Ultralight, Compact, Deployable, High-Performance Solar Concentrator Array for Lunar Surface Power

Henry W. Brandhorst, Jr. and Julie Anna Rodiek
Space Research Institute, Auburn University, AL 36849-5320

Mark J. O'Neill
ENTECH, Inc., Keller, TX 76248

Michael I. Eskenazi
ATK-Space, Goleta, CA 93117

In NASA's ambitious vision for space exploration, return visits to the moon are the initial focus. While these early missions anticipate the use of fuel cells to provide electrical energy to the landers and crew, it is likely that solar arrays will also become a major power source as well. This paper will project the performance of a 25-30 kW lightweight, high efficiency Stretched Lens Array on the SquareRigger platform (SLASR) using multijunction solar cells for a lunar polar region with high daylight during the year, an equatorial location during the day and an array in a permanently shadowed crater relying on laser illumination.

I. Introduction

In NASA's ambitious vision for space exploration, return visits to the moon are the initial focus. While these missions are not well defined other than in contractor system study reports, a common theme is to return to the lunar polar regions to search for primordial ice deposits initially, then expand the landings across the lunar surface including the rear side of the moon. In the early stages the missions will last from four to fourteen days, to avoid the challenge of energy storage over the nighttime. While these early missions anticipate the use of fuel cells to provide electrical energy to the landers and crew, it is likely that solar arrays will also become a major power source as well.

These arrays should have the following characteristics: high efficiency, light weight, high packaging density and be able to withstand the broad temperature swings on the moon. In addition, for those robotic missions that will explore the permanently dark polar craters, it is possible that beamed laser power may be an option to radioisotope powered rovers. Of course beamed laser power may also be applicable to providing power over the nighttime.

In this study, we will use the Stretched Lens Array on the SquareRigger platform as the basis (SLASR). At the present time this design has the following characteristics: specific power – 300 W/kg, areal power density – 300 W/m^2, stowed power – 80 kW/m^3 and capable of high voltage (>600 V) operation. Figure 1 shows a 2.5 x 5 m full scale building block module of the SLASR. This module is sized to produce 3.75 kW and weighs only about 10 kg.

Figure 1: Full scale SLASR module

These current benchmarks will be projected to the 2015 time frame with known improvements in cell and array technologies for a 25-30 kW array. Specific power will increase beyond 500 W/kg and similar improvements will be shown in the other parameters. One critical aspect of the study is the operating temperature on the moon. The wide temperature swings on the equator over one year do not compare to the frigid temperature within the craters at the pole where the temperatures may reach as low as 50 K. Thus the orientation of the solar array and the possible need to reduce the surface background must all be included. Several surface treatments have been described in the past and will be used in this study.

The projected performance of a 25-30 kW lightweight, high efficiency SLASR array using multijunction solar cells expected to be available in 2010 time frame will be determined for a lunar polar region with high daylight during the year, an equatorial location during the day and an array in a permanently shadowed crater relying on laser illumination. The latter array will have GaAs solar cells matched to a nominal 800 nm wavelength laser and be sized for about 500 W. Temperature effects will be included.

II. SLA Background

SLA is a unique ultra-high-performance, ultra-light, cost-effective photovoltaic concentrator array using refractive concentrator technology. Refractive Fresnel lens concentrators can be configured to minimize the effects of shape errors unlike reflective concentrators. This enables 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] 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 with a mini-dome lens concentrator.[2] It was proven quite successful. In the middle 1990's, a new line-focus Fresnel lens concentrator, which is easier to make and more cost-effective than the mini-dome lens concentrator, was developed. In 1994 the SCARLET® (Solar Concentrator Array using Refractive Linear Element Technology) solar array was flown on the Deep Space 1 NASA mission.[3] SCARLET used a (8.5 cm wide aperture) silicone Fresnel lens to focus sunlight at 8X concentration onto radiatively cooled triple-junction cells. The Stretched Lens Array (SLA) is an evolved version of SCARLET, retaining the essential power-generating elements. Figure 2 shows the basic concept of SLA, and various array versions of this unique SLA technology.

