

The Stretched Lens Array SquareRigger (SLASR) for Space Power

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For the past three years, our team has been developing, refining, and maturing a unique solar array technology known as Stretched Lens Array SquareRigger (SLASR). SLASR offers an unprecedented portfolio of state-of-the-art performance metrics, including areal power density, specific power, stowed power density, high-voltage capability, radiation hardness, modularity, scalability, mass-producibility, and cost-effectiveness. SLASR is particularly well suited to high-power space missions, including solar electric propulsion (SEP) space tugs, major exploration missions to the Moon and Mars, and power-intensive military spacecraft. SLASR is also very well suited to high-radiation missions, since the cell shielding mass penalty is 85% less for the SLASR concentrator array than for one-sun planar arrays. The paper describes SLASR technology and presents significant results of developments to date in a number of key areas, from advances in the key components to full-scale array hardware fabrication and evaluation. A summary of SLASR's unprecedented performance metrics, both near-term and longer term, will be presented. Plans for future SLASR developments and near-term space applications will also be outlined.

I. Introduction and Background

ENTECH, NASA, and other team members have been developing refractive photovoltaic concentrator systems for producing space power from sunlight since the middle 1980's¹. The first such technology developed and successfully flown in space was the point-focus mini-dome lens array, shown in Fig. 1. This array used mechanically stacked GaAs/GaSb cells from Boeing in the focal point of ENTECH's silicone mini-dome Fresnel lens concentrators. The lenses were coated with a multi-layer oxide coating to protect the silicone lens material from solar ultraviolet (UV) radiation and monatomic oxygen (AO). The mini-dome lens array in Fig. 1 flew in 1994-95 on the NASA/USAF year-long PASP-Plus flight test in a very high-radiation elliptical orbit (363 km by 2,550 km at 70-degree inclination). Of the 12 advanced photovoltaic array types included on PASP-Plus, the mini-dome lens provided the highest performance and the least degradation².

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After the mini-dome lens array success, ENTECH, NASA, and other team members next developed the line-focus arched lens array, which evolved into the SCARLET array that performed flawlessly for the full thirty-eight-month mission on NASA's Deep Space 1 probe, shown in Fig. 2. SCARLET (acronym for Solar Concentrator Array using Refractive Linear Element Technology) employed silicone Fresnel lens material made by 3M using a high-speed continuous process. ENTECH laminated this silicone lens material to 75-micron-thick ceria-doped glass arches, which provided support and UV protection for the lenses. Monolithic triple-junction (GaInP/GaAs/Ge) cells were placed in the focal lines of the SCARLET lenses. The SCARLET array powered both the spacecraft and the ion engine on Deep Space 1 and performed as predicted on this highly successful mission³.

Shortly after the SCARLET array delivery, ENTECH discovered a simpler approach to deploy and support the line-focus silicone lenses, thereby eliminating the fragile, bulky, and expensive glass arches used on SCARLET.

The new approach uses simple lengthwise tensioning of the lens material between end arches for lens deployment and support on orbit, as shown in Fig. 3. Called the Stretched Lens Array (SLA), the new ultra-light concentrator array also enables a very compact stowage volume for launch⁴. SLA is compatible with a variety of space array platforms, from small unfolding rigid-panel wings to large deployable flexible-blanket wings. Of all the platforms evaluated for SLA to date, the lightest and most compact is ATK Space Systems' SquareRigger. Originally developed for the Air Force Research Lab as a platform for thin-film solar cell arrays in space, SquareRigger is an even better match for the high-efficiency, ultra-light SLA technology⁵.

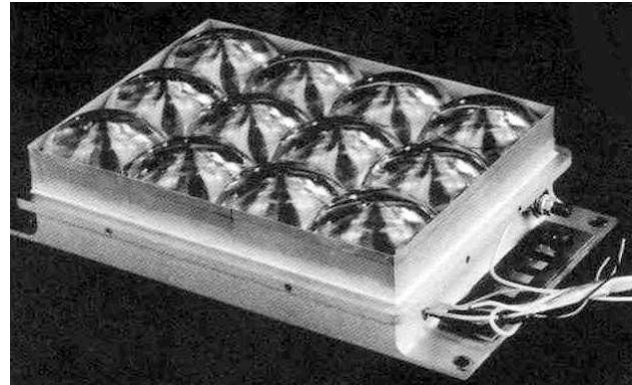


Figure 1. Mini-dome lens array for the PASP-Plus flight test (1994-1995).

