

Ultra-light stretched Fresnel lens solar concentrator for space power applications

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ABSTRACT

A unique ultra-light solar concentrator has recently been developed for space power applications. The concentrator comprises a flexible, 140-micron-thick, line-focus Fresnel lens, made in a continuous process from space-qualified transparent silicone rubber material. For deployment and support in space, end arches are used to tension the lens material in a lengthwise fashion, forming a cylindrical stressed membrane structure. The resultant lens provides high optical efficiency, outstanding tolerance for real-world errors and aberrations, and excellent focusing performance. The stretched lens is used to collect and focus sunlight at 8X concentration onto high-efficiency multi-junction photovoltaic cells, which directly convert the incident solar energy to electricity. The Stretched Lens Array (SLA) has been measured at over 27% net solar-to-electric conversion efficiency for space sunlight, and over 30% net solar-to-electric conversion efficiency for terrestrial sunlight. More importantly, the SLA provides over 180 W/kg specific power at a greatly reduced cost compared to conventional planar photovoltaic arrays in space. The cost savings are due to the use of 85% less of the expensive solar cell material per unit of power produced. SLA is a direct descendent of the award-winning SCARLET array which performed flawlessly on the NASA/JPL Deep Space 1 spacecraft from 1998-2001.

Keywords: Ultra-light, Fresnel lens, solar concentrator, photovoltaic, multi-junction cells, space power, silicone, stressed membrane, stretched lens array, specific power

1. INTRODUCTION

Fig. 1 shows the basic concept of the Stretched Lens Array (SLA) in an early functional prototype. Thin (140 micron), flexible, line-focus Fresnel lenses, made from a space-qualified silicone polymer (Dow Corning DC93-500), are deployed and supported by end arches, which tension the lenses in their lengthwise direction forming a stressed membrane optical element. These stretched lenses collect space sunlight and focus it onto narrow state-of-the-art multi-junction photovoltaic (PV) cell receivers, which are mounted to thin (125 micron) carbon composite sheet radiators for waste heat rejection to deep space.

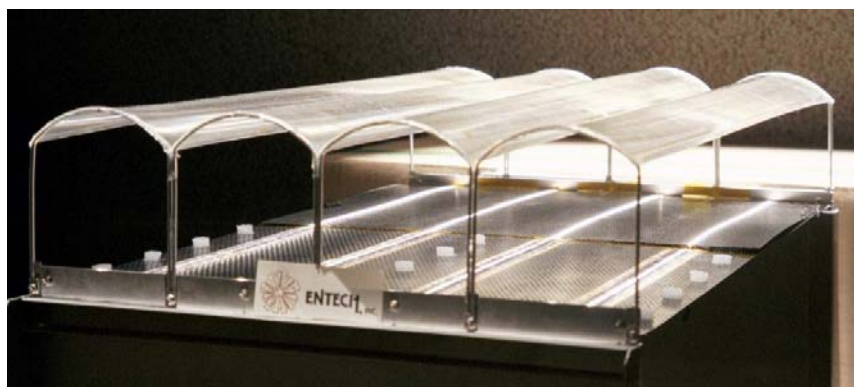


Figure 1 – Stretched Lens Array (SLA) with Four Lenses and Receivers

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The arched-shaped lenses are each 8.5 cm wide, and focus sunlight onto PV cells which are 1.0 cm wide, for a geometric concentration ratio of 8.5X. This 8.5X concentration ratio was selected to provide ± 2 degrees of sun-pointing tolerance without appreciable power loss. Compared to conventional planar one-sun photovoltaic arrays, SLA's principal and inherent advantages include a significantly lower mass (kg/m^2) and a substantially lower cost ($\$/\text{W}$). SLA's weight advantage is due to the simple fact that the lens, radiator, and narrow photovoltaic receiver assembly, all taken together, weigh about half as much per square meter as a one-sun solar cell assembly by itself. SLA's cost advantage is due to the use of 85% less of the expensive photovoltaic cell material per Watt of power produced. In addition, SLA offers better electrical performance (W/m^2) than conventional planar one-sun photovoltaic arrays, due to the normal gain in cell conversion efficiency with concentration. The small size of the photovoltaic receiver in SLA enables super-encapsulation of the photovoltaic circuit with very little mass penalty. Such super-encapsulation can be tailored to enable high-voltage operation in space plasma and/or to provide radiation hardness for space missions in high charged-particle radiation environments.

Since a stressed membrane support method will never provide a near-perfect shape for the optical element, the lens is engineered to be extremely shape-error tolerant. This shape error tolerance is obtained by configuring the lens to a unique arch shape, wherein each prism comprising the lens symmetrically refracts the solar ray passing through it. As shown in Fig. 2, for each prism in the lens, the solar ray angle of incidence at the smooth outer surface is equal to the solar ray angle of emergence at the prismatic inner surface. This symmetrical refraction condition, combined with the refractive index of the lens material, fully defines the lens shape and prismatic pattern, and implies that each prism is oriented at its minimum-deviation condition. The symmetrical refraction lens has two key optical benefits: minimum total reflection loss at the two lens/vacuum interfaces (thereby maximizing throughput transmittance) and a unique and remarkable slope error tolerance. Compared to a reflective concentrator of any kind or to a conventional flat Fresnel lens, the slope error tolerance of the symmetrical refraction lens is more than 100 times better, as further discussed in later sections of this paper. This shape error tolerance is critical to the excellent optical performance of the SLA and of

