STRETCHED LENS ARRAY (SLA), A RELIABLE SOLAR ARRAY FOR ANY ORBIT

Julie A Rodiek[1], Henry W. Brandhorst[2], and Mark J. O'Neill[3]
[1,2]Space Research Institute, Auburn University, AL 36849
[3]ENTECH, Inc., Keller, TX 76248

INTRODUCTION

On any satellite, the solar array is exposed to the harshest environment compared to the other systems and payloads; therefore, it is not surprising to find in the last ten years 117 satellite solar array anomalies have been reported with 12 satellites being retired due to solar array failure. Eighty-three (71%) of these anomalies have occurred in geosynchronous orbit with electrostatic discharges being the primary fault. Solar array reliability has become a serious issue. A solar array that can withstand the hazards of the space environment and is continually reliable is imperative in order to reverse the increases in insurance costs and restore international confidence in U.S. satellites.

The Stretched Lens Array (SLA), shown in Fig. 1, is a superior solar array for all orbital applications. The SLA is a refractive photovoltaic concentrator array with efficiencies greater than 27%. It has outstanding performance ratings, provides arc-free high voltage operation, and is resistant to micrometeoroid impacts. The SLA is lightweight, affordable, durable, and, most importantly, reliable.

This paper will discuss solar array satellite anomalies mentioned at *Prospector XII – Space Solar Array Cost Reduction Workshop* and document these same trends through the use of AirClaims's Ascend SpaceTrak database. These anomalies affect the cost and design of today's solar arrays. The SLA is capable of reliable operation without the anomalies affecting most solar arrays. Analytical modeling and terrestrial test results of the SLA will be presented and examined to demonstrate its ability to operate in all orbits, SEP missions, and planetary outposts.

Fig. 1. Stretched lens array in sunlight

SOLAR ARRAY RELIABILITY

Providing reliable power over the anticipated mission life is critical to all satellites; therefore solar arrays are one of the most vital links to satellite mission success. Furthermore, solar arrays are exposed to the harshest environment of virtually any satellite component. Over the last ten years Airclaims's Ascend SpaceTrak database has documented 117 satellite solar array anomalies, 12 of which resulted in total satellite failure. Through an in-depth analysis of satellite anomalies it is clear that solar array reliability is a serious, industry-wide issue.

Prospector XII – Space Solar Array Cost Workshop

Last September, *Prospector XII – Space Solar Array Cost Reduction Workshop* was held in Park City, Utah. The two main objectives of the workshop were to determine what the major drivers of spacecraft solar array-related costs are and to make recommendations as to what steps could be taken to implement changes across the industry to reduce these solar array-related costs to the benefit of all space sectors. Prospector attendees quickly came to the consensus that cost reduction strategies must lead to significant increases in solar array reliability verses cost cutting in the design and fabrication of solar arrays and cells. The approach for making major cost reductions is best achieved by reliability improvements and subsequently demonstrated solar array durability in ground testing. Another recommendation was to embrace new technologies that are inherently designed to withstand the environmental factors causing most solar array anomalies.

Solar Array Anomalies

In an effort to better understand and face the challenge of solar array anomalies on orbit, more feedback and dissemination of the data to the entire industry is essential. After the conclusion of the workshop a detailed statistical analysis of satellite anomalies was started to find out what is reality versus what is perception. This paper examines trends in the types of anomalies seen in satellites in the past ten years by using information from the Airclaims's Ascend SpaceTrak database. This database is the space industry's leading events-based launch and satellite database and reports events as they occur.

It was 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. Figure 2 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.

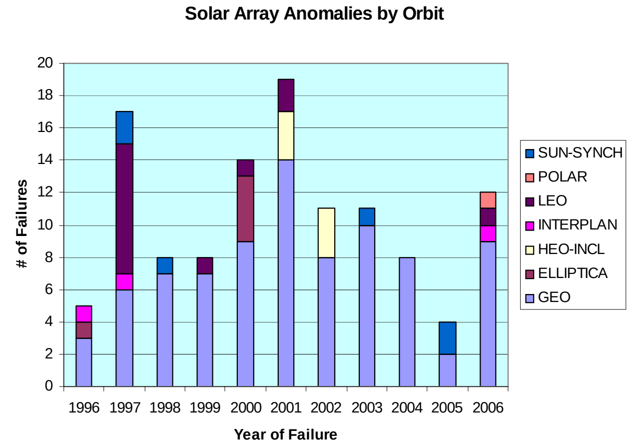

Fig. 2. Satellite failures by orbit

The number of solar array anomalies in satellites in GEO coincide quite well with the classic infant mortality curve as can be seen in Figure 3. 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. Nearly all manufacturers have this problem; therefore defects in construction are an unlikely cause. However, new designs are usually rejected due to the belief that flight heritage is the best proof of performance. These anomalies affect the cost and design of today's solar arrays. Insurance premiums are directly related to industry claims and past performance. A solar array that can withstand the hazards of the space environment and is continually reliable is imperative in order to reverse the increases in insurance costs and restore international confidence in U.S. satellites.