Figure 2: Stretched Lens Module in Sunlight

The stretched lens optical concentrator shown in Figure 2 is the defining feature of SLA that enables the elimination of many elements of the SCARLET array. The pop-up arches stretch the silicone Fresnel lens only in the lengthwise direction causing the lenses to become self-supporting stressed membranes. SCARLET's glass arches can now be removed, eliminating complexity, fragility, expense, and mass in the new SLA.[4] With this substantial lens-related mass reduction, the supporting panel structural loads are reduced, making ultra-light panels practical for SLA. SLA saves over 85% of the required area, mass and cost of the multi-junction solar cells per watt of power produced due to its 8.5X geometric concentration ratio. 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). 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. Its demonstrated high performance and radiation tolerance, coupled with its substantial mass and cost advantages, will lead to many applications, both government and commercial missions.

In addition to the near-term, low-risk rigid-panel version of SLA, an advanced flexible-blanket version of SLA is also under development. The most advanced version is the flexible-blanket SLA on ATK's SquareRigger platform, shown schematically in Figure 1. Stretched Lens Array SquareRigger (SLASR) offers unprecedented performance capabilities in terms of array power capacity, stowed power density, specific power, and high-voltage operation. For this SLA version, the lenses form one flexible blanket while the radiator elements, containing the photovoltaic receivers, form a second flexible blanket. Both blankets fold up into a very compact stow volume for launch, and automatically deploy on orbit. The SquareRigger platform was originally developed by ABLE under funding from the Air Force Research Laboratory for use with thin-film photovoltaic blankets in space. However, with the much higher efficiencies achievable with SLA compared to thin-film photovoltaics, the marriage of SLA and SquareRigger provides unprecedented performance metrics, as summarized in Table 1.[5]

Table 1: Performance metrics of SLASR

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

SLASR technology offers spectacular 300-500 W/kg specific power and 80-120 kW/m^3 stowed power in the next 5-10 years. In the longer term (2020-2025), with constantly improving solar cell efficiencies and incorporation of new cells and technology materials into the lens and radiator elements, SLA's technology roadmap leads to 1,000 W/kg solar arrays.[6] The SLA is unique among all solar array technologies in its portfolio of attributes, which include world record level solar-to-electric conversion efficiency (high W/m^2), ultra-light mass density (low kg/m^2), spectacular stowed power density (kW/m^3), highly scalable power (kW to multi-MW), high-voltage capability (kV), modularity (individual lens/cell building blocks), mass-producibility, and cost effectiveness.

III. Lunar Design Considerations

Lunar base power system design considerations include: extreme temperature cycling, limited heat transfer modes, gravity, reflectivity of solar energy, radiation, micrometeoroid bombardment, soil abrasiveness, atmospheric contamination, electrostatic charging of dust, opacity, and extended night.

The maximum temperature at the lunar equator at noon has been calculated at 387 K.[7] Temperatures drop below 100 K during the lunar night. Thus materials used on the lunar surface would need to withstand the severe stress of this temperature cycling. Figure 3 shows typical lunar temperature profiles and a comparison to Mars.

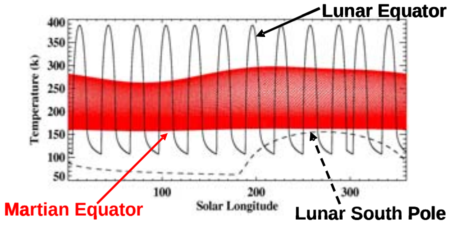

Figure 3: Lunar and Mars surface temperatures (Courtesy MIT & Draper)

High daytime temperatures cause difficulty in cooling the system. The three heat loss mechanisms are convection, conduction and radiation. The lack of atmosphere eliminates convection. Conduction is limited due to the poor thermal conductivity of the regolith. The surface can heat to 380 K but at a depth of 1 meter the temperature stays at 238 K. Thus radiation is the only practical method to reject unwanted heat. Waste heat from a power system will be rejected through radiation to the surroundings. The high lunar temperature during the day lowers the ability of a radiator to dissipate waste heat efficiently. In order to reduce the heat sink; the area around the radiator could be covered with a highly reflective aluminized blanket. This would decrease the sink temperature to 230 K and would only increase the mass of the radiator system by less than 0.1 kg/m^2. [8] Neither changing the cell substrate size nor decreasing the module concentration ratio will have a significant impact on the cell temperature. The thermal radiation exchange with the environment sets the average radiator temperature, and this sets the minimum temperature for the cell, regardless of the other design features (radiator thickness or concentration ratio). So if the back of the radiator is looking at a very hot lunar surface, the radiator is going to run hot regardless of concentration ratio. An aluminized blanket will help but will also have to deal with the issue of dust accumulation. A perfect infrared reflector would let the back of the SLA radiator effectively view deep space (via reflection) rather than the hot lunar surface. Dust covering the reflector will be a challenge. It is important to mention that a tracking SLA should run a lot cooler than a one-sun array placed on the surface of the moon, since SLA will be able to radiate from both the front and the back of the radiator.

