A SEP MISSION TO JUPITER USING THE STRETCHED LENS ARRAY

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Abstract: As space exploration continues to be a primary focus of NASA, solar electric propulsion becomes a forerunner in the mode of transportation to reach other planets in our solar system. Several critical issues emerge as potential barriers to this approach such as reducing solar array radiation damage, operating the array at high voltage (>300 V) for extended times for Hall or ion thrusters, and designing an array that will be resistant to micrometeoroid impacts and the differing environmental conditions as the vehicle travels further into space. It is also of great importance to produce 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 on the Stretched Lens Array, an array that meets all these requirements, and will detail its use in a solar electric mission to Jupiter. The SLA is durable, reliable, radiation resistant, lightweight, and cost-effective making it an optimal candidate for deep space electric propulsion missions to Jupiter and beyond.

INTRODUCTION

As space exploration continues to be a primary focus of NASA, solar electric propulsion (SEP) becomes a forerunner in the mode of transportation to reach other planets in our solar system. Several critical issues emerge as potential barriers to this approach such as reducing solar array radiation damage, operating the array at high voltage (>300 V) for extended times for Hall or ion thrusters, and designing an array that will be resistant to micrometeoroid impacts and the differing environmental conditions as the vehicle travels further into space. It is also of great importance to produce 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 on the Stretched Lens Array (SLA), an array that meets all these requirements, and will detail its use in a solar electric mission to Jupiter. The analysis will consist of a spiral out trajectory to Jupiter including a radiation analysis of the SLA through the Van Allen Belts and Jupiter's radiation belts. Calculations of solar cell efficiency loss due to radiation using the SAVANT radiation damage code will be presented, and the results will be used to optimize solar cell cover glass thickness. Terrestrial and space testing of the SLA will be documented showing its applicability to a SEP mission. The SLA is durable, reliable, radiation resistant, lightweight, and cost-effective. The Stretched Lens Array is an optimal candidate for deep space electric propulsion missions to Jupiter and beyond.

BACKGROUND

The SLA is a unique ultra-high-performance, ultra-light, cost-effective photovoltaic concentrator array using refractive concentrator technology. Unlike reflective concentrators, these refractive Fresnel lens concentrators can be configured to minimize the effects of shape errors, enabling straightforward manufacture, assembly, and operation on orbit. By using a unique arch shape, these Fresnel lenses provide more than 100X larger slope error tolerance than either reflective concentrators or conventional flat Fresnel lens concentrators [1]. The first refractive concentrator array was developed and flown on the PASP-Plus mission in 1994-95, which included a number of small advanced arrays with a mini-dome lens concentrator [2]. It outperformed all the other advanced arrays and showed minimal degradation. In the late 1990's, a new line-focus Fresnel lens concentrator, which is easier to make and more cost-

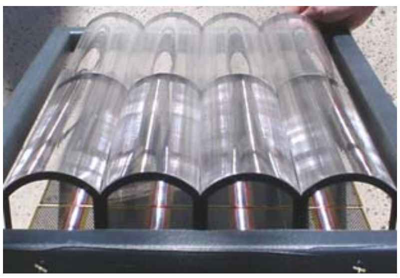

Fig. 1. Lightweight SLA module

effective than the mini-dome lens concentrator, was developed. It was flown from 1998-2001 in NASA's Deep Space 1 mission that validated the use of ion propulsion for extended space missions [3]. This array performed flawlessly and within 2% of its projected performance over the entire mission. That design has evolved into the Stretched Lens Array (SLA) shown in figure 1. 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. Because of its 8.5X geometric concentration ratio, SLA saves over 85% of the required area, mass and cost of the multi-junction solar cells per watt of power produced. Significantly, the total combined areal mass density (kg/m^2 of sun-collecting aperture area) of the lens material, the radiator sheet material, and the fully assembled photovoltaic receiver is much less (about 50%) than for a one-sun multi-junction cell assembly alone. Thus, SLA has a substantial inherent mass advantage over planar, one-sun multi-junction-cell solar arrays. Similarly, due to its 85% cell area and cost savings, SLA has a substantial inherent power cost advantage ($/W) over such planar multi-junction-cell arrays. The Stretched Lens Array (SLA) offers unprecedented performance (>80 kW/m^3 stowed power, >300 W/m^2 areal power, and >300 W/kg specific power) and cost-effectiveness (50-75% savings in $/W compared to conventional solar arrays).