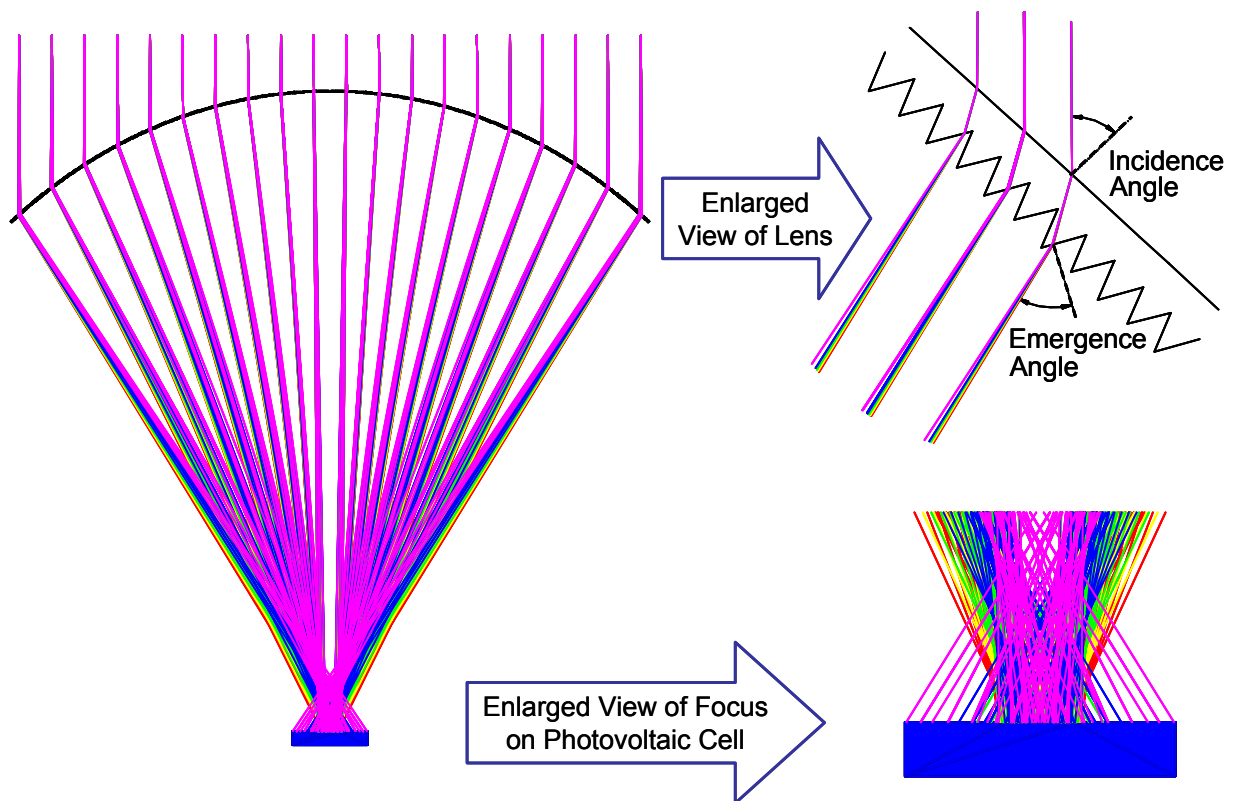


Figure 2 – Symmetrical Refraction Lens with False-Color Rays Showing Wavelengths in the Photovoltaic Cell Response Range (0.36 μm to 1.80 μm for All Three Junctions of a Triple-Junction GaInP/GaAs/Ge Cell)

its predecessor solar concentrator arrays which also used the symmetrical refraction lens approach. The following section compares the symmetrical refraction lens approach with reflective concentrator arrays which have recently experienced highly publicized problems on communication satellites.

2. FRESNEL LENS VERSUS MIRROR SOLAR CONCENTRATORS: VASTLY DIFFERENT

In the past two years, significant problems with large reflective concentrator arrays on six GEO communication satellites have been highly publicized [1-3]. These reflective concentrator arrays use vastly different technology than the stretched lens array (SLA), which is the subject of this paper. The reflective concentrator arrays use 60-degree tilted mirrors on both sides of planar photovoltaic panels to increase the solar flux on these panels, an approach which has also been attempted in large terrestrial solar arrays, which also suffered from significant problems [4]. The basic concept of using tilted mirrors to augment the solar flux on planar photovoltaic panels is shown in the left sketch of Fig. 3. If such mirrors could be made and maintained in a perfect optically flat configuration, the reflected solar flux would be uniform over the planar photovoltaic panel, nearly doubling the total solar flux on the panel. Unfortunately, shape errors in these mirrors can cause significant losses and non-uniformity of the reflected solar flux on the planar photovoltaic panel, as shown in the right sketch of Fig. 3. If the mirror errors lead to concavity, the reflected flux can have spikes and voids. If the mirror errors lead to convexity, the reflected flux can be reduced by significant reflected ray losses. Both types of mirror errors are shown in the right sketch of Fig. 3, for an example value of the maximum slope error of 10 degrees at the edges of the mirrors.