The gravity on the moon's surface is 1.623 m/s^2, approximately 1/6th of the gravity on earth. This may increase the size of the supports needed to hold the SquareRigger platform but will not change the overall design significantly. The SLASR will have to track the sun within 2 degrees as it rises and sets in the two week time frame. The intensity of solar energy falling on the lunar surface is about 1370 W/m^2. Radiation is also experienced in the form of cosmic rays, the solar wind, and solar flares. With no atmosphere, micrometeoroid damage is prevalent on the moon. Meteoroids range from 10 g to 100 kg with velocities ranging from 2.4 to 72 km/s.[9] A lunar base system must be designed to withstand the impact of some of these particles.

The consistency of the regolith ranges from dust to silt to fine sand. Electrostatic charging of lunar dust will be a problem for any surface system. Dust will cause thermal control problems by reducing the emissivity of surface thus lowering its radiative properties. Dust also does damage by abrading materials leading to seal failures.[10] Raising the SLASR several meters off of the lunar surface will decrease the dust issue due to the dust storm phenomenon at the day-night line. Dust removal systems are under review.

The deploying of the SLASR is another issue on the lunar surface. Automatic deployment is preferred and can be seen in Figure 4. This design will be modified slightly for the positioning of it above the lunar surface.

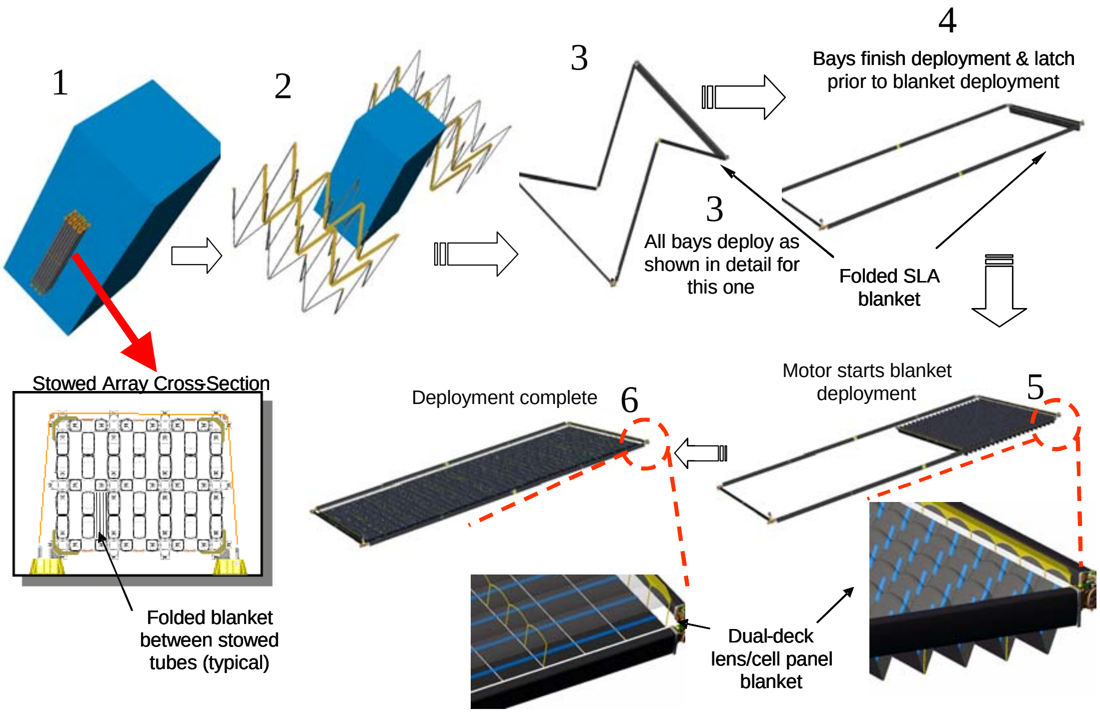

Figure 4: Deployment of the SLASR

IV. Power and Temperature Analysis

The temperature of the solar array is dependent on the location of the SLASR on the lunar surface. The three main areas being studied in this paper are a lunar polar region with high daylight during the year, an equatorial location during the day, and an array in a permanently shadowed crater relying on laser illumination.

