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Point-Focus Concentration Compact Telescoping Array

Extreme Environments Solar Power Base Phase Final Report

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December 2017

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Abstract

Orbital ATK, in partnership with Mark O'Neill LLC (MOLLC), has developed a novel solar array platform, PFC-CTA, which provides a significant advance in performance and cost reduction compared to all currently available space solar systems. "PFC" refers to the Point Focus Concentration of light provided by MOLLC's thin, flat Fresnel optics. These lenses focus light to a point of approximately 100 times the intensity of the ambient light, onto a solar cell of approximately 1/25th the size of the lens. "CTA" stands for Compact Telescoping Array, which is the solar array blanket structural platform originally devised by NASA and currently being advanced by Orbital ATK and partners under NASA and AFRL funding to a projected TRL 5+ by late-2018.

The NASA Game Changing Development Extreme Environment Solar Power (EESP) Base Phase study has enabled Orbital ATK to refine component designs, perform component level and system performance analyses, and test prototype hardware of the key elements of PFC-CTA, and increased the TRL of PFC-specific technology elements to TRL ~4. Key performance metrics currently projected are as follows: Scalability from < 5 kW to >300 kW per wing (AM0); Specific Power > 500 W/kg (AM0); Stowage Efficiency > 100 kW/m^3; 5:1 margin on pointing tolerance vs. capability; >50% launched cost savings; Wide range of operability between Venus and Saturn by active and/or passive thermal management.

Acronyms & Abbreviations

AU	Astronomical Unit
CGF	Composite Grid Frames
CLM	Concentrator Lens Modules
CPM	Concentrator Power Modules
CTA	Compact Telescoping Array
CTE	Coefficient of Thermal Expansion
EESP	Extreme Environment Solar Power
GCR	Geometrical Concentration Ratio
ISS	International Space Station
LILT	Low Intensity, Low Temperature
MOLLC	Mark O'Neill, LLC
NFL	Nominal Focal Length
OA	Orbital ATK
OCR	Optical Concentration Ratio
PFC	Point Focus Concentrator
PV	Photovoltaics
SEP	Solar Electric Propulsion
TRL	Technology Readiness Level

Introduction

For decades now, NASA and others have been investing in technologies to enable affordable, reliable exploration of the more inhospitable reaches of our solar system. One of the technologies to enable this goal is solar-powered electric propulsion (SEP)[1], primarily for its extremely high specific impulse. The challenge however is how to efficiently generate adequate power where the sunlight is much dimmer, down to as low as 1% of the intensity at Earth orbit. Without enhancements such as optical concentration or special solar cell screening, deep space conditions result in solar cells operating too cold and with too little current and voltage to effectively produce power. The surface area required to gather enough light energy grows to unreasonable sizes, and the cost and mass increase, especially given the radiation shielding that must be applied over the active photovoltaics for missions near Jupiter and Saturn. Optical concentration promises to address all these challenges, with the additional benefit of lowering system cost.

Along many fronts, but most intensively under the subject NASA EESP-Game-Changing Technology program Base Phase which this report reviews, Orbital ATK and its partners have been rapidly developing the constituent elements required to make our Point Focus Concentrator (PFC) Compact Telescoping Array (CTA) system ready for near-term mission infusion. Since PFC-CTA is not contingent on any particularly low-Technology Readiness Level (TRL) elements, and since preliminary performance projections have all proven to be conservative upon refined analysis, the authors can confidently project success in crossing the infamous “valley of death” between the present system-level TRL 4 to TRL 5-6 by the completion of the optional EESP study phases.

CTA: Optimal System Architecture for Efficiency and Accuracy

Due to the high optical concentration ratio (OCR) employed by PFC, the alignment between lenses and PV collectors must be maintained within a limited tolerance window, depending on the chosen geometrical concentration ratio (GCR). Precise alignment is achievable with the unique attributes of the Compact Telescoping Array (CTA) architecture, which is a lightweight, compactly stowed and automatically deployable structural platform for blanket array deployment and support. The basic idea for CTA was originally proposed by NASA[2], and CTA has been rapidly advanced by two Phase-II SBIRs led by Angstrom Designs, Inc., with Orbital ATK as partner. A full listing of programs actively developing and/or leveraging CTA is provided in Table 6. CTA comprises tensioned photovoltaic (PV) blankets supported by a central truss mast, a configuration reminiscent of the iconic solar arrays on the International Space Station (ISS). Indeed, this architecture has been demonstrated[3] to provide the most efficient known means of deploying and supporting a planar blanket array, given typical spacecraft structural and packaging requirements, and it is an ideal platform for PFC lens and receiver blankets as well. Extremely high values achieved for key efficiency metrics by the CTA platform (deployed blanket area per system mass & volume and high deployed stiffness & strength) also contribute to the enabling performance achieved with PFC blankets and optical concentration. An overview of the PFC-CTA system is shown in Figure 1.

