Advances in Radiation-Tolerant Solar Arrays for SEP Missions

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Abstract: As the power levels of commercial communications satellites reach 20 kW and higher, new options begin to emerge for transferring the satellite from LEO to GEO. In the past electric propulsion has been demonstrated successfully for this mission. Of course this approach requires that the loss in solar array power during transit of the Van Allen radiation belts is not excessive and still enables the 15 to 20 year mission life. Several critical issues emerge as potential barriers to this approach: reducing solar array radiation damage, operating the array at high voltage (>300 V) for extended times for Hall or ion thrusters, designing an array that will be resistant to micrometeoroid impacts and the differing environmental conditions as the vehicle travels from LEO to GEO, producing an array that is light weight to preserve payload mass fraction – and to do this at a cost that is lower than today's arrays. This paper will describe progress made to date on achieving an array that meets all these requirements and is also useful for deep space electric propulsion missions.

I. Introduction

AS power levels of commercial communications satellites reach 25 kW and higher, new options begin to emerge for transferring the satellite from LEO to GEO. In the past electric propulsion has been demonstrated successfully for this mission – albeit under unfortunate circumstances when the kick motor failed. The use of

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propellant for the electric propulsion (EP) system compromised the life of that vehicle, but did demonstrate the viability of using electric propulsion for orbit raising. Removing the kick motor on a satellite and replacing that mass with additional propellant for the EP system as well as mass for additional revenue-producing transponders should lead to major benefits for the satellite owner. Of course this approach requires that the loss in solar array power during transit of the Van Allen radiation belts is not excessive and still enables the 15 to 20 year mission life. Many other missions could also benefit from radiation-resistant solar arrays, including solar electric propulsion (SEP) missions to Jupiter, with its exceptional radiation belts, which mandate a radiation-resistant solar array to compete with a radioisotope alternative.

Several critical issues emerge as potential barriers to this approach: reducing solar array radiation damage, operating the array at high voltage (>300 V) for extended times for Hall or ion thrusters, designing an array that will be resistant to micrometeoroid impacts and the differing environmental conditions as the vehicle travels from LEO to GEO (or at Jupiter), producing an array that is light weight to preserve payload mass fraction – and to do this at a cost that is lower than today's arrays. This paper will describe progress made to date on achieving an array that meets all these requirements and is also useful for deep space electric propulsion missions.

The Stretched Lens Array (SLA) is a refractive concentrator array that is an optimal candidate for SEP missions. It was developed by ENTECH Inc., and was integrated into the Square-Rigger array by ATK as shown in Figs. 1 and 2. Much attention has been devoted to demonstrating durability of this array to the space environment. Combined electron and proton testing and UV and VUV testing of lens segments coated with resistant materials have been completed. In addition, samples have flown on MISSE 1 on the ISS with both uncoated and lenses coated with early coating compositions will be presented. Fully encapsulated SLA cell circuits have been tested to voltages over 1000 V while under hypervelocity particle impact in a plasma environment with no arcing. Array segments are under test for corona breakdown that can become a critical issue for long term, high voltage missions.

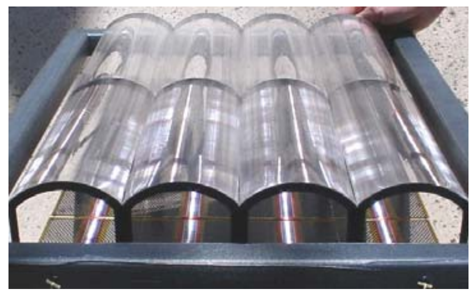

Figure 1. SLA demonstrator in sunlight

In order to confirm all of these advances with a space demonstration, a test experiment is being designed. This experiment will compare performance of the SLA concentrator technology with that of conventional planar arrays. Finally, examples of calculated SEP missions showing the performance of the SLA compared to planar arrays are presented below. The SEP tug mission study supported by NASA will be described in detail.