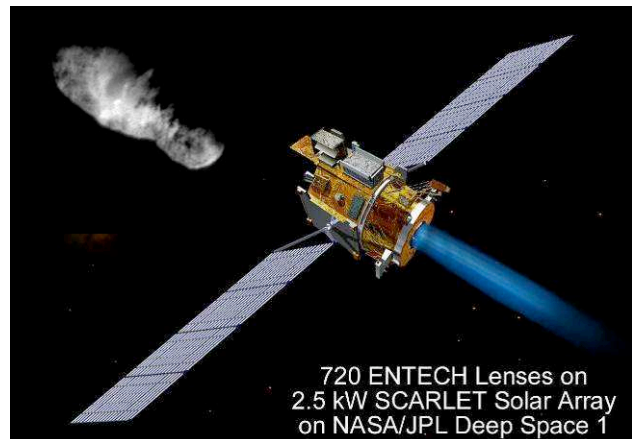


Figure 2. SCARLET array on NASA/JPL Deep Space 1 probe (1998-2001).



Figure 3. Stretched Lens Array (SLA) prototype.

II. Stretched Lens Array SquareRigger (SLASR) Technology

SLASR offers an amazingly compact stowed volume and an extremely light-weight deployed platform for the flexible-blanket version of SLA for high-power space missions, as shown schematically in Fig. 4. For launch, SLASR's carbon composite structural tubes stow in a very compact volume, with the two folded and interleaved blankets of lenses and radiator sheets (containing the solar cell circuits) nested between the tubes. On orbit, the tubes automatically deploy to form rectangular "bay" structures, each about 2.5 m x 5.0 m in size. After the bay tubular frame structure deploys and locks, the lens and radiator blankets are automatically pulled across the frame to form the deployed solar array. Recently, a full-scale SLASR bay has been fabricated and successfully deployed. Fig. 5 shows the two-minute deployment sequence for the frame structure. Fig. 6 shows the 15-minute deployment sequence for the lens and radiator blankets. A single motor is used to provide both deployments (frame and blankets). Fig. 7 shows a front view of the deployed bay.