The ISS masts, built by Orbital ATK (then known as AEC-Able Engineering), were constructed of aluminum and aircraft cable, and require a substantial canister for stowed containment and mast deployment. CTA, in contrast, comprises a lattice truss of high-modulus carbon fiber (nearly 6x the specific stiffness of aluminum), and deployment of the CTA wing is accomplished by a single motorized lead screw which pulls the nested mast segments out from their stowed positions into their deployed, precisely latched, positions.

A second key difference between CTA and the ISS arrays is that the CTA blanket panels are not subjected to bending loads from tensioning the blankets. Thanks to the segmented, telescoping mast construction, the mast is able to extend beyond the blanket length. This enables the use of tension-carrying elements (“stays”) running between the blanket tapes and the mast ends. Eliminating bending loads from the blanket panels saves significant mass and volume, since the blanket panels no longer require a deep beam section.

A secondary function of the telescoping mast extending beyond the blanket length is to provide clearance between the blanket and electric propulsion plume, and to avoid shadowing of the blanket by the spacecraft.

While CTA blanket panels are of similar honeycomb sandwich construction as typically employed for conventional planar solar arrays, for CTA, the total panel area required is on the order of 3% of the blanket area, vs. 100% for a planar array.

Finally, on a related note, the blanket panels fold to stow alongside the mast root segment, providing a compact rectangular stowed volume, which is much easier to package alongside the spacecraft bus than the "T" stowed configuration posed by the ISS (and many other tensioned blanket arrays).

The thermal stability and precision deployment provided by CTA's open lattice, carbon fiber construction, deployed with a bare minimum of joints and latches, are truly enabling for PFC's alignment performance. The only source of mast deployment position repeatability error is from the latches at the root of each moving segment, so these latches incorporate high-precision, self-preloading features, which practically eliminate deployed positional uncertainty, and provide a stiff, determinate joint between deployed mast segments. The effects of these latches on pointing, as well as bending of the mast due to thermal expansion, have been included in pointing budgets and margins developed under the subject EESP study.