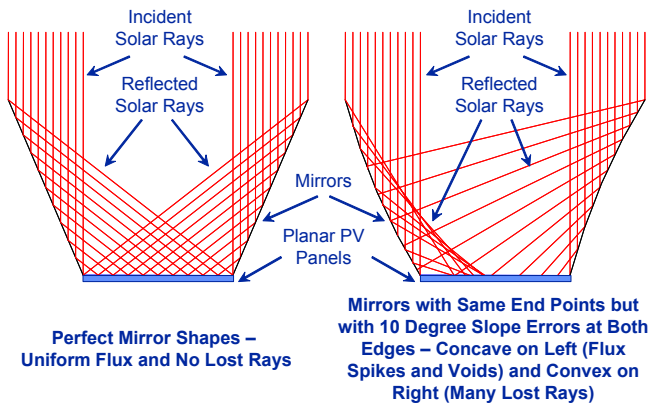


Figure 3 – Ray Traces for 60° Tilted Mirrors for Perfect Mirrors (Left) and for Mirrors with Shape Errors (Right)

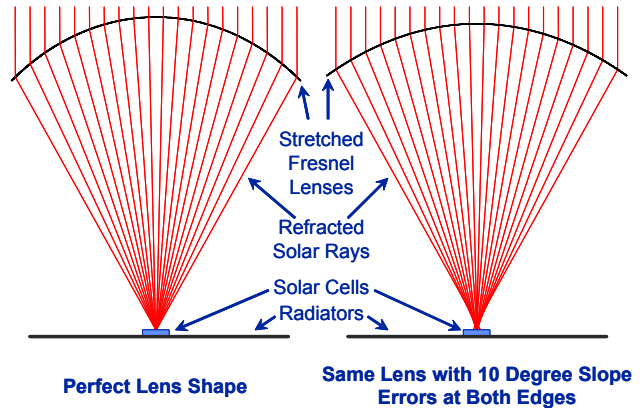


Figure 4 – Ray Traces for Symmetrical-Refraction Lens for a Perfect Lens Shape (Left) and for a Lens with Shape Errors (Right)

In contrast to reflective optics, the stretched lens array (SLA) uses a symmetrical-refraction Fresnel lens, described in the previous section, which is by far the most error-tolerant optical concentrator yet developed [5,6]. The symmetrical-refraction lens concentrator approach is shown in the left sketch of Fig. 4. The right sketch shows a ray trace for the same symmetrical-refraction lens with its shape distorted by a similar amount as for the mirrors in Fig. 3, i.e., with 10 degree slope errors at both edges. Note that the lens still focuses almost perfectly despite these large slope errors. This unique error tolerance has been fully described in previous publications about the symmetrical-refraction lens, which is more than 100 times as tolerant of shape errors as any reflective concentrator [6]. A direct comparison of the right sketches of Figs. 3 and 4 shows why shape errors are the most critical optical problem for reflective concentrators of all types, while shape errors are not even a significant concern for the symmetrical refraction lens.

While the shape error tolerance of the symmetrical-refraction lens (Fig. 4) is its most dramatic advantage over reflective concentrators (Fig. 3), a more complete comparison of these two concentrator approaches is provided in Table 1 (on the following page). A conventional planar array is also included in this comparison as the point of departure for both concentrator designs. The primary reason for using concentrators instead of planar arrays is to save cell area, mass, and cost, and the higher concentration of SLA leads to much higher savings than for the reflective concentrator. The space flight heritage of the Fresnel lens concentrators has been excellent, in contrast to the reflective approach. Boeing has

Item	Planar Array	2X Mirror-Augmented Array (Reflective Trough Array)	8.5X Stretched Lens Array (SLA)
Cell Savings vs. Planar Array: Area, Mass, and Cost per Watt	0%	50%	85%
Space Flight Heritage and Experience	Numerous Successful Programs	Significant Performance Problems on 6 Boeing 702 Comsats (and Geometry Is Conducive to Outgassing/Photofixing)	Extremely Successful: PASP+ and SCARLET on Deep Space 1 (and Geometry Discourages Photofixing)
Terrestrial Experience for Similar Technology	Numerous Successful Programs	Significant Performance Problems for Reflective Systems (e.g., ARCO Solar 5 MW System at Carissa Plains – Mirrors Reduced Power)	Several Successful Programs (e.g., Best Performance of All 20 kW PVUSA Arrays for 10 Years)
Optics – Inherent Shape Error Problems	N/A	Significant Problem (Efficiency and/or Flux Uniformity)	Negligible Problem (200X Advantage Over Mirrors)
Predictable, Same, Unchanging Photon Flux on Each Solar Cell in Each Source Circuit	Yes	No – Reflective Optics Are Inherently Sensitive to Minuscule Shape Errors (e.g., Hubble Telescope Primary)	Yes – ENTECH’s Error-Tolerant Refractive Optics
Cell Operating Temperature on GEO	50-60C	120-130C	75-80C
Super-Encapsulation of Cells for High-Voltage and/or High-Radiation Missions	Difficult and Heavy	Relatively Difficult and Relatively Heavy	Simple and Lightweight – Auburn Micrometeoroid Tests with Cells at 1,000 V

Table 1 – Fundamental Comparison of Different High-Efficiency Space Solar Arrays

diagnosed the problems on the 702 communication satellite arrays, and believes that outgassing products from the hot photovoltaic panels caused deposits on the mirrors, which were within the line-of-sight of the panel outgassing source. This deposition of outgassing products on the mirrors was enabled by a “photofixing” process made possible by the direct solar flux on the mirrors [3]. The material deposited on the mirrors could then itself outgas and cause deposits on the photovoltaic panels, which were within the line-of-sight of the mirror outgassing source. The deposition of outgassing products on the photovoltaic panels was enabled by the “photofixing” process made possible by the direct solar flux on the cells [3]. SLA’s geometry inherently discourages this complex process, since only the outer lens surface is exposed to direct solar flux. SLA’s predecessor, the SCARLET (Solar Concentrator Array using Linear Element Technology) array, which performed flawlessly for 38 months on Deep Space 1, did not experience any of the unexpected power degradation problems experienced by the Boeing 702 communication satellite arrays.