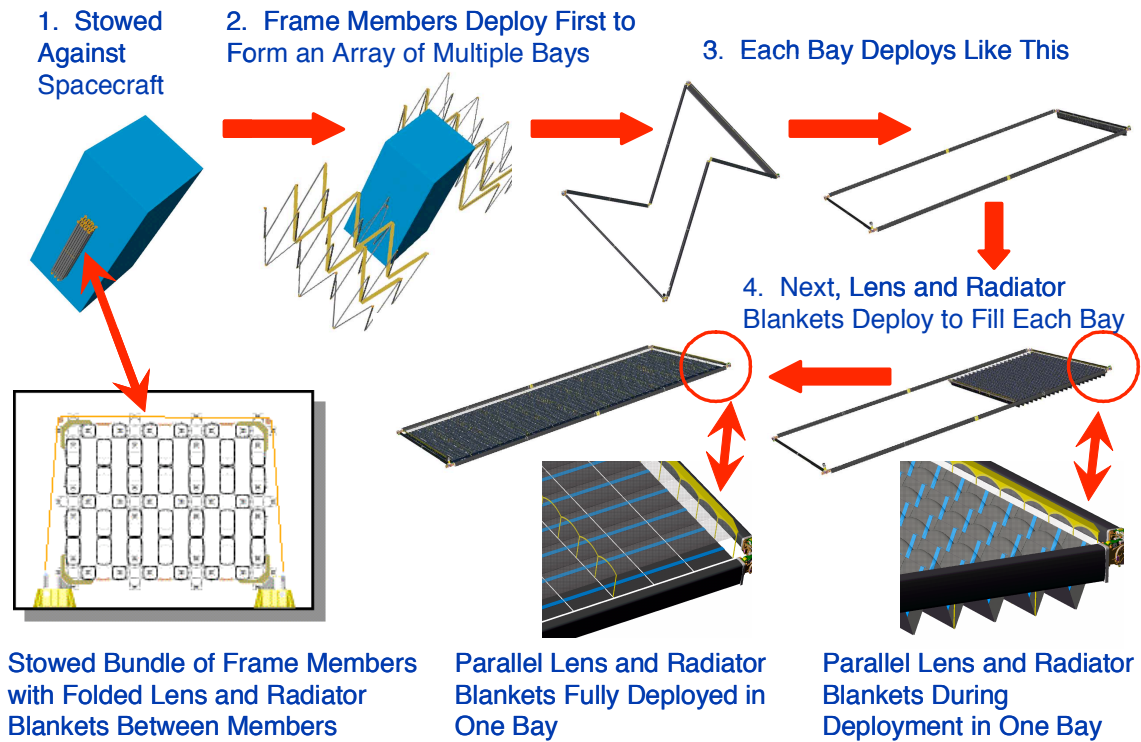


Figure 4. Stretched Lens Array SquareRigger (SLASR) schematic.

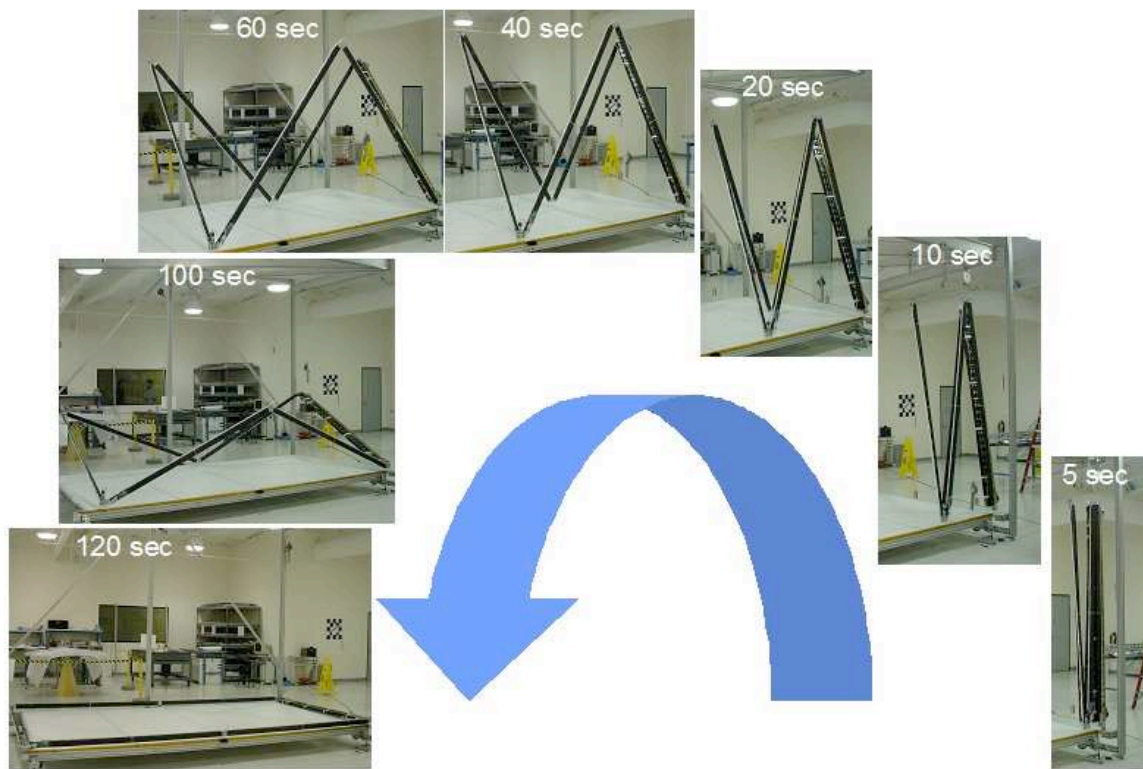


Figure 5. SLASR bay structure deployment.