II. Stretched Lens Array

The Stretched Lens Array (SLA) developed by ENTECH Inc. in Keller, TX is a refractive concentrator array with efficiencies greater than 27%. Because of the concentrator design, the ~4 cm^2 cells designed for 8x concentration can be shielded against radiation damage at about $1/8^{th}$ the mass of a conventional planar array. The SLA has demonstrated its durability to the space environment through its proven flight history, stringent ground testing, and computation modeling and analysis. The SLA is reliable, scalable, cost-effective, durable, and efficient. It is an optimal candidate for SEP missions to GEO, the moon, Mars, and beyond.

A. Flight History

The point-focused mini-dome lens array was the first refractive photovoltaic concentrator system to successfully fly in space. It flew on the PASP+ flight test in a high radiation orbit and provided the highest performance and least degradation of twelve advanced solar arrays. From 1998-2001, NASA flew the Deep Space 1 mission that validated the use of solar-powered ion propulsion for extended space missions. This highly successful three-year mission also used a novel SCARLET solar array that concentrated sunlight eight-fold onto small area solar cells. This array performed flawlessly and within 2% of its projected performance over the entire mission. That design has evolved into the Stretched Lens Array. The primary difference between SCARLET and the SLA is that no additional glass cover is used over the silicone lens. This has led to significant mass, cost and complexity reductions. The module shown in figure 2 is the latest

Figure 2. Full scale SLASR panel

version of the design using ATK Space Systems' SquareRigger Platform. This design leads to a specific power exceeding 300 W/kg at voltages exceeding 300 V.

B. Today's Performance Metrics

SLA offers unprecedented performance (>80 kW/m^3 stowed power, >300 W/m^2 areal power, and >300 W/kg specific power), high voltage operation (300-600 V), and cost-effectiveness (>50% savings in $/W compared to planar arrays). SLA achieves these outstanding attributes due to its 8X optical concentration by employing flexible Fresnel lenses. This minimizes solar cell area, mass, and cost and allows for super-insulation and super-shielding of the solar cells to enable high-voltage operation and radiation hardness in the space environment without detrimental mass penalties. Recent studies show that SLA offers a 3-4X advantage over competing arrays in specific power for many NASA Exploration missions, and that SLA is ideally matched to Solar Electric Propulsion (SEP) applications. One study showed SLA with SEP could save NASA >$10 billion for lunar exploration cargo transportation.[1,2]

One of the key design issues includes the deployment mechanism. Figure 2 shows a 2.5 x 5 m SLA SquareRigger (SLASR) module that would produce approximately 3.75 kWe if fully populated with SLA units. It weighs only 10 kg and has been deployed successfully several times. Figure 3 shows the unique step-by-step deployment of the stretched lens array on the SquareRigger platform. The SLA technology can also be deployed with the conventional array designs in use today. `