As summarized in Table 1, the terrestrial experience for both reflective and refractive concentrator approaches has also been problematic for the mirrors, and successful for the lenses. In fact, a 5 MW installation of 2X mirror-augmented silicon photovoltaic panels was installed by ARCO Solar in the middle 1980’s, and degraded rapidly in power output [4]. In fact, when the system was being dismantled in the early 1990’s, tests were run on array segments with and then without the mirrors in place, and more power was measured with the mirrors removed than with them in place [4]. In stark contrast, the line-focus Fresnel lens array at the U.S. Department of Energy-sponsored Photovoltaics for Utility Scale Applications (PVUSA) test site in Davis, California, outperformed all of the other photovoltaic technologies in an independent, side-by-side field test throughout the whole decade of the 1990’s [7].

The inherent shape-error tolerance of the symmetrical-refraction lens enables the concentrated solar flux profile over the solar cell to be tailored by design and then accurately produced and maintained over the operational life of the system. In contrast, minute shape errors in reflective concentrators cause substantial variations in the concentrated solar flux profile, not only over an individual solar cell, but also from cell-to-cell in a series string of cells forming a source circuit. These photon flux variations from cell-to-cell in a source circuit, and the cell current variations they produce, are the Achilles’ heel of reflective concentrator optics, since they can substantially degrade the source circuit power output.

As summarized in Table 1, an additional problem for the mirror-augmented panel (reflective trough) is the high cell operating temperature caused by the increased solar flux without a corresponding increase in heat rejection area. SLA does not suffer from this problem, since its heat rejection area equals its sunlight-collecting aperture area, just like a one-sun planar array. Furthermore, the SLA's small individual lens size was selected based on radiator heat conduction from the line-focus solar cell receiver laterally outward into the surrounding radiator area. For the selected 8.5 cm aperture width, only a 125 micron thick graphite cloth radiator is needed to efficiently spread the waste heat laterally into the radiator. Thus, the operating cell temperature for SLA is about 50°C cooler than for the reflective trough.

Finally, the SLA enables super-encapsulation of the photovoltaic cell circuit with very little mass penalty, due to the small size of the cells compared to the aperture area of the array. Such super-encapsulation enables high-voltage operation of the SLA in the space plasma, reducing cabling size and mass, and minimizing the need for voltage-boosting electronics for high-voltage loads such as electronic thrusters. Such super-encapsulation can also provide radiation hardness for the solar cells, especially for high-radiation missions or military missions. Such super-encapsulation is heavy and expensive for lower concentration arrays or planar arrays, due to the much larger cell area per unit power output.

In summary, the technologies for mirror-augmented photovoltaic panels and Fresnel lens photovoltaic concentrators are vastly different. The track records of these two competing concentrator approaches have also been completely different, both in space and on the ground. Clearly, experiences, good or bad, for either one of these two technologies do not apply to the other.

The following paragraphs further describe the Fresnel lens photovoltaic concentrator array technology.

3. BACKGROUND

Since 1986, ENTECH and NASA have been developing and refining space photovoltaic arrays using refractive concentrator technology [8]. As discussed above, unlike reflective concentrators, these refractive Fresnel lens concentrators are 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 two orders of magnitude better shape error tolerance than reflective concentrators or conventional flat Fresnel lens concentrators [6].

In the early 1990's, the first refractive concentrator array was developed and flown on the PASP Plus mission, which included a number of small advanced arrays [9]. The refractive concentrator array used ENTECH mini-dome lenses over Boeing mechanically stacked multi-junction (MJ) cells (GaAs over GaSb). The mini-dome lenses were made by ENTECH from space-qualified silicone (DC 93-500), and coated by Boeing and OCLI to provide protection against space ultraviolet (UV) radiation and atomic oxygen (AO). This array performed extremely well throughout the year-long mission in a high-radiation, 70-degree inclination, 363 km by 2550 km elliptical orbit, validating both the high performance and radiation hardness of the refractive concentrator approach [9]. In addition, in high-voltage space plasma interaction experiments, the refractive concentrator array was able to withstand cell voltage excursions to 500 V relative to the plasma with minimal environmental interaction [9].

In the middle 1990's, ENTECH and NASA developed a new line-focus Fresnel lens concentrator, which is easier to make and more cost-effective than the mini-dome lens concentrator. Using a continuous roll-to-roll process, 3M can now rapidly mass-produce the line-focus silicone lens material in any desired quantity. In 1994, ABLE joined the refractive concentrator team and led the development of the SCARLET solar array [10]. SCARLET (Fig. 5) used a small (8.5 cm wide aperture) silicone Fresnel lens to focus sunlight at 8X concentration onto radiatively cooled triple-junction

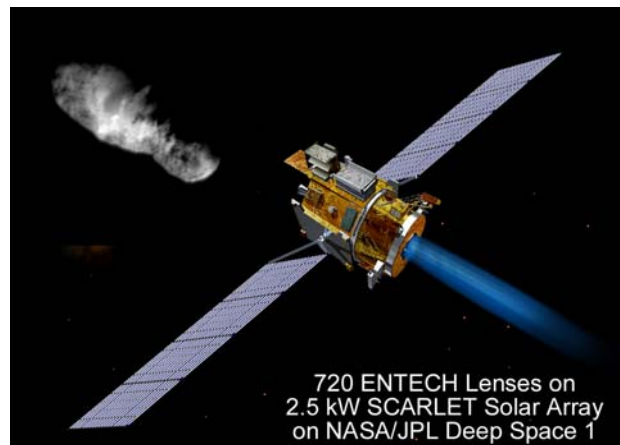


Figure 5 – SCARLET Array on Deep Space 1

cells. Launched in October 1998, the 2.5 kW SCARLET array powered both the spacecraft and the ion engine on the NASA/JPL Deep Space 1 probe, shown in Fig. 5.