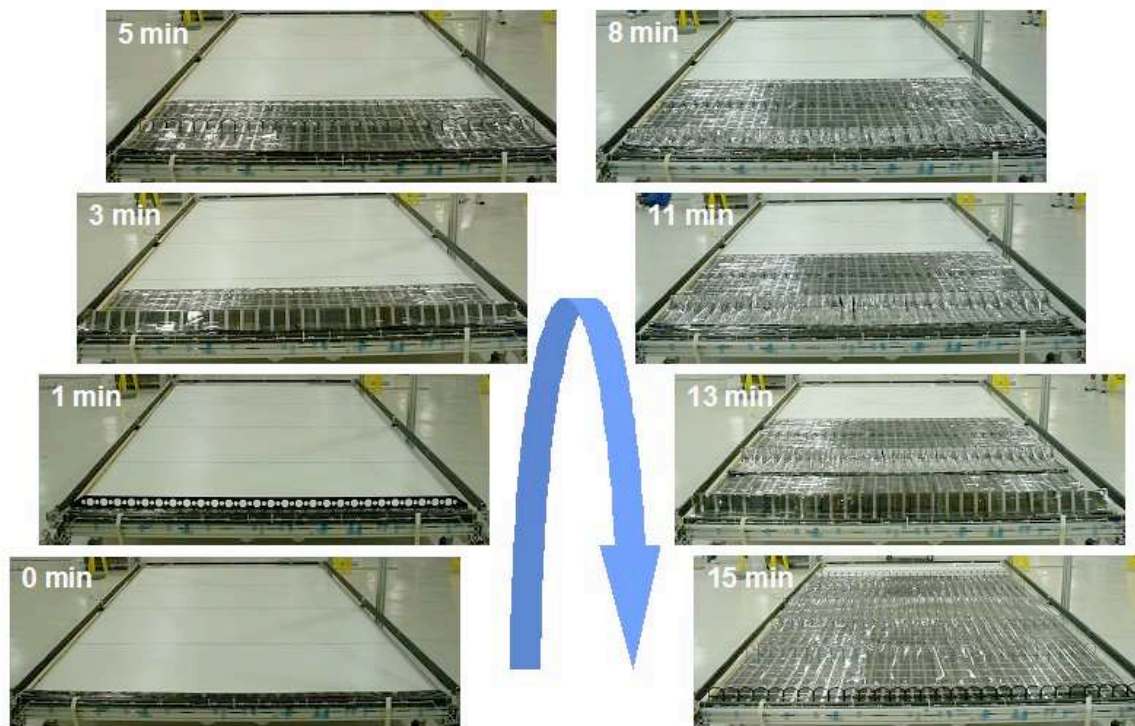


Figure 6. SLASR lens and radiator blanket deployment.

Multiple bays of the 2.5 m x 5.0 m size shown in Fig. 7 are employed to form large solar array wings for high-power space missions. Since each bay provides about 4 kW of power on orbit, two 12-bay wings will provide about 100 kW on orbit. For this 100 kW point design, Fig. 8 shows the mass breakdown. The lens and radiator blankets comprise about 70% of the total wing-level mass, which corresponds to only 0.85 g/m² for this large array size.