Fig. 2. Full scale SLASR panel

SLA's small cell size also allows super-insulation and super-shielding of the solar cells to enable high-voltage operation and radiation hardness in the space environment. SLA's demonstrated high performance and radiation tolerance, coupled with its substantial mass and cost advantages, will lead to many applications including SEP. The module shown in figure 2 is the latest version of the design. This design leads to a specific power exceeding 300 W/kg at voltages exceeding 300 V.

TRAJECTORY MODELING

Our desire was to find a plausible trajectory to Jupiter using SOA thrusters. We opted for a converged trajectory with the assumption of a launch with an Atlas 551, which is what the JPL solar powered Europa study used [4]. This is a reasonable approach to performing SEP missions. We also opted for a direct earth to Jupiter transfer. Had we done a Venus and/or Earth flyby, performance would have been much better. We used the simple inverse square power model rather than one that would have approximated multi-junction cell technology. Our spacecraft was initially 4000 kg. It took 230 days to spiral out to GEO. The total mission time to Jupiter is 8.96 years. The spacecraft weighted 1786 kg upon arriving at Jupiter. The Earth departure trajectory can be seen in figure 3. The Jupiter trajectory looks the same but with different scales. A sample trajectory to Europa can be seen in figure 4.

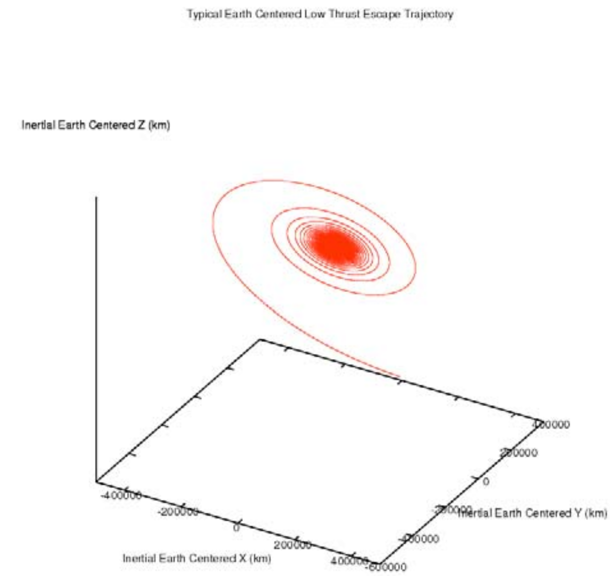

Fig. 3. Earth departure from Jupiter

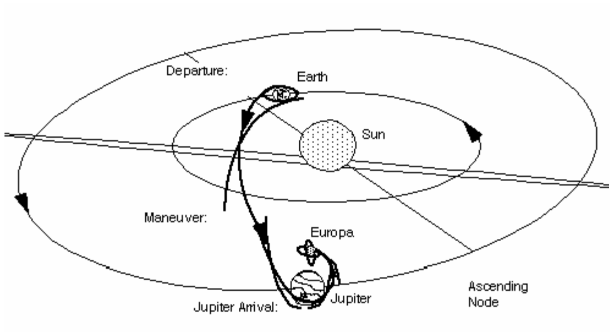

Fig. 4. Sample Jupiter trajectory taken from a probe study at www.tsgc.utexas.edu/archive/design/europa

RADIATION ANALYSIS

SEP missions to Jupiter, with its exceptional radiation belts, would mandate a radiation-resistant solar array to compete with a radioisotope alternative. Because of the concentrator design, the

~10 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.