SCARLET achieved over 200 W/m² areal power density and over 45 W/kg specific power, the best performance metrics up to that time [11]. With SCARLET working flawlessly, Deep Space 1 had a spectacularly successful rendezvous with the comet, Borrelly, in September 2001, capturing the highest-resolution images of a comet to date and other unprecedented comet data. At the end of the 38-month extended mission, in December 2001, SCARLET's power was still within $\pm 2\%$ of predictions.

Over the past four years, the team, now including Auburn University, has developed an evolved version of the flight-proven SCARLET array, called the Stretched Lens Array (SLA), with much better performance metrics [12-17]. A prototype SLA wing is shown in Fig. 6, and the new SLA approach is described in the following section.

4. STRETCHED LENS ARRAY (SLA) DESCRIPTION

The Stretched Lens Array (SLA) is an evolved version of SCARLET, retaining the essential power-generating elements (the silicone Fresnel lens, the multi-junction solar cells, and the composite radiator sheet) while discarding the non-power-generating elements (the lens glass arch superstrates, the lens support frames, the photovoltaic receiver support bars, and most of the honeycomb and back face sheet material in the panels). The defining feature of SLA (Fig. 6) that enables the elimination of so many elements of the SCARLET array is the stretched lens optical concentrator (Fig. 7). By using end arches to stretch the silicone Fresnel lens in the lengthwise direction only, these lenses become self-supporting stressed membranes. SCARLET's glass arches are thus no longer needed, eliminating their complexity, fragility, expense, and mass in the new, patented SLA [13]. With this substantial lens-related mass reduction, the supporting panel structural loads are reduced, making ultra-light panels practical for SLA. This cascading mass-reducing effect of the stretched lenses continues throughout the SLA wing structure, resulting in unprecedented performance metrics.

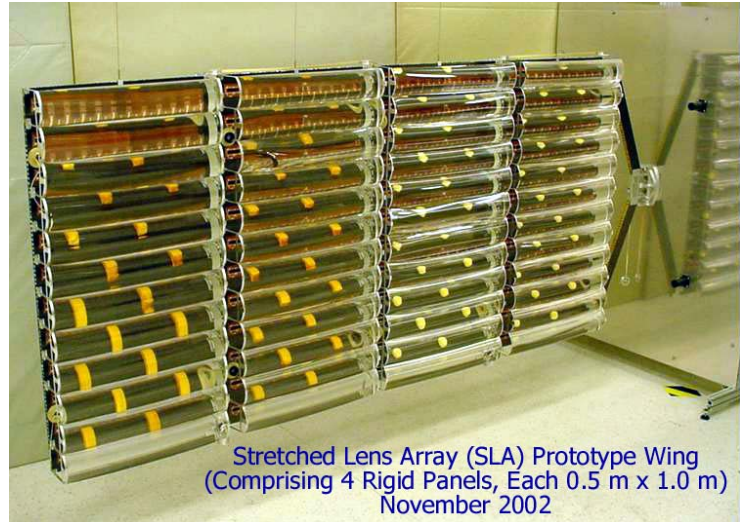


Figure 6 – Stretched Lens Array (SLA) Wing

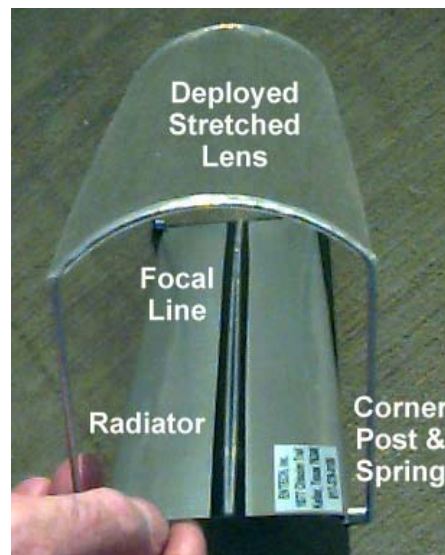


Figure 7 – Model Showing Basic Stretched Lens Approach

5. HARDWARE DEVELOPMENT AND TESTING

In the past year, the SLA team has fabricated and successfully evaluated a subscale four-panel array (Fig. 6), including 48 stretched lenses and 4 fully functional photovoltaic receivers, each containing 14 series-connected solar cells (Fig. 8). The four receivers included two using triple-junction (GaInP/GaAs/Ge) cells from Spectrolab and two using triple-junction cells from EMCORE. Two of the receivers used prism covers over the cells to eliminate gridline shadowing losses and two used more conventional ceria-doped microsheet covers. The receivers were assembled as flex circuits, including both cells and bypass diodes, and were fully encapsulated to enable high-voltage operation. To verify high-voltage operation, each of the receivers was wet hi-pot tested, with 500 V applied between the cell string and the composite panel, while distilled water was sprayed onto the receiver and panel. The water simulated space plasma, which can lead to leakage currents or arcs from photovoltaic circuits to the panel structure for conventional cell circuits exposed to high voltage operation. None of the four circuits had more than 1 micro-Amp leakage current during the test. Similar wet hi-pot testing has been used in the past to verify the encapsulation on SLA photovoltaic receiver coupons which were successfully tested at 1,000 V in simulated space plasma while being subjected to simulated micrometeoroid impacts [15]. These latest results extend the earlier single-cell coupon high-voltage test results to more flight-like 0.5-meter-long SLA receivers.