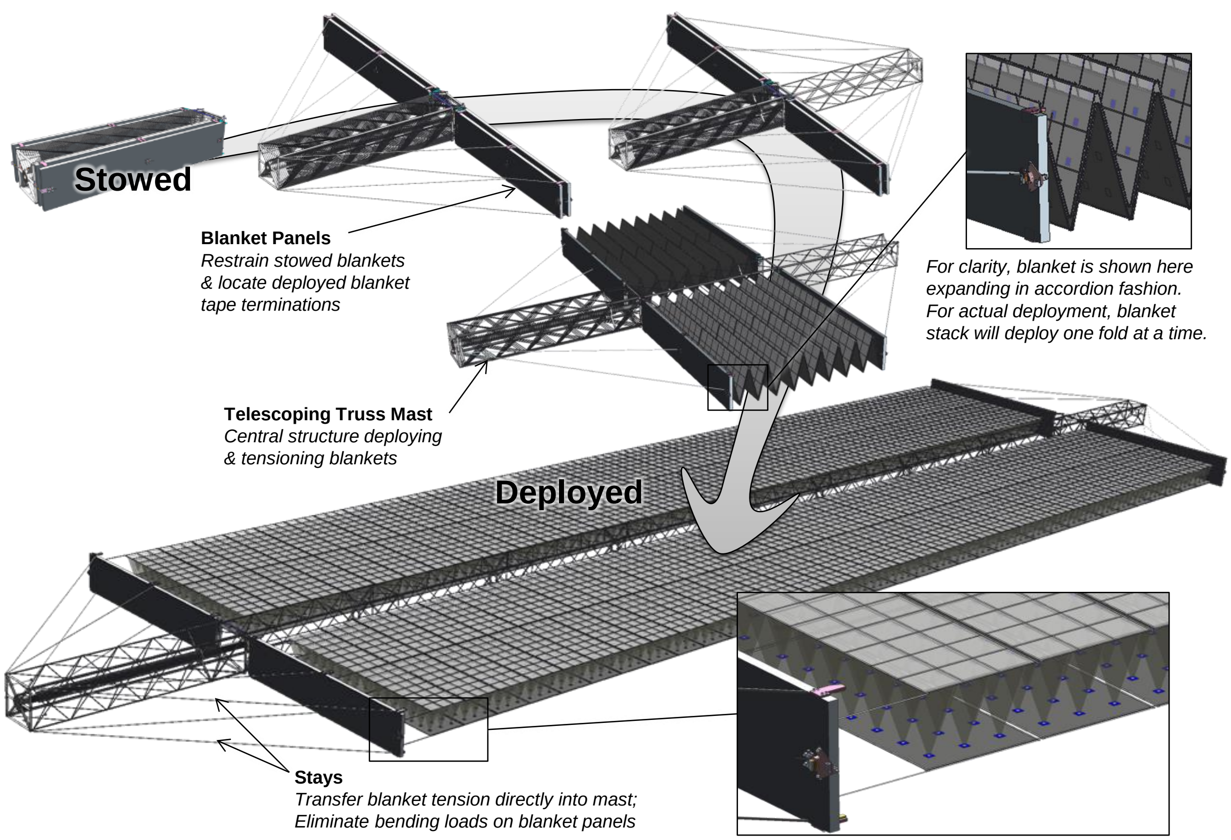


Figure 1. PFC-CTA System Overview

CTA's use of tensioned blankets is beneficial to PFC in virtually eliminating the possibility of bending or bowing in the blanket long axis. Additionally, having the blanket supported only at the root and the tip of the mast, reduces the maximum off-pointing of the blanket by 50% compared with a blanket that is attached continuously along the mast length. CTA's use of discrete tension tapes between the base and tip panels also facilitates a key feature of PFC on CTA: the ability to easily adjust the focus of the lenses vs. the PV for **robust thermal management** at near-sun orbits, discussed below.

Another key innovation employed by PFC-CTA is the use of composite grid frames (CGF) on the lens and PV blankets. The grid frames provide the structure needed to keep each blanket flat despite being tensioned with a limited number of tapes. The thin, near-zero-CTE grid frames maintain flatness between tape constraints, a span of approximately 1 m and contribute only a trivial amount of misalignment relevant to the pointing budget.

CGFs enable low-cost manufacturing of modular CPMs and CLMs (Concentrator Power Modules and Concentrator Lens Modules) and are also a simple and effective method to manage the vibration loading that the stowed blanket is subjected to during launch. For in-plane loads, the composite strips manage compressive loads between distributed masses in a blanket out to the blanket outer edges, where they are snubbed by constraints located periodically on the blanket panels. For out-of-plane loads, the grid strips stack directly on grid strips of adjacent CPMs and/or CLMs, providing a stiff load path, and since the grid spacing is relatively frequent, there are no large spans of unsupported lens or PV/radiator area, ensuring high stowed resonance modes and correspondingly low stresses in these components.

Both the Lens Blanket and Cell Blanket are assembled by fastening the modular CGF subassemblies to the longitudinal blanket tapes. The baseline blanket tape material is carbon fiber, the same material used for the mast construction. Matching the CTE between mast and blanket minimizes the stroke required of blanket tensioning springs (reducing mass and volume of these simple mechanisms). The low CTE also minimizes the in-plane displacement between the lens and PV blankets. In the Optional phases, the blanket tape design details will be developed and validated, to provide the required level of robustness to folding for stowage and/or MM/OD damage.

EESP Base Phase Study Tasks and Results

Orbital ATK (OA) developed and followed a Work Breakdown Schedule (WBS) for the subject EESP study which was structured to mitigate the key risks associated with advancing the PFC system in preparation for space flight operation. The Base Phase activity provided the ideal conditions for rapidly and cost-effectively mitigating these risks, preparing the technology for the high fidelity, detailed design, analysis and testing to be performed in the two optional follow-on EESP study phases. This work was roughly divided into two categories: hardware development/testing and system analysis. This combination provided the ability to incorporate lessons learned from prototype hardware build and test experiences and was a key to identifying and validating baseline materials, dimensions, assembly techniques, function and performance.

Risk Assessment/ Mitigation Status and Plans

Since the PFC Study was first proposed to NASA under the EESP program, the risks that threaten the feasibility of PFC have been identified and tracked. Mitigation of these risks has constituted the majority of the work performed in this study, and guided plans for future work (including EESP Options).