III. SLASR Component Improvements

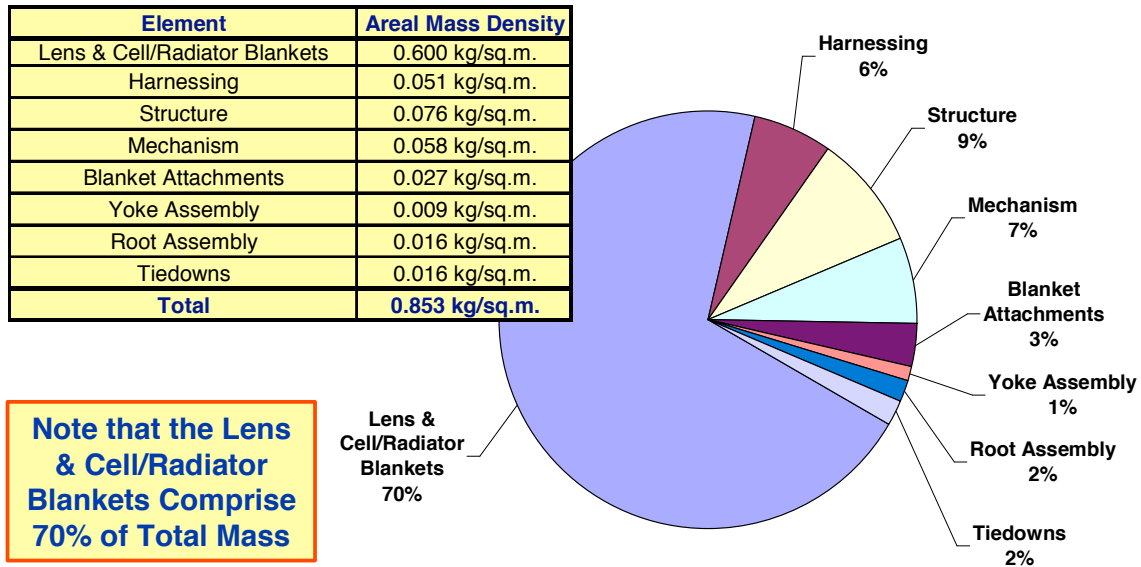
Over the past year, SLASR technology maturation work included the development of several improved key components. Two of these improved components are:

- Mission-Tailorable-Thickness (0.2-5.0 microns) Protective Coating for the Silicone Stretched Lens
- Integral-Diode High-Efficiency Multi-Junction Photovoltaic Cell (Optimized for 8 Suns Irradiance)

The new lens coating work is based on the latest thin protective coating from SLASR team member, Ion Beam Optics. This coating very effectively blocks vacuum ultraviolet (VUV) wavelengths in space sunlight from reaching and possibly damaging the silicone lens material beneath the coating, as shown in Fig. 9.

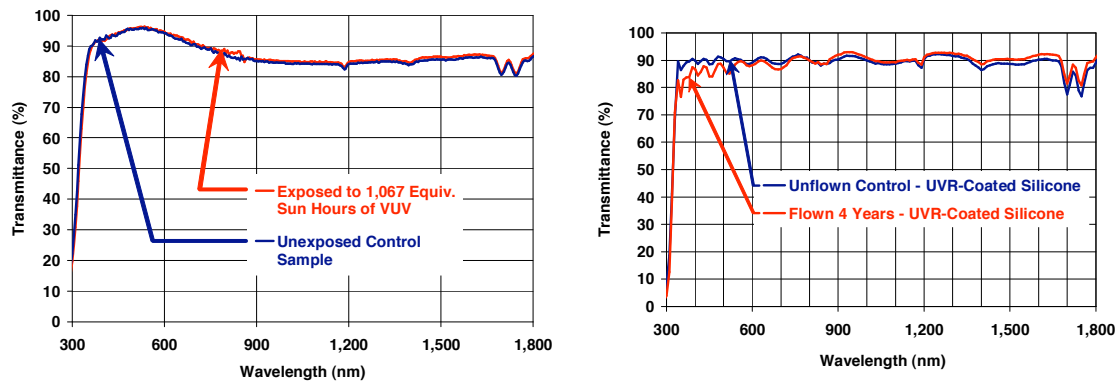


Figure 7. Full-scale SLASR bay.



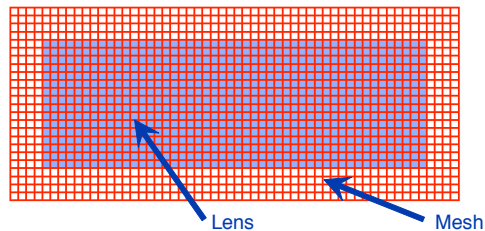
This mass breakdown is for a near-term 100 kW SLASR with today's 30% efficient cells and today's lens and radiator thicknesses

Figure 8. Mass breakdown for 100 kW SLASR array.