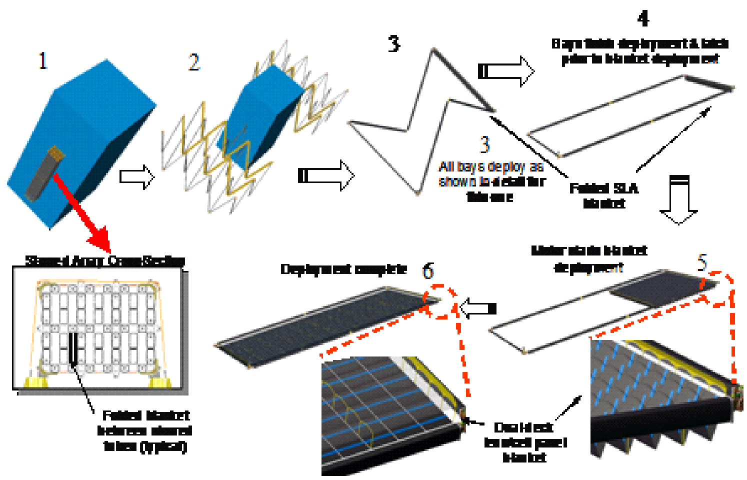

Figure 3. Stretched Lens Array SquareRigger Deployment

C. Material Testing

In the SLA's predecessor, SCARLET, the lens had a glass covering. Since this has been eliminated, much attention has been devoted to showing that the lens is durable to the space environment. Combined electron and proton testing has been conducted at NASA Marshall Space Flight Center (MSFC) that confirms the durability to those hazards. Testing has shown that the silicone lens material can tolerate 5x10^{10} rads of combined electron and proton exposure with only minor degradation. This is equivalent to 10 years on GEO using the current AE8/AP8 environments. Spectral transmittance data from NASA MSFC testing of lens material with UV-rejection coatings shows no damage after more than 1000 equivalent sun hours of combined vacuum ultraviolet (VUV) and near ultraviolet (NUV) exposure. The current lens coating blocks the VUV wavelengths below 200nm which are known to be the damaging wavelengths that cause yellowing of the silicone lens material. In addition, space tests on MISSE 1 on lens material with early coating compositions show excellent performance with minimal degradation after four years on orbit. Spectral transmittance measurements taken at NASA MSFC matched results from the unflown control proving minimal degradation. Lens material samples were also tested on MISSE 5 but those data are still unavailable at this time. Samples of the current lens coating will be flown on MISSE 6.

D. High Voltage Operation

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.[3] 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.

To test the sustainability of SLA in high voltage operations, array segments are under test for corona breakdown. ENTECH has fabricated and tested a number of such single-cell SLA receiver samples 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."[3] The samples have been undergoing testing at 2,250 V for over 200 days and have shown 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.

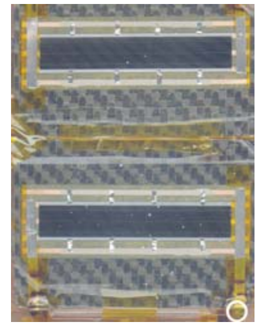

Figure 4. SLA module after testing

E. Resistance to Micrometeoroid Bombardment

In an effort to assess the SLA's resistance to micrometeoroid bombardment, hypervelocity impact tests were performed on an ENTECH, Inc. concentrator solar cell module and the silicone lens material. The module was tested to voltages over 1000 V while under hypervelocity particle impact in a plasma environment with no arcing. The DC 93-500 silicone lens material was held in tension as would be the case in space throughout testing and no tearing of the lens was seen. In fact, the SLA lens acts as a meteoroid bumper and thus provides additional protection for the cells. Figures 4 and 5 show the SLA module and lens sample after hypervelocity testing.[4]

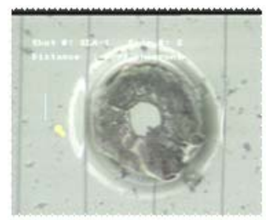

Figure 5. Lens sample after hypervelocity test

F. Flight Mission

A study was recently conducted to determine the practicality and potential advantages of an SEP space tug to deliver satellites to a GEO orbit. The tug was designed for a minimum of seven round trips. A SLASR array was used to provide direct-drive power to the Hall-effect thrusters. A spreadsheet model was generated to estimate the spiral trajectories and other mission parameters. A tug mass of 1000 kg was chosen to be the standard and analysis was done with the assumption that a satellite would be transferred on both the outbound and return legs of the mission. Variations of these parameters were run but due to a minimal change in the results they will not be discussed. The array for this mission requires additional shielding since the tug will slowly spiral through the radiation belts on each round trip between LEO and GEO. A 100 kWe SLA, adequately shielded with a 20 mil coverglass, will still have a specific power of 260 W/kg after seven round-trip LEO-GEO missions. A conventional planar one-sun array with the same amount of shielding would only have 70 W/kg after such a mission.