Figure 5 shows the relationship between temperature and maximum power for an advanced triple-junction solar cell. This relationship is based upon the temperature coefficients for an advanced triple-junction high efficiency solar cell in space applications. It assumes the lunar temperature range with cell beginning of life performance with no radiation damage. The maximum power increases as the temperature drops of the cell decreases. To determine the maximum power of the solar array at various points on the lunar surface the temperature of the array must be calculated. It is important to note that the SLA will be tracking the sun so the lens side of the array will be radiating to deep space. The emittance factor for the front side of the SLA radiator is about half than that of the back because the lens acts like a thermal radiation shield. This means the radiator exchanges radiation with the lens, which exchanges radiation with deep space. The backside of the array receives radiation from the warm lunar surface along with reflected sunlight, albedo radiation, from the ground. It is possible to paint the back of the radiator white to minimize the albedo heat load but this would add mass to the radiator sheet. However, the mass addition will not cause a major mass increase.

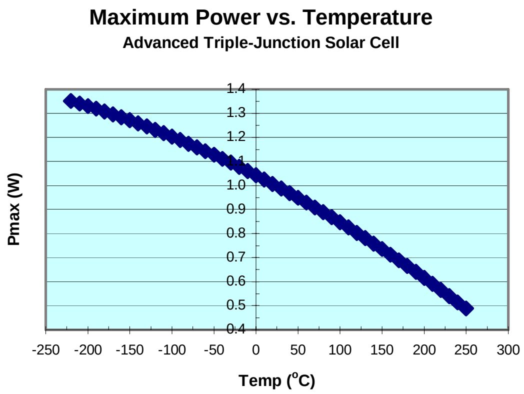

Figure 5: Variation of power with temperature for an ATJ solar cell

An aluminized blanket could be placed on the surface surrounding the array. This will reduce the noon equatorial lunar temperature from over 300 K to 230 K[7, 8]. This will help keep the cell temperature lower at noon. Noon is the worst case scenario because the array will be horizontal to the lunar surface. At other times of the month, the array is tilted allowing the rear side to see the aluminized blanket. The surface solar reflectance can vary from about 5% to 35% depending on location. However, with the worst case scenario at noon the solar reflectance won't really matter much. The lunar surface radiation incident on the back side of the array radiator will include two parts. The beneficial effect of solar array shading on the lunar surface will initially be neglected. Part one is the reflected sunlight or albedo, which is equal to the soil reflectance multiplied by the solar constant. The second part is the infrared emitted radiation which is the soil absorbance multiplied by a solar constant. This equals the Stefan-Boltzmann constant multiplied by the soil emittance multiplied by the soil temperature to the fourth power. The total radiation (albedo plus infrared) leaving the illuminated lunar surface will equal the solar constant regardless of individual reflectance and absorptance values, since when added they equal one at steady state conditions.

Using the worst-case condition, the SLA cell temperature would be about 155 ºC. This will cause the cell efficiency to fall to 23% from 31% at room temperature. Figure 5 show the power would decrease from 0.99 W to 0.73 W, for a 27% decrease. In reality, the cell temperature will be lower because the back of the array sees the lunar surface in its own shadow, which causes the surface temperature to be lower. For locations other than the equator the solar constant hitting the lunar surface at noon will be reduced by the cosine of the latitude angle. At times other than noon the solar constant will be further reduced by the cosine of the solar noon longitude angle minus the local array longitude angle. The SLA cell temperature on the lunar surface at the equator as a function of the solar longitude compared to the array longitude (0 deg at solar noon, 90 deg at solar sunrise or sunset) is shown in figure 6. The cell temperature ranges from approximately 155 ºC for solar noon at the equator to 70 ºC at equatorial sunrise/sunset. This information can then be related to the maximum power graph in figure 5 to determine the power loss of a solar cell in an equatorial position is 27% versus 8% at sunrise/sunset.