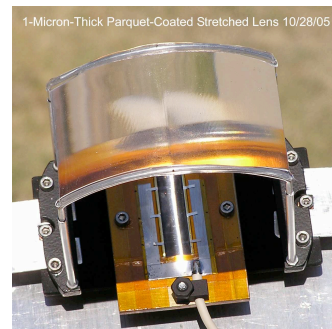


Latest Ion Beam Optics Thin Lens Coating Blocks UV Very Well as Shown in These NASA Tests

Silicone with Earlier Thin Coating Held Up Well for 4 Years on International Space Station (MISSE-1 Experiment)



For High-Radiation Missions, a Thick (1-5 Microns) Parquet Coating, Using a Mesh During Deposition of the Thick Layer, Will Offer Additional Lens Radiation Hardness While Maintaining Lens Flexibility



Sample Parquet-Coated (1 Micron Thick Coating) Stretched Silicone Lens Focusing onto Triple-Junction Solar Cell

Figure 9. Mission-tailorable thick parquet lens coating.

The two graphs in Fig. 9 show the spectral transmittance of coated silicone samples before and after 1,067 hours of simulated space UV exposure and 4 years of actual space UV exposure on the International Space Station. The thin lens coating will provide adequate lens protection for many missions (e.g., LEO, GEO, or Deep Space). For very high radiation missions (e.g., belt flyers or space tugs flying between LEO and lunar orbit), a thicker coating would be desirable to reduce the charged particle radiation dose reaching the silicone. Dose-depth profile calculations show that a coating thickness up to 5 microns could be desirable for such missions. Such a thick coating will be relatively rigid, making it seem to be incompatible with the stretched lens approach. However, by using a parquet approach to the coating application, the thick coating can be separated into small regions, allowing the lens as a whole to remain flexible enough to stow and deploy as a stretched lens. The new process uses a mesh screen during coating application to provide the patterned parquet geometry, as shown in Fig. 9. The SLA module in Fig. 9 demonstrated predicted performance for a 1-micron-thick parquet coating on a stretched lens focusing onto a triple-junction solar cell, showing the practicality of the new process.

Under previous Stretched Lens Array (SLA) development programs, the photovoltaic receiver used discrete bypass diodes to protect the multi-junction cells from reverse-bias damage. These discrete diodes were relatively large, and were positioned alongside the solar cells, making the overall circuit about 2.0 cm wide, although the cells were only 1.2 cm wide, including busbars. The whole photovoltaic circuit (cells and diodes) must be well insulated, both above and below the circuit, to operate reliably at high voltage in space. To reduce the mass and complexity of the SLASR photovoltaic receiver, SLASR team member, EMCORE, has developed an integral-diode concentrator cell as shown in Fig. 10. To increase reliability and to minimize diode temperature excursions under bypass operation, redundant diodes are being used on the new cell. Two end tabs will be used to connect the back of the neighboring cell to both top busbars of the SLASR concentrator cell, as well as closing the circuit between the tops of the diodes and the busbars on the SLASR concentrator cell. The total photovoltaic receiver width is about 40% narrower for this approach than for prior SLA receiver approaches, reducing mass proportionally. New cells have been produced by EMCORE, as shown in the photo in Fig. 10. While these new cells have not yet been fully evaluated at 8 suns, EMCORE's one-sun data indicate that the new integral-diode cells should match earlier SLA cells with over 30% efficiency at 8 AM0 suns and 25C.

IV. SLASR Performance Metrics

The key near-term performance parameters and system-level metrics for SLASR are summarized in Table 1, which also shows the basis for each value. The bottom-line areal power density, specific power, and stowed power are all unprecedented values, well above the current state of the art for space solar arrays of any kind. Within the next five years, we anticipate major improvements in cell