A SEP mission to Jupiter will involve significant times in the radiation belts of Earth (while spiraling out from Earth) and Jupiter (while spiraling into its magnetosphere). In the case of the proposed mission, it is the radiation damage on high efficiency triple junction cells that should be considered. The solar cells used in the SLA are of the following lay up (top to bottom):

X mils of CMG ceria-doped cover glass (X is the mission-optimized Thickness, 3 < X < 20 mils, typically)
1 mil (25 microns) of DC93-500 silicone adhesive
5.5 mils (140 microns) of Ge/GaAs/GaInP multi-junction cell
Cell substrate

Trajectory information for SEP spiral orbits in the Jovian and terrestrial magnetospheres was provided by John Riehl of GRC. We ran into some unexpected difficulty with obtaining a trajectory around Jupiter that enabled a detailed radiation analysis. We were forced to take a more simplistic approach to the radiation analysis by equating it to the radiation dose accumulated in the Earth's belts. The maximum electron and proton densities are roughly an order of magnitude higher in the Jovian belts than in the terrestrial belts [5]. The total time in the Jovian belts was estimated to be about 2 years during the spiral orbit, equivalent to about 20 years in Earth's belts. Since the total time in Earth's Van Allen belts was much less than a year, the radiation damage in Earth's belts would be small compared to that in Jupiter's, and the damage over the entire mission could be approximated by that during the mission time in the Jovian magnetosphere. The final destination at one of the Jovian moons is still well within the Jovian belts, so the total mission time at Jupiter is the final determiner of the total radiation dose.

The models used to evaluate radiation damage to these cells were of the Non-Ionizing Energy Loss (NIEL) Displacement Damage Dose (Dd) variety. These are the type of model used in the SAVANT (Solar Array Verification and Analysis Tool) and have been shown to give good results for radiation-induced power loss on solar arrays in Earth's magnetosphere [6]. Scott Messenger, of NRL, ran the Dd model for the SLA type solar cells for a one-year mission in the heart of Earth's proton radiation belts (expected to cause the most damage). His results for one year at solar max using a 1000x2500 km orbit in Earth's magnetosphere gave the following proton displacement damage doses and power losses for cover glasses of varying thickness as seen in Table 1.

Table 1: Proton Displacement Damage Doses and Power Losses in Earth's Radiation Belts

Cover Glass Thickness (mils SiO_2)	Total Displacement Damage Dose (MeV/g)	Pmax/Pmax0(%)
1	5.57E+09	0.858
3	4.44E+09	0.875
6	3.64E+09	0.889
12	2.68E+09	0.909
20	1.96E+09	0.927
30	1.49E+09	0.941
60	9.26E+08	0.960

It can be seen that for thick cover glasses, the radiation losses are miniscule. When this is scaled up to 20 years in Earth orbit [7] corresponding to the spiral part of the SLA SEP mission at Jupiter, we have the following proton doses and power losses as seen in Table 2.

Table 2: Proton Displacement Damage Doses and Power Losses at Jupiter

Cover Glass Thickness (mils SiO_2)	Total Displacement Damage Dose (Me V/g)	Pmax/Pmax0(%)
1	1.14E+11	0.565
3	8.88E+10	0.589
6	7.28E+10	0.610
12	5.36E+10	0.642
20	3.92E+10	0.674
30	2.98E+10	0.703
60	1.85E+10	0.750

It should be noted that these are very rough estimates, but we believe they are valuable as a guide to what thickness of cover glass must be used on SEP-to-Jupiter triple junction cells. The total radiation doses agree roughly with estimates for other Jovian missions such as JIMO.

Here it can be seen that in order to obtain acceptable power losses (that do not lead to excessive masses for arrays scaled up to provide adequate end-of-life power), very thick cover glasses must be used, on the order of 30 mils or more. Such thick cover glasses would be weight-prohibitive if used on a conventional solar array. For the SLA, since most of the array area is concentrator area, not solar cell area, the thick cover glasses needed for radiation protection add only an acceptable amount of mass.

