacuum using the same type of fully encapsulated receiver samples. These tests are being conducted using the guidelines found in ESA's IEC International Standard #343 (1991): "Recommended test methods for determining the relative resistance of insulating materials to breakdown by surface discharges [6]." The samples underwent testing at 2,250 V for ten and a half months and showed no change. Due to the SLA's inherent protection against electrostatic discharge it is especially well suited for electric propulsion missions. The SLA is also fully compliant with the new NASA-STD-4005 Low Earth Orbit Spacecraft Charging Design Standard.

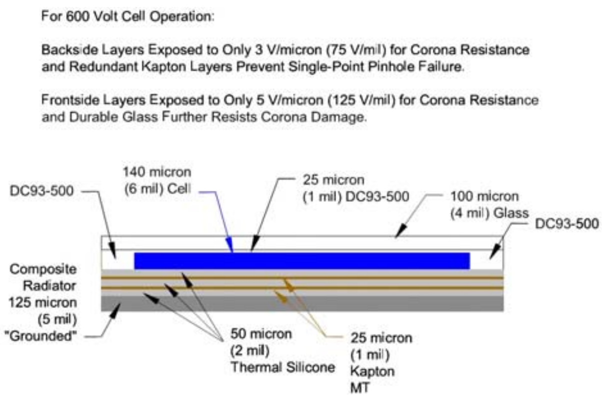

Figure 9. Test sample configuration

6. MICROMETEROIDS

The SLA module has been tested to voltages over 1000 V while under hypervelocity particle impact in a plasma environment with no arcing. Micrometeoroid impacts on solar arrays can lead to arcing if the spacecraft is at an elevated potential. Therefore, hypervelocity testing of the solar array is necessary. A concentrator solar cell module supplied by ENTECH, Inc was tested at Auburn University's Hypervelocity Impact Facility. The module consisted of a string of concentrator multijunction solar cells in series completely covered with cover glass (Fig. 10). The overhang extended well beyond the cell boundaries and was also filled with silicone providing a sealed environment. The test sample in the last test is shown in Fig. 11. No surface arcs occurred over the sample despite visible particle impact penetrations of the covers. Additional tests were performed with the stretched lens in place over the samples, and the lens provided excellent shielding of the cell circuits. The sample was also exposed to rear-side impact test shot with bias voltage at –1027V. Although there were many impacts no arcing was observed.

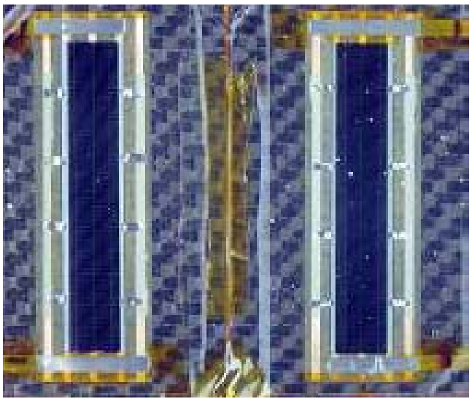

Figure 10. SLA module after hypervelocity testing

Figure 11. Sample after Hypervelocity shot

7. WIND

On the Martian plains, the Viking Landers measured typical wind speeds of 2-7 m/sec and wind gusts up to only 26 m/sec at an elevation of 1.6 m [7]. The shape error tolerance of the ENTECH lens is critical to the excellent long-term performance of concentrator systems using this technology. In contrast, the lack of shape error tolerance has contributed to the poor performance of many reflective photovoltaic concentrator systems both on the ground and in space. Detailed analyses show that the symmetrical-refraction lens offers a shape error tolerance that is 200 times better than for any reflective concentrator and 100 times better than for a conventional flat Fresnel lens. A comparison of the shape error tolerance of refractive versus reflective concentrators is shown in Fig. 12.

A model of the SLA was placed in front of a floor fan to model the wind forces that might be seen on Mars. Even with the distortion of the lens material the light remained focused on the solar cells as seen in Fig. 11. Distortion of the lens material due to the wind on Mars will not affect SLA performance. The only time the light does not remain on target is if the lens flips over on itself.