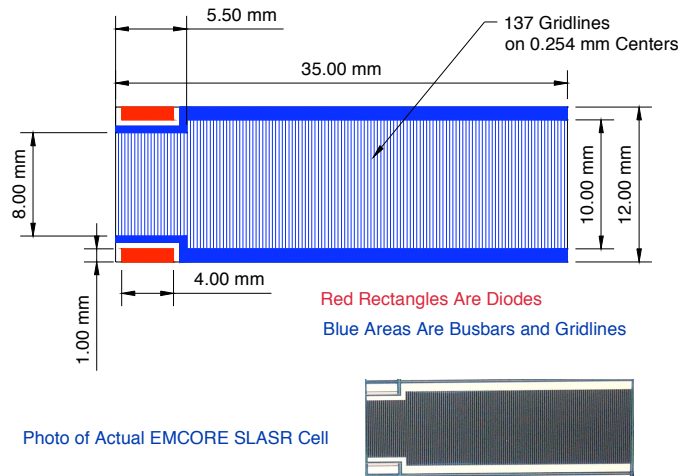


Figure 10. New integral-diode concentrator cell.

Table 1. Key SLASR near-term performance parameters.

Parameter	Value for SLASR	Measurement or Model
Lens Transmittance	92%	Measurement
Cell Efficiency @25C	30%	Measurement
Net Lens/Cell Efficiency @25C	27.6%	Measurement (NASA Lear Jet Confirmed)
Cell Temperature on GEO	71C	Model (Validated on SCARLET)
Cell Temperature Knockdown Factor	91%	Measurement (Cell Temperature Coefficients)
Input Irradiance to SLA Lens	1,366 W/sq.m.	Measurement (International Standard)
SLA SquareRigger Gross Areal Power Density	343 W/sq.m.	Model
Wiring/Mismatch/Packing Knockdown Factor	90%	Model
SLA SquareRigger Net Areal Power Density	309 W/sq.m.	Model
SLA SquareRigger Wing Mass Density	0.853 kg/sq.m.	Model (Based on Prototype)
SLA SquareRigger Net Specific Power	362 W/kg	Model
SLA SquareRigger Stowed Power Density	80 kW/cu.m.	Model (Based on Prototype)

efficiency (to 38% at 8 AMO suns and 25C), areal power density (to 400 W/m²), specific power (to 500 W/kg), and stowed power density (to 120 kW/m³). These gains are due primarily to the rapidly increasing cell efficiency, and secondarily to slight reductions in cell and radiator thickness and mass.

V. SLASR Future Plans and Applications

With its unique portfolio of performance metrics, SLASR offers substantial advantages over other space (and near-space) power systems for many future missions, as shown in Fig. 11. For missions requiring extreme radiation hardness (e.g., national security space assets, belt flyers, reusable space tugs, etc.), SLASR's small mass penalty for super-shielded cells could be mission-enabling. For missions requiring extremely low mass (e.g., lunar surface power, high-altitude airships, etc.), SLASR's unprecedented specific power could be mission-enabling. For solar electric propulsion (SEP) missions, SLASR's high areal power density is critical to minimize residual atmospheric drag, SLASR's high specific power is critical to minimize parasitic mass, SLASR's radiation hardness is critical to withstand several slow spiraling transits through the radiation belts, and SLASR's high-voltage capability is critical to enable direct drive of the electric thrusters. Recently, a version of SLASR has even been developed to work in the dark. This new SLASR version collects and converts beamed infrared laser light to electrical power with spectacular performance metrics⁶. Prototypes of the laser version of SLASR have already demonstrated net conversion efficiencies above 45% at room temperature, with expected near-term improvement to over 55%. Performance metrics for the laser version of SLASR are outstanding, including over 800 W/kg specific power⁶. One important application of the laser version of SLASR is for powering exploration and resource extraction missions in the eternally dark lunar polar craters, which are known to contain hydrogen and oxygen. The source of the laser beams for such missions could be solar-powered lasers on the rims of the lunar polar craters, which are bathed in eternal sunlight. Such an application could use the solar version of SLASR to power the lasers and the laser version of SLASR to convert the beamed laser light to useful electrical power.

Future plans for SLASR include a near-term flight test to validate the predicted performance metrics. The flight experiment will be developed and fabricated under a Missile Defense Agency (MDA) contract. Future plans also include further development of SLASR-powered solar electric propulsion (SEP) systems under a NASA contract.