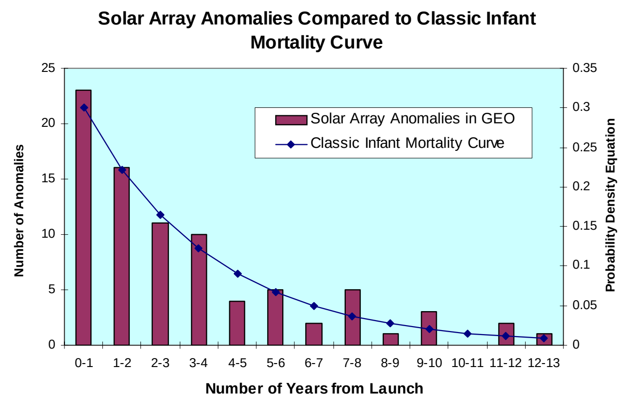

Fig. 3. Solar array anomalies compared to infant mortality curve

Insurance Costs

Prospector helped show the link between solar array costs and increased insurance premiums due to the high failure rate. The majority of insurance claims are due to solar array anomalies as seen in Fig. 4. The astounding fact that truly shows the significance of increasing reliability is that solar arrays made up 49% of the value of all insurance claims as shown in Fig. 5. Insurance premiums are directly related to industry claims and past performance. This results in not only increases in future insurance premiums (~50% of the satellite cost), but the requirement by the insurance industry to design additional margin into power budgets before even issuing a policy is considered. Past insurance claims also decrease the confidence of new investors. The impact of solar array anomalies must be addressed and a reliable array must be found.

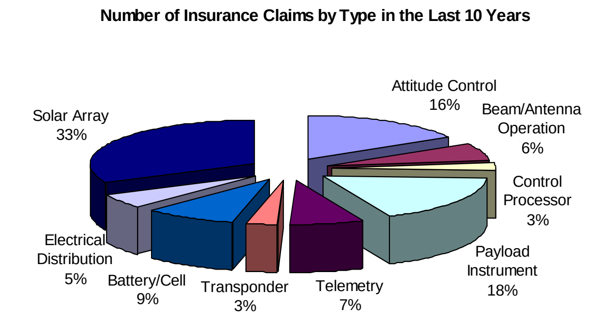

Fig. 4. Insurance claims from anomalies

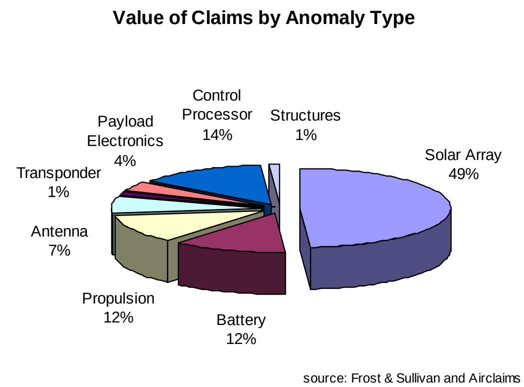

Fig. 5. Value of insurance claims for 2004

STRETCHED LENS ARRAY

The Stretched Lens Array (SLA), shown previously in Fig. 1, is a superior solar array for all orbital applications. The SLA is a refractive photovoltaic concentrator array with efficiency greater than 27%. Its design characteristics protect against electrical discharge, micrometeoroid impacts, and radiation degradation. It provides arc-free high voltage operation because the cells are fully encapsulated providing a sealed environment. The SLA provides reliable, predictable power delivery over the mission life which is critical to all satellites. Reliable solar arrays are integral to mission success and the SLA withstands the hazards of space operation regardless of orbit.

Performance Ratings

SLA's unique, lightweight, and efficient design leads to outstanding performance ratings (>80 kW/m^3 stowed power, >300 W/m^2 areal power, and >300 W/kg specific power). The SLA is a cost effective solution with 50-75% savings in $/W compared to planar solar arrays. Thicker shielding and increased insulation to protect against radiation degradation and arcing can be added with minimal mass and weight detriment.