Risk I.D. 1: "Given that PFC lenses are newly developed, there is a possibility that these lenses (lens arrays) will be more expensive to produce than expected"

This risk encompasses the basic technical feasibility of building flat Fresnel lens arrays suitable for space flight, and the economics of the constituent materials and processes. To address this question, a number of flight-like lenses were produced by Orbital ATK's PFC team member Mark O'Neill, LLC (MOLLC) at the outset of the Study and assembled into developmental composite grid frames. The lenses were intended to be similar to Flight construction, but with adjustments made for schedule and cost feasibility. The silicone used was very similar to that planned for flight, but medical-grade, not space-grade. The lens prisms were oriented in line-focus configuration, since point focus lens tooling was not yet available at the outset of the current Study. Shortly after the current EESP study was awarded, MOLLC was awarded a SBIR Phase IIE, in part to build point-focus lens tooling, which has since been employed to successfully produce a number of lenses with the optical design baselined for PFC-CTA. The mesh reinforcement on the brassboard lenses was geometrically similar to a leading option for what was envisioned for flight but testing showed it was not a suitable material due to low strength and high CTE.

The brassboard lens samples were produced on tooling, which is capable of producing 10 MW of tooling in a matter of days. The tools are compact and can be efficiently stacked and/or arrayed for dispensing of the silicone, addition of the reinforcing mesh, and for curing. The silicone for the brassboard lenses was manually mixed and spread, whereas a production run would employ mix-meter-dispense equipment, which is well-established in the silicone plastics production industry – medical supplies, for example.

These adjustments and compromises were justified based on the high initial costs associated with making a very small, prototype quantity for this study. These initial costs relate primarily to tooling and/or minimum buy requirements, costs that are well known and therefore do not pose actual "risk" to a future flight program.

Another aspect related to this Risk topic is the fact that MOLLC is the proprietor of much of the technology behind the PFC lenses. This risk is mitigated by the fact that MOLLC has much experience in licensing and transferring technology to larger organizations. MOLLC has successfully negotiated license to five different companies for terrestrial solar power, daylighting and space solar power products. This model would be followed similarly for Orbital ATK to procure lenses for PFC.

This risk was also addressed during the Base Phase by building brassboard lens grid assemblies. This exercise was informative in selecting materials, sizing components, and developing assembly methods. The basic concept for grid frame assembly is presented in Figure 2 and Figure 3.