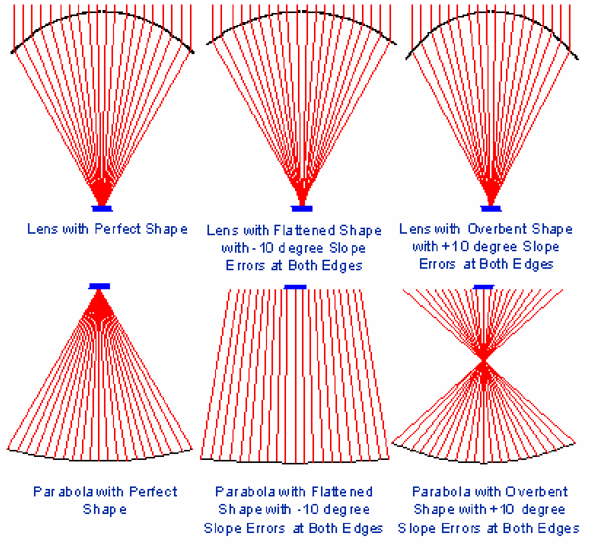

Figure 12. Direct Ray-Trace Comparison of Shape Error Tolerance of ENTECH's Lens versus Reflective Concentrator

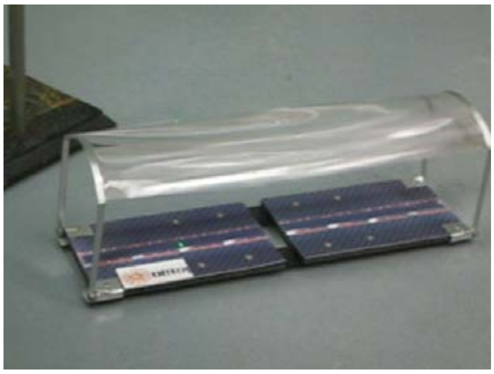

Figure 13. Picture of wind distortion to lens with light remaining focused on cells

8. DUST

Another power limiting factor is the settling of dust onto the surface of the solar array which can be seen on planetary operations to the moon or Mars. Cleaning options consists of vibrating the tracking system to shake off the dust on the lenses along with the inherent dust mitigation of the lens being tilted. If this was insufficient the array could also be periodically rotated into a vertical orientation and vibrated to increase dust removal. It is important to note that dust devils have been helpful in cleaning off the arrays on Mars rovers Spirit and Opportunity but cannot be the only dust removal strategy. It is important to note that the dust on the moon is more difficult to remove due to its rough edges. An array that is substantially off the ground and is tilted has the best chance to avoid power loss due to dust accumulation. The curvature of the SLA's lens also reduces dust accumulation.

9. TEMPERATURE EXTREMES

Fig. 14 shows typical lunar and Martian temperature profiles. Thermal considerations for SLA will be similar to those of a one-sun array on earth and cause no difficulty in operation. Temperature measurements on the SCARLET array on Deep Space 1 verified an operating cell temperature of about 70C at a 1 AU distance from the sun. SLA's cell temperature is typically about 10C warmer than for a high-efficiency one-sun cell array on the same orbit.

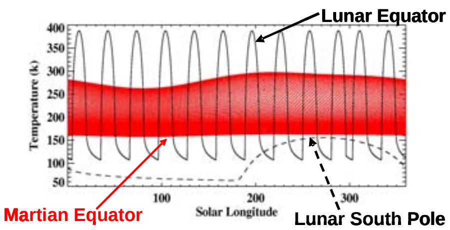

Figure 14. Lunar and Mars surface temperatures (Courtesy MIT & Draper)

Fig. 15 shows the relationship between temperature and maximum power for an advanced triple-junction solar cell. This relationship is based upon the temperature coefficient for an advanced triple-junction high efficiency solar cell in space applications. It assumes the Martian and lunar temperature range with cell beginning of life performance with no radiation damage. The maximum power increases as the temperature of the cell decreases.