Figure 8 – Photovoltaic Receivers Undergoing 500 V Wet Hi-Pot Testing

The four SLA receivers were performance-tested for one-sun performance in ABLE’s Large Area Pulsed Solar Simulator (LAPSS), using NASA-Glenn-Lear-Jet-flown triple-junction reference cells from the same production lots, in addition to individual reference cells of each of the three junction types. Then the panel was equipped with stretched lenses, and the receivers were again LAPSS-tested for SLA performance. Fig. 9 shows the measured results (AM0, 20°C) for the two receivers using Spectrolab cells with and without the lenses installed. The solid curves represent the receiver with prism covers over the cells, while the dashed curves represent the receiver with ceria-doped microsheet over the cells. Note that the one-sun efficiency of the prism-covered-cell receiver was approximately 29%, while the net lens/receiver efficiency for the same prism-covered-cell receiver was approximately 28%. When these results were corrected to the standard reporting temperature of 28°C, the net lens/receiver efficiency for the prism-covered-cell receiver was 27.5%. As expected, the net lens/receiver efficiency for the microsheet-covered-cell receiver was slightly lower at 26.1% at 28C.

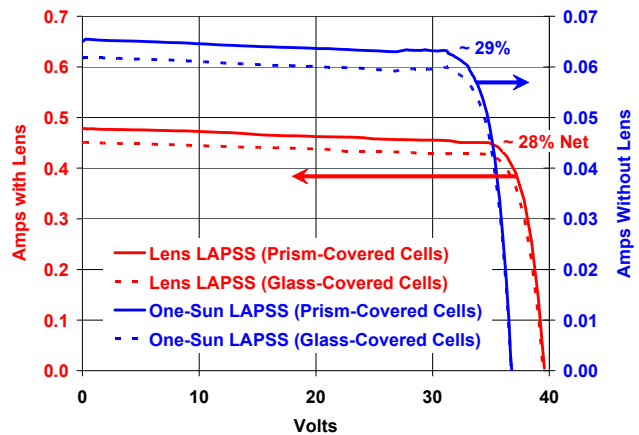


Figure 9 – Measured Performance Results (Air Mass Zero, 20°C)

The measured performance results of the 0.5-meter-long lenses and receivers extend the earlier results for single lens/cell units which were flown by NASA Glenn on their Lear jet test platform for AM0 current calibration, and then LAPSS-tested for AM0 performance. These lens/cell units also had over 27% net lens/cell efficiency (AM0, 25°C), using prism-covered cells from either Spectrolab or EMCORE [14,15]. All of these results are also in close agreement with individual lens optical efficiency measurements and prism-covered solar cell conversion efficiency measurements. The stretched lens provides $90\% \pm 2\%$ net optical efficiency in collecting photons and placing them onto the triple-junction solar cells. This excellent lens performance is due in large part to the unique color-mixing design of the lens, which eliminates chromatic aberration losses in the multi-junction cells [17]. The prism-covered multi-junction cells are over 30% efficient (8 suns AM0, 28°C) in converting sunlight into electricity [16,18]. This excellent cell performance is due in large part to the gain in efficiency with concentration, an 11% relative improvement for the Spectrolab triple-junction cells [16,18].

The mass of every element in the prototype four-panel wing of Fig. 6 was carefully measured, and ABLE used these results to accurately estimate the mass of the prototype wing if it had been fully populated with 48 photovoltaic receivers under 48 stretched lenses. The result of this mass estimate is 6.46 kg for a fully populated four-panel wing of the prototype’s size (2.06 m² total wing area). ABLE also estimated the on-orbit beginning-of-life (BOL) power output of this prototype wing, including the power reduction at the GEO operating temperature of 75°C compared to the standard test temperature of 28°C and all other normal array losses (e.g., packing factors, cabling and blocking diode losses, etc.). The result of this performance estimate is 629 W for a fully populated wing of the prototype’s size. Ratios of these values provide the prototype wing’s key performance metrics of 305 W/m² areal power density and 97 W/kg specific power. The areal power density goal for a near-term SLA was 300 W/m², which has been met. The wing-level specific power value also falls right on the predicted curve of SLA specific power versus wing power level (Fig. 10). Note also that NASA’s target value for future lightweight solar arrays of 175 W/kg for a 7 kW wing, as detailed in the recent New Millennium Program Space Technology 8 (NMP ST8) procurement is exceeded by SLA.

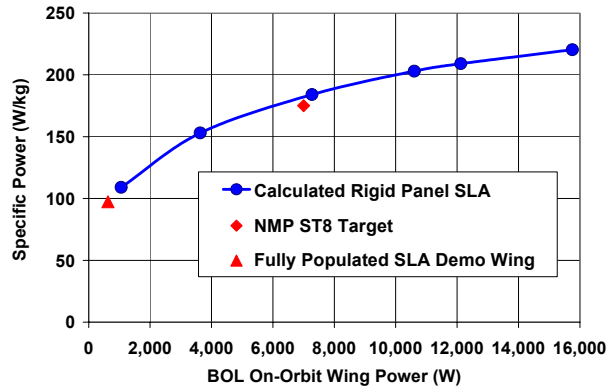


Figure 10 – SLA Specific Power vs. Wing Power on Geostationary (GEO) Orbit at Beginning of Life (BOL)

In addition to verifying the performance and mass estimates for SLA, the prototype four-panel wing of Fig. 6 also validated, via numerous deployments, the basic SLA mechanical approaches for deploying the four panels and the 12 lenses on each panel (Fig. 11).