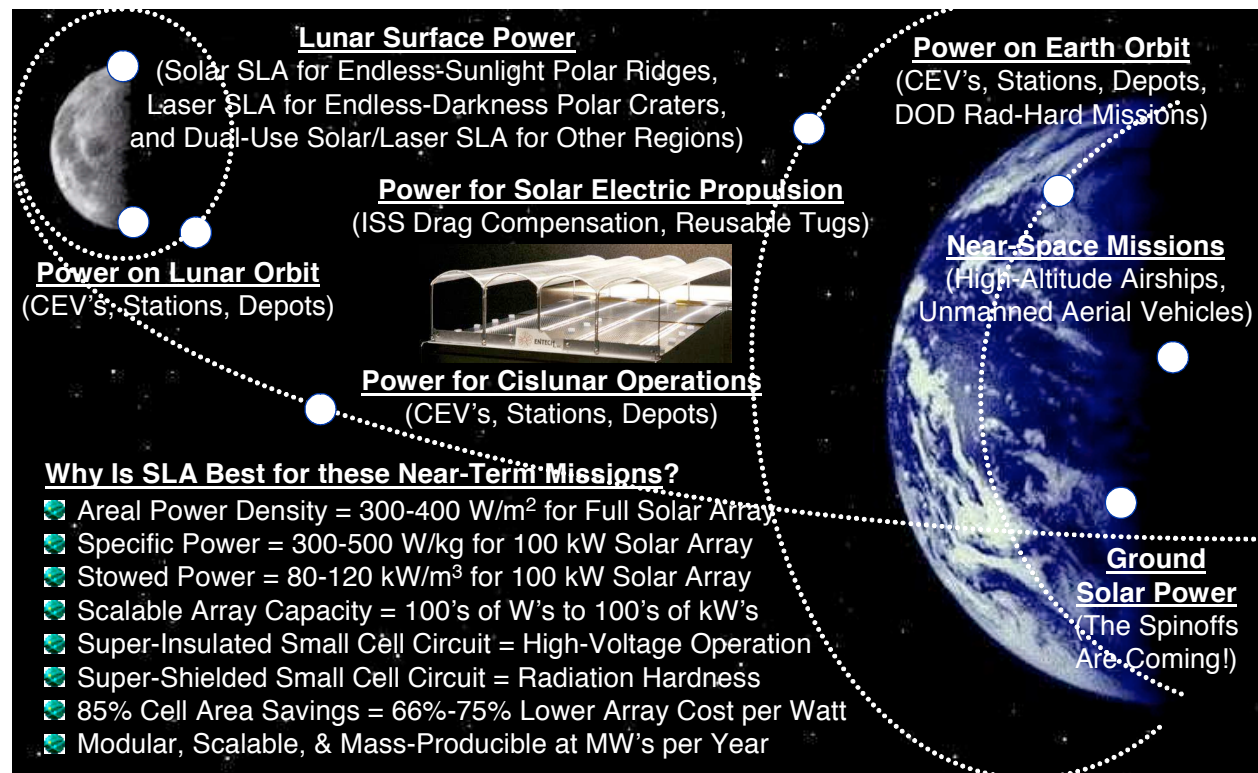


Figure 11. SLASR near-term applications in the Earth-Moon neighborhood.

VI. Conclusion

A new photovoltaic concentrator technology for space power has been developed with outstanding performance metrics for many classes of missions for NASA, DOD, and commercial customers. The new array is the Stretched Lens Array SquareRigger (SLASR). Over the past three years, all of the key elements of SLASR have been developed and successfully tested, including the protectively coated lenses, the multi-junction photovoltaic cells with integral bypass diodes, the fully encapsulated photovoltaic receiver circuits, the carbon-fiber-fabric composite sheet radiator, the SquareRigger deployment and support platform, and the flexible blankets of stretched lens and cell/radiator elements. Despite its unprecedented portfolio of performance metrics, SLASR technology is firmly based on flight-proven predecessor technologies, including the SCARLET array on Deep Space 1 and the earlier mini-dome lens array on PASP-Plus.

Acknowledgments

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