If the mission lifetime within the Jovian magnetosphere is extended, power losses will be proportionally increased. The maximum power decreases as the logarithm of the dose or exposure time. However, the mass advantages of using SLA rather than conventional arrays will still be valid.

While adding cover glasses of sufficient thickness or adding solar array area to conventional arrays to make up for EOL power in the Jovian magnetosphere would lead to prohibitively massive conventional solar arrays, SLA can be designed to use cover glasses of sufficient thickness to prevent large power losses without large mass increases. Thus, one can say that SLA enables the SEP mission to Jupiter.

GROUND TESTING

The SLA is capable of high voltage operation and sustainability in a high radiation environment which is essential for solar electric propulsion. 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 [8]. 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.

Hypervelocity Impact and corona discharge tests have confirmed the durability of this array design for high voltage operation. Auburn and ENTECH Inc. have performed testing based on guidelines for the terrestrial test from the European community (IEC 343) [9]. The purpose of corona testing is to determine the lifetime of solar array designs under high voltage stress in the space environment. ENTECH has performed initial long-term ground tests of Stretched Lens Array photovoltaic circuit samples at very high voltage (2,000-5,000 VDC) under water, which crudely simulates space plasma. Auburn has conducted similar tests in vacuum using the same type of fully encapsulated receiver samples. The sample is maintained at room temperature under a vacuum of approximately $6x10^{-5}$ torr. The samples underwent testing for ten and a half months at 2,250 V and showed no change. Due to the SLA's inherent protection against electrostatic discharge it is especially well suited for electric propulsion missions.

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 as shown in Fig. 5. The SLA lens acts as a meteoroid bumper and thus provides additional protection.

Fig. 5. Lens sample after hypervelocity shot

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. 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. All aspects of the SLA have tested durable to the space environment.

Future terrestrial testing efforts include a direct drive experiment of a 600 V SunLine concentrator photovoltaic array with a Russian T-100 Hall thruster being performed at Auburn University. The goal is to prove reliable operation of the Hall thruster from the high voltage concentrator array. Testing will include the addition of Stretched Lens Array hardware in the chamber at Auburn to measure plume impingement effects at various positions relative to the exhaust axis of the thruster. The schematic of the planned direct-driven HET and SLA test configuration can be seen in Fig. 6.

CONCLUSION

This paper described how the Stretched Lens Array meets all the requirements for a SEP mission to Jupiter. The SLA is durable, reliable, radiation resistant, lightweight, and cost-effective. It enables high voltage operation and sustainability in a high

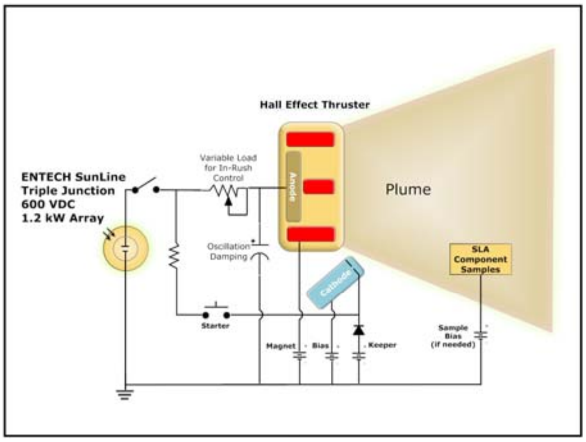

Fig. 6. Schematic of planned direct-driven HET and SLA test configuration.

radiation environment which is essential for SEP missions. While adding cover glasses of sufficient thickness or adding solar array area to conventional arrays to make up for EOL power in the Jovian magnetosphere would lead to prohibitively massive conventional solar arrays, SLA can be designed to use cover glasses of sufficient thickness to prevent large power losses without large mass increases. Thus, one can say that SLA enables the SEP mission to Jupiter.

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