Flexible blanket and rigid panel versions of the SLA have been developed and tested over the last decade. A 3.75 kW scale (2.5 x 5.0 m) building block of the Stretched Lens Array on the SquareRigger platform has been successfully demonstrated as seen in Fig. 6. That demonstration confirmed that the specific power goal of >300 W/kg is achievable.

Fig. 6. 3.75 kW SLA on a SquareRigger platform

Analytic Modeling

Radiation shielding can be increased with little impact on array 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. This is due to its 8X concentration which reduces the area, hence mass, of solar cells needed for the desired power range. To understand and compare the various radiation environments for these orbits, simulations have been run using The European Space Environment Information System (SPENVIS) The SPENVIS model provides the 1 MeV equivalent electron radiation doses for given orbits and durations. 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. A high radiation orbit of 5000 km with a 28 degree inclination angle was chosen as an example. 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. Figure 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.

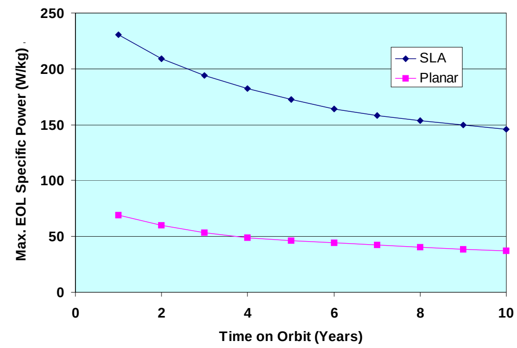

Fig. 7. EOL specific power with optimal shielding

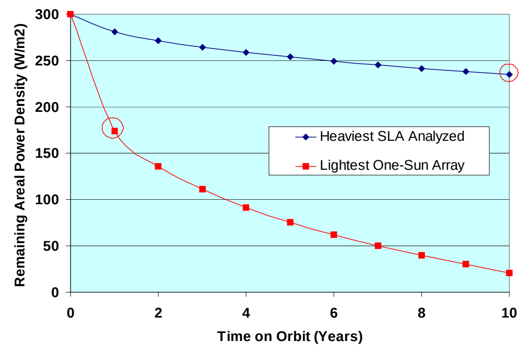

Fig. 8. SLA/planar areal power density comparison

Terrestrial & Space Test Results

The SLA enables high voltage operation and sustainability in the GEO environment which is especially dangerous for solar arrays. As is well known, operating spacecraft buses at 100 V and above has led to arcing in GEO communications satellites, so the issue of spacecraft charging and solar array arcing remains a serious design problem. A beneficial design feature of the SLA is the entire cell and cell edges are fully encapsulated by a cover glass that overhangs the cell perimeter and the silicone adhesive covers the cell edges providing a sealed environment limiting the chance of electrostatic discharge. 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). 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 have been undergoing testing at 2,250 V since January 5, 2007 and have shown no change. Due to the SLA's inherent protection against electrostatic discharge it is especially well suited for electric propulsion missions and high power geosynchronous orbits. The SLA is also fully compliant with the new NASA-STD-4005 Low Earth Orbit Spacecraft Charging Design Standard.

Fig. 9. Lens sample after hypervelocity shot

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. 9. The SLA lens acts as a meteoroid bumper and thus provides additional protection.

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 5×10^{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.

CONCLUSION

Solar arrays are vital to satellite mission success; however, solar array anomalies continue to occur, thus making them unreliable and costly liabilities. Analysis has shown that GEO is the most hazardous orbit for solar arrays with 71% of anomalies occurring there. The consequences of failures affect the industry though high insurance rates and a negative perception on the space industry as a whole. A solar array that can withstand the hazards of the space environment and is continually reliable is imperative in order to reverse the increases in insurance costs and restore international confidence in U.S. satellites.

The Stretched Lens Array (SLA) is a superior solar array for all orbital applications. Analytical modeling and terrestrial test results of the SLA have been examined to demonstrate its ability to withstand the hazards of the space environment in all orbits. SPENVIS simulations predicting the degradation, EOL specific power, and EOL areal power density 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 without arcing. Hypervelocity testing at Auburn University showed the SLA’s resistance to micrometeoroid impacts and electrostatic discharge even at voltages as high as 1000V. In conclusion, the SLA is a practical and affordable, not to mention reliable solution to solar array power needs in all orbits, SEP missions, and planetary outposts.