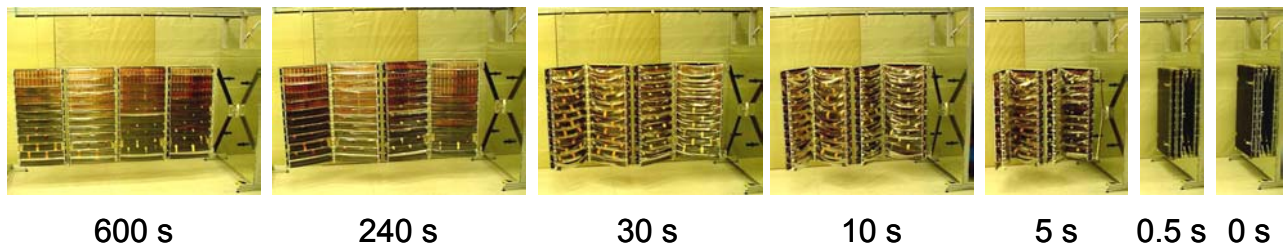


Figure 11 – SLA Prototype Wing Deployment

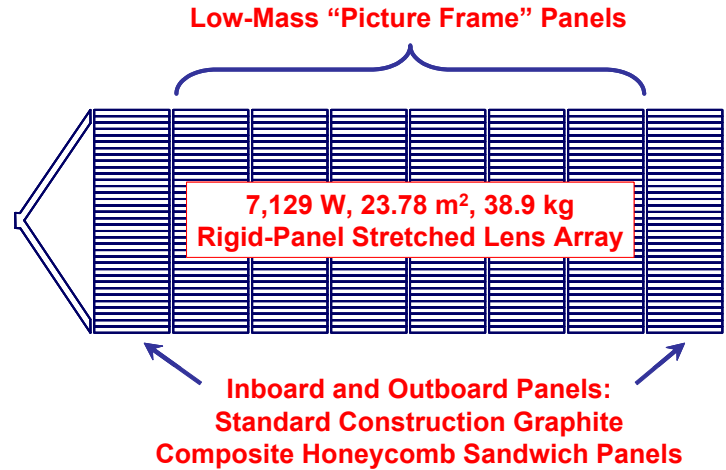
The following section describes a point design of an SLA solar array wing rated at 7 kW of output power, a wing size typical of today’s communication satellites.

6. POINT DESIGN OF A 7 KW SLA WING

As shown in Fig. 10, the performance advantages of SLA increase rapidly with increasing wing size, with the specific power reaching more than 180 W/kg at the important wing size of 7 kW. Since this wing size is typical of the latest generation of GEO communication satellites, the SLA team has generated a detailed point design for a 7 kW wing, as shown in the sketch and table below (Fig. 12). This wing design is conventional and conservative in configuration and components, with robust structural stiffness parameters. The beginning-of-life (BOL) areal power density is slightly lower than already demonstrated on the prototype hardware described above. Future multi-junction cells will no doubt eclipse the demonstrated values, providing even higher performance metrics than those shown in Fig. 12. While cost values are not presented, the SLA team has analyzed costs in detail, and due to more than 85% savings in cell area and cost compared to a planar multi-junction array, the SLA wing will cost 50% less than a planar wing of equal power.

7. RELATED WORK

The SLA team is also performing space environmental effects testing of key SLA components [19,20]. This ongoing testing includes solar ultraviolet and charged particle radiation exposure of stretched lenses, and micrometeoroid impact testing of lenses and photovoltaic receivers at high voltage in simulated space plasma. In addition, the SLA team has analyzed additional SLA performance metrics for a wide variety of different missions, and in each case, SLA provides excellent advantages over the planar array competition [21].



Feature	Value or Characteristic
Point Design Basis	7,129 Watts (BOL)
SLA Implementation	Pop-up lenses
Base Platform Design Maturity	Most components flight proven on DS1
Specific Power	183 W/kg
Stowed Volume	0.11 m ³ /kW
Stowed Stiffness	40 Hz
Deployed Stiffness	0.1 Hz
Stowed Power	Easily implemented on outer panel
Ease of Adding Planar Panel	Easily implemented on outer panel
Flatness & Warping	Well understood flat stable platform
Deployment Testing	Can use existing off-loaders
Power Testing	Pop-up lenses allow each panel to be tested as a complete assembly before wing integration
Commercial Appeal	Easier to integrate on commercial spacecraft. Readily accepted configuration.
Self Shadowing	No self shadowing

Figure 12 – Point Design for 7 kW SLA Wing

8. ALTERNATE VERSIONS OF SLA

While the rigid-panel wing, described in Sections 4 through 6, is the near-term, conservative embodiment of SLA for near-term missions, alternate flexible-blanket versions of SLA are also under development. These versions use lenses and photovoltaic receiver/radiator elements that accordion fold for compact launch stow volume, and then deploy as an end-tensioned dual-blanket (stretched lenses on top and stretched radiator sheets with photovoltaic receivers on bottom) array on orbit. In fact, Fig. 1 shows a small model of the flexible-blanket SLA.