G. Radiation Resilience

The SLA must survive seven round-trip slow spiraling transits through the Earth's radiation belts with the requirement that the loss in solar array power is not excessive and still enables the 15 to 20 year mission life. Even for today's advanced triple-junction solar cells, the radiation dose for this mission requires significant radiation shielding of the cells to keep power degradation in a reasonable range. Because of the concentrator design, the ~4 cm^2 cells, designed for 8x concentration can be shielded against radiation damage at about 1/8th the mass of a conventional planar array.

The total mission radiation environment must be analyzed to determine the optimal amount of shielding needed to withstand the radiation dose. A trajectory must first be determined because the electron and proton radiation fluences vary widely with orbital altitude and inclination. The spreadsheet model estimates the spiral trajectories and the length of time the tug is in each

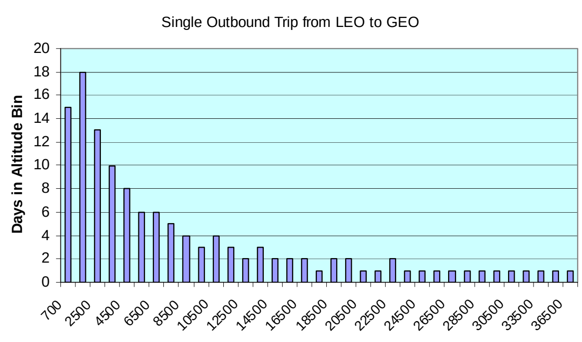

Figure 6. Number of days in each altitude bin for one outward bound trip from LEO to GEO

altitude bin. Figure 6 shows the estimated time that the tug will be in each altitude bin on one outward bound trip to GEO. This information can be used with ESA's Space Environmental Information System model (SPENVIS) to estimate the degradation of the solar array. Figure 7 shows the power degradation of a tug mission after 7 round trips through the Van Allen Belts. It is important to note that these calculations take into account the tug carrying the weight of a new satellite out to GEO and then carrying an old and outdated satellite back to LEO to then be returned to earth. If a satellite is not being brought back on the return trip the transit time is only 23% as long as the outbound trip for a 1000 kg tug. Therefore, the degradation will be lowered slightly due to the reduced time in the Van Allen radiation belts. Even for the worse case scenario of transferring a satellite both ways, the degradation in power will be only about 10% with twenty mils of coverglass. With additional shielding the percentage can be lessened to 5% but the weight increase will offset the degradation advantage to a certain point. Specific power calculations can be used to judge the optimal point between the choices.

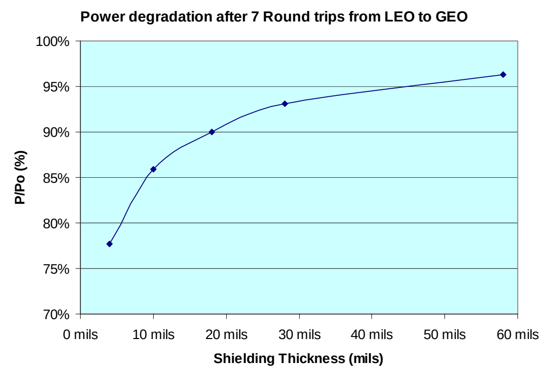

Figure 7. Power degradation of tug mission after 7 round trips.

H. Mass Advantage Over Planar

Comparisons of the end-of-life specific power between a SLA and a planar array are presented for an orbital transfer mission from LEO to GEO in Fig. 8. After seven round-trip missions where satellites are being transferred in both directions with a tug mass of 1000 kg, the SLA will still have a specific power of 260 W/kg compared to only 70 W/kg for a planar (one-sun) array. These calculations do not take into account that a heavier planar array would need more fuel for the round trip, which would increase the overall weight and trip time. Thereby, increasing the radiation damage and lowering the specific power. Several variations in tug mass and trip time were analyzed and results stayed relatively the same. The SLA has a huge mass advantage especially in high radiation environments making it an optimal candidate for SEP missions through the Van Allen Belts or even to Jupiter.