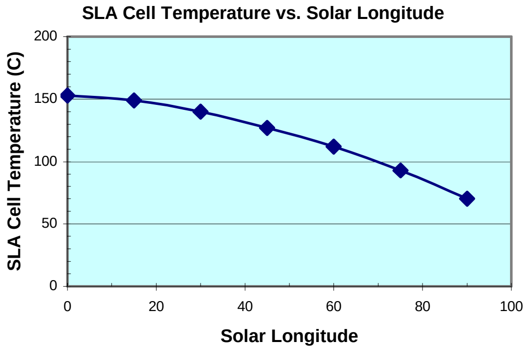

Figure 6: SLA cell temperature on lunar surface versus longitude

Figure 6 can also be used to determine temperatures at any lunar latitude. A solar longitude of 90º is equivalent to a location at the lunar poles for a temperature of 70 ºC. Similarly longitude values of 30º or 60º will correspond to a maximum noon temperatures of 140 ºC and 112 ºC respectively. These temperatures will also benefit from additional reflection of the solar energy by the reflective ground cover.

These are the worst case numbers because the shading effect on the lunar surface due to the array, the reflective blanket on the surface, and thermal control coating on the back of the radiator were not included in the calculations. It is quite feasible to incorporate some of these design features and keep the solar array operating at a lower temperature, hence higher power. By using an 80%-reflective solar reflector sheet (e.g., 0.25-mil aluminized Mylar) on the ground around the SLA, and also adding an 80%-reflective white thermal control coating to the back of the SLA radiator, the cell temperature at solar noon on the lunar equator will fall to about 109 ºC and only a 17% solar cell power loss. This still not include the shadowing effect of the array or the possibility of directing the reflected sunlight away from the back of the array. Using current benchmarks projected to the 2015 time frame with known improvements in cell and array technologies for a 25-30 kW specific power will increase beyond 500 W/kg.

For operation as a laser receiver, cell efficiencies will be in the range of 40-50% (measured), hence the rejected heat load will be lower and cell temperatures will also be reduced. For a Stretched Lens Array in a lunar polar crater, cell operating temperatures under laser illumination may be on the order of -150 ºC. This will lead to power levels more than 70% greater than for solar irradiance alone. Part will be due to the increased cell conversion efficiency and part will be due to the reduced operating temperature. Therefore, attention should be devoted to study of beamed power for lunar applications at any lunar location.

V. Conclusion

The SLASR is very efficient, lightweight, has a high packaging density, and is able to withstand the broad temperature swings on the moon. It is also adaptable to beamed laser power. SLA is an ultralightweight, compact, deployable, high-performance solar concentrator array that can be used for lunar surface power. Minor design modifications and in depth temperature verses power analysis would allow SLASR to be a power option for all lunar sites chosen for exploration.

VI. References

1. O'Neill, M.J., "Silicon Low-Concentration, Line-Focus, Terrestrial Modules," Chapter 10 in Solar Cells and Their Applications, John Wiley & Sons, New York, 1995.
2. Curtis, H. and Marvin, D., “Final Results from the PASP Plus Flight Experiment,” 25th IEEE PVSC, Washington, 1996.
3. Jones, P.A., et al., “The SCARLET Light Concentrating Solar Array,” 25th IEEE PVSC, Washington, 1996.
4. O’Neill, M.J., “Color-Mixing Lens for Solar Concentrator System and Methods of Manufacture and Operation Thereof,” U.S. Patent 6,031,179, 2000.
5. O’Neill, M.J., et al., “Recent Progress on the Stretched Lens Array (SLA),” 18th Space Photovoltaic Research and Technology (SPRAT) Conference, Cleveland, 2003.
6. O’Neill, M.J., “1,000 W/kg Solar Concentrator Arrays for Far-Term Space Missions, Space Technology & Applications International Forum (STAIF 2004), Albuquerque, 2004.
7. Juhasz, A., “An analysis and Procedure for Determining Space Environmental Sink Temperatures With Selected Computational Results,” 2000 International Conference on Environmental Systems
8. Juhasz, A.J., and Bloomfield, H.S., “Development of Lightweight Radiators for Lunar Based Power Systems,” Prepared for 5th Symposium on Space and Environmental Control Systems and the 24th International Conference on Environmental Systems, May 1994.
9. Weber, J., Lunar Base Power System Design Considerations, Master’s Thesis, March 1992. pg. 3-13.
10. Gaier, J.R., and Creel, R.A., “The Effects of Lunar Dust on Advanced EVA Systems: Lessons from Apollo,” Presentation Jan. 2005.