One of the most attractive approaches for deploying and supporting the flexible-blanket version of SLA on orbit is ABLE Engineering's SquareRigger platform, originally developed for the Air Force Research Laboratory. SLA on SquareRigger could provide very large power arrays (50 kW to MW class) for a variety of future space missions. Fig. 13 (on the following page) shows a schematic of the SLA/SquareRigger array. The stowed package of SquareRigger is

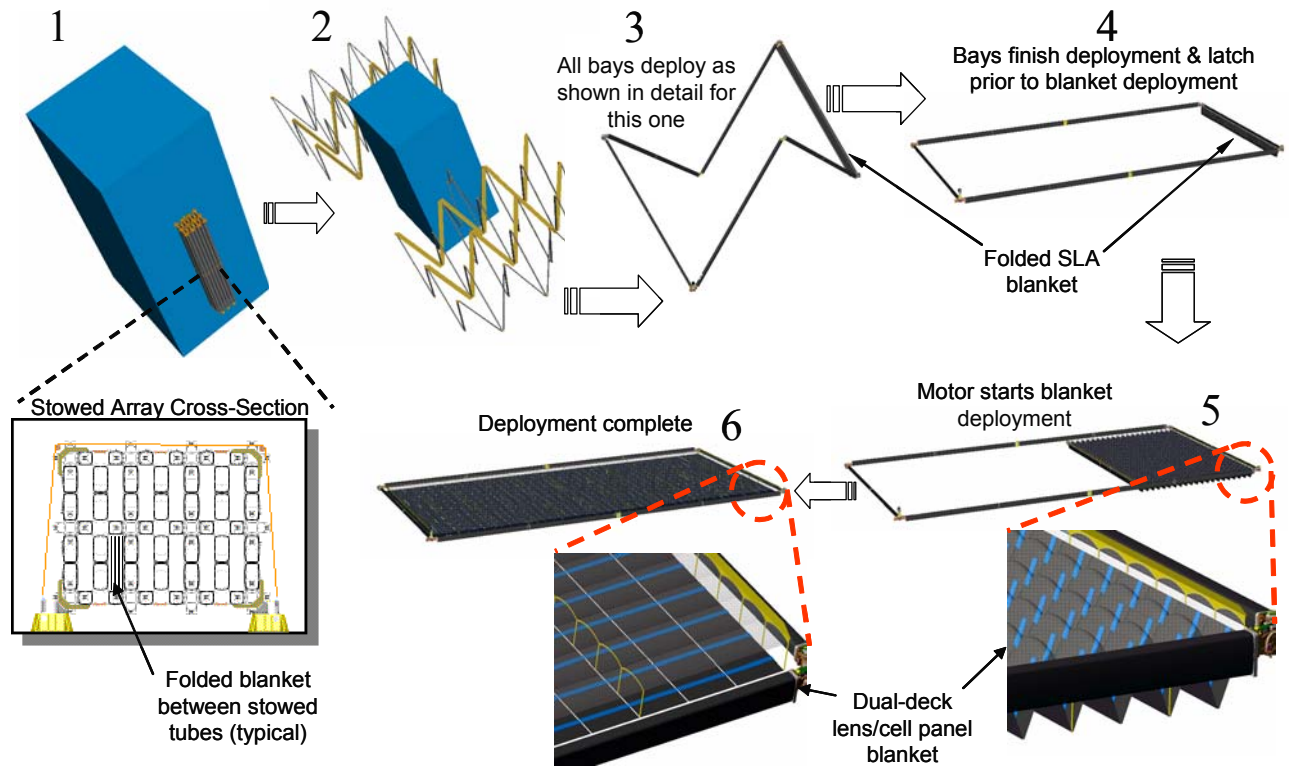


Figure 13 – Stretched Lens Array (SLA) on SquareRigger Platform

a tight bundle of structural tubes with the flexible blanket elements (flexible silicone lenses and composite radiator sheets with photovoltaic receivers mounted to the sheets) folded tightly between tubes. The tubes deploy first to form initially empty rectangular bays.

As shown in Fig. 13, after tube deployment is complete, a motor automatically unfolds the flexible blanket photovoltaic array from one end to the other until the bay is fully populated. While SquareRigger was initially envisioned as a thin-film photovoltaic blanket platform, it is ideally suited to the more efficient SLA technology. The combination of SLA and SquareRigger provides an unmatched set of performance metrics for large-capacity space power arrays, as summarized in Table 2.

Time Frame	< 5 Years	5-10 Years
Power Capability (kW)	100	1,000
BOL Specific Power (W/kg)	330	500
Stowed Power (kW/m ³)	80	120
Voltage	1,000	TBD

Table 2 – Performance Attributes of SLA on ABLÉ’s SquareRigger Platform

ABLE Engineering is currently completing a NASA Phase I SBIR contract related to the integration of SLA with SquareRigger, including fabrication of a small demonstration unit. The results of this contract have confirmed the expected advantages of marrying SLA to SquareRigger.

In addition to space applications, the combination of color-mixing symmetrical-refraction Fresnel lenses and multi-junction photovoltaic cells should have spin-off applications in the terrestrial solar energy marketplace. Developments are already underway on terrestrial versions of these high-performance photovoltaic concentrators. Indeed, numerous outdoor performance tests of a space-optimized SLA mini-concentrator module have demonstrated over 30% net-aperture-area solar-to-electric conversion efficiency. These results are believed to represent the first time that the 30% efficiency threshold has ever been broken by any type of solar energy converter tested outdoors under natural terrestrial sunlight [15].

9. CONCLUSIONS

A new type of space solar power system is being developed with unprecedented performance and mass properties. The Stretched Lens Array (SLA) uses ultra-thin refractive optical elements to collect and focus sunlight onto narrow state-of-the-art multi-junction photovoltaic cells, which are mounted to ultra-thin composite radiator sheets. SLA is being developed in two versions:

- A rigid-panel SLA, which uses a conventional and low-risk approach to deployment and support on orbit. This version of SLA offers substantially improved performance metrics for near-term solar array wings up to 20 kW.
- A flexible-blanket SLA, which uses more advanced and higher performance approaches to deployment and support on orbit. This version offers transformational performance metrics for longer-term solar array wings in the 50 kW to MW class.

Hardware developments to date have verified the performance, mass, and cost advantages of the new SLA technology.

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