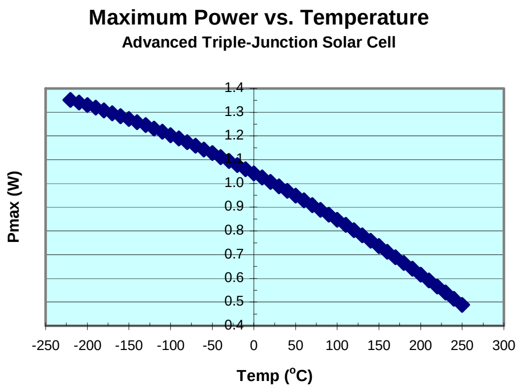

Figure 15. Effect of temperature on the maximum power of an ATJ solar cell

10. FUTURE FLIGHT AND TESTING OPPORTUNITES

Use of the SLA will open up the space market by providing more orbits for use with reliable and consistent operation. NASA is particularly interested in high-power SEP applications of the high-voltage SLA, since reusable SLA-powered SEP space tugs could carry lunar exploration cargo from low earth orbit to lunar orbit at a fraction of the cost of conventional chemically propelled cargo tugs. An important ongoing experiment is a direct drive test located at Auburn University. The purpose of this project is to test the compatibility of a 600 Volt DC 1 kW NASA/ENTECH SunLine concentrator solar array for the direct drive operation of a Russian made T-100 1.2 kW Hall thruster provided by NASA Glenn Research Center. The goal of this demonstration is to prove reliable operation of the Hall thruster from the high voltage concentrator array. Testing will include the addition of SLA hardware in the chamber at Auburn to measure plume impingement effects at various positions relative to the exhaust axis of the thruster. A schematic of planned testing can be seen in Fig. 16.

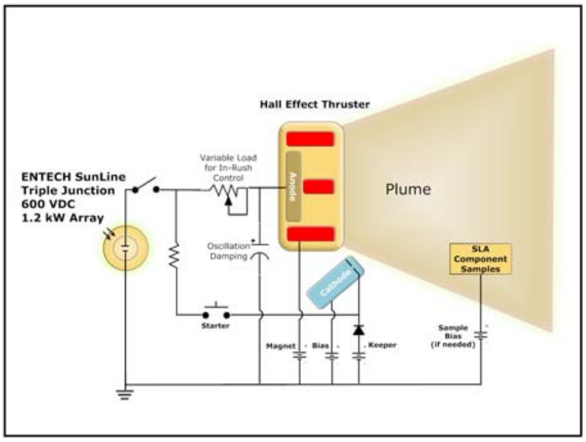

Figure 16. Schematic of planned direct-driven HET and SLA test configuration.

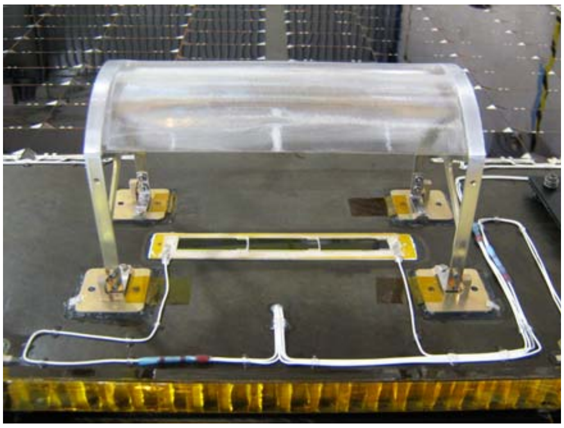

Figure 17. SLATE-T4 mounted on TacSat IV Solar Array Panel

A SLA flight module known as SLATE-T4 (Fig. 17) was successfully mounted and delivered to NRL for launch late next year on the TacSat IV spacecraft. This will provide validation of the survivability of the current SLA hardware in a high radiation orbit.

11. CONCLUSION

Extensive ground and flight testing has proven the SLA's durability to the space environment. The stretched lens has been tested under UV/VUV and electron and proton radiation simulating the radiation found in GEO. Corona and micrometeoroid tests have proven reliable operation in high voltage operations. The SLA is capable of operation in wind, dust, high radiation, and thermal extreme situations and can be shielded at minimal mass detriment. The SLA is ready for flight missions with array sizes from 1 to 100 kW at substantial cost savings. The SLA is a reliable solution to the solar array power needs of today and tomorrow especially in harsh environments.

12. REFERENCES

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