I. Future Flight Demonstrations

In order to confirm all of these advances through a space demonstration, a small test experiment is being implemented. This experiment will compare the performance of the SLA concentrator technology with that of conventional planar arrays. A subset of this experiment called the Stretched Lens Array Technology Experiment (SLATE-T4) is scheduled to fly on TacSat IV in 2008 in a high radiation orbit.

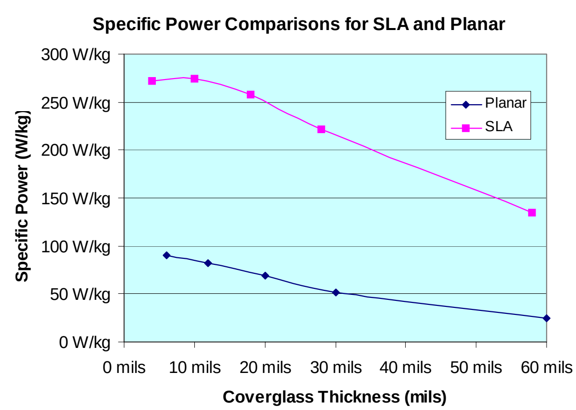

Figure 8. Specific power comparison for SLA and Planar Arrays

III. Conclusion

This paper has described progress made to date on the Stretched Lens Array which meets all the requirements for use on an SEP tug that travels between LEO and GEO. It is also potentially useful for deep space electric propulsion missions. The SLA can withstand the radiation damage needed to traverse the Van Allen Belts because it can be heavily shielded without a huge mass penalty (about 1/8th the mass of a conventional planar array) due to its 8X concentration which reduces the area, hence mass, of solar cells needed for the desired power range. SPENVIS simulations predicting the degradation and EOL specific power have shown the SLA's benefits and huge advantage over a planar array. Ground testing consisting of combined electron and proton testing and UV/VUV testing have confirmed the durability of the lens material and coating to space hazards. Corona testing had proven the SLA can operate at high voltage (>300 V) for extended times for Hall or ion thrusters. Hypervelocity testing at Auburn University showed the SLA's resistance to micrometeoroid impacts and electrostatic discharge even at voltages as high as 1000V. The SLA is an array that can withstand the differing environmental conditions as the vehicle travels from LEO to GEO (or at Jupiter). It is also an array that is light weight to preserve payload mass fraction – and to do this at a cost that is lower than today's arrays. The SLA is fully compliant with the new NASA-STD-4005 Low Earth Orbit Spacecraft Charging Design Standard. In conclusion, the SLA is reliable, scalable, cost-effective, durable, and efficient. It is an optimal candidate for SEP missions to GEO, the moon, Mars, and beyond.

Acknowledgments

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References

[1]O'Neill, M. J., Piszczor, M., Brandhorst, H., Carpenter, C., McDanal, A.J., "Stretched Lens Array (SLA) Solar Electric Propulsion (SEP) Space Tug: SLA-SEP Offers Multi-Billion-Dollar Savings Delivering Lunar Exploration Cargo," *4th World Conference on Photovoltaic Energy Conversion*, Waikoloa, Hawaii, 2006.

[2]Kosmann, W. J., "A Solar Electric Propulsion Lunar Exploration Architecture Evaluation," *57th International Astronautical Congress*, Valencia, Spain, October 2-6, 2006.

[3]Hamley, J. A., Sankovic, J. M., Lynn, P., O'Neill, M. J., Oleson, S. R., "Hall Thruster Direct Drive Demonstration," *33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Seattle, 1997.

[4]IEC International Standard #343 (1991): "Recommended test methods for determining the relative resistance of insulating materials to breakdown by surface discharges."

[5]Brandhorst, Jr., H. W., Ferguson, D. C., Piszczor, M. F., Vayner, B. V., O'Neill, M. J., "Impact of Solar Array Designs on High Voltage Operation in Space," *57th International Astronautical Congress*, Valencia, Spain, October 2-6, 2006.