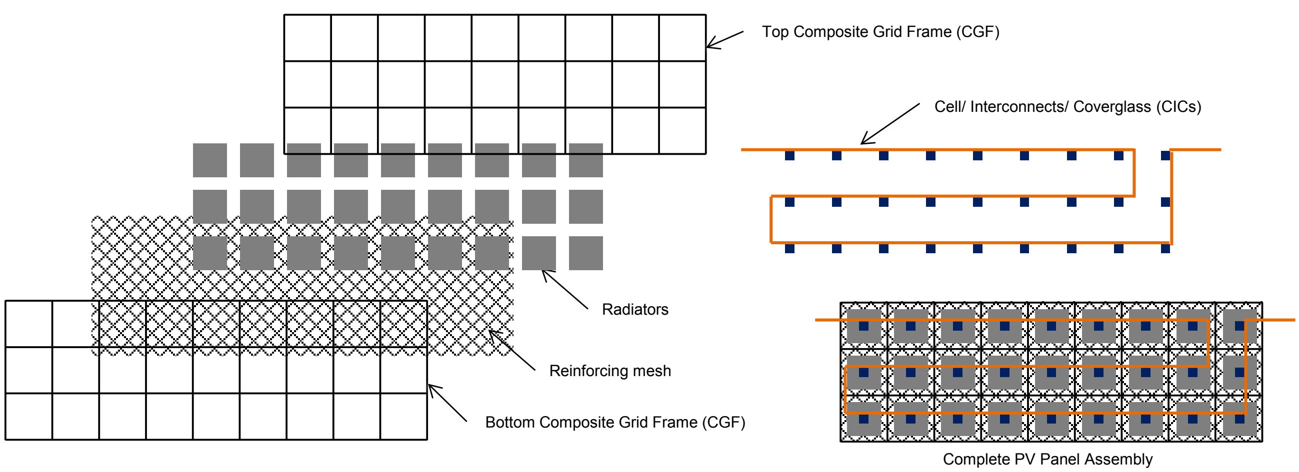


Figure 2. PV Panel Assembly

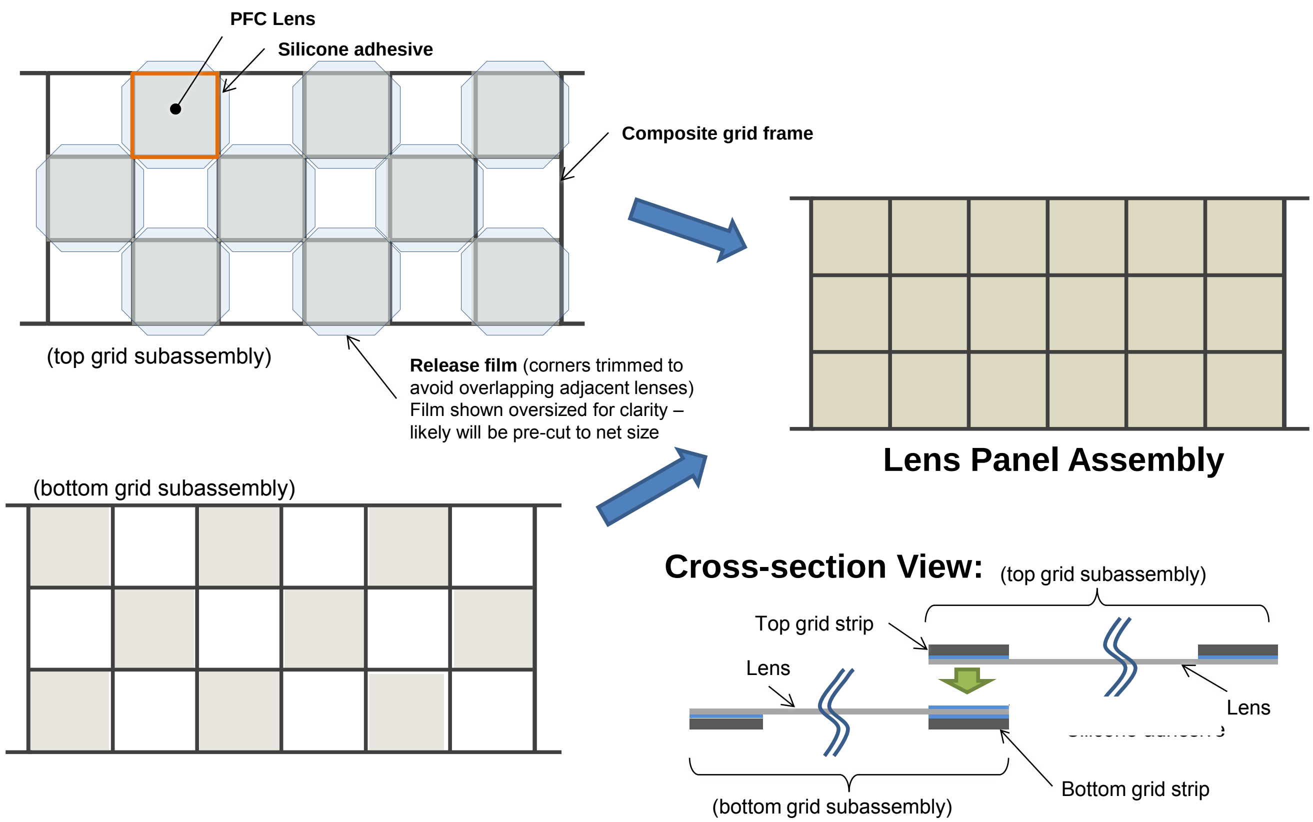


Figure 3. Lens Panel Assembly

It should also be noted that a key to the affordability and scalability of PFC relative to other deep space solar arrays is related to the 25X concentration factor. Photovoltaic cell production is a complicated, capital-intensive process, and LILT operation further reduces yields. The current global capacity for space photovoltaics is on the order of 1-2 MW/ year. If NASA were to pursue missions requiring high power for deep space, say a single mission requiring 500 kW, the PV production required for a “1-sun” array would pose a significant challenge to the industry (approximately ¼ of total capacity for a single mission). If this mission utilizes 25X concentration, the same 500 kW power production is achieved with only 20 kW of PV area, equivalent to merely a pair of typical commercial satellites. The significant cost benefits of high concentration on spacecraft and launch costs are considered further in Figure 11 and accompanying text.

Risk I.D. 2: Given that there is a limited pointing tolerance for a PFC solar array, there is a possibility that the lenses fail to maintain acceptable optical alignment with PV cells throughout mission

The risk of the lenses failing to focus light onto the collector cell is fundamental to any concentrator array, but the CTA architecture has been evaluated in detail in the course of this Study, and perhaps surprisingly, as structural and thermal models have been refined, pointing budgets have generally improved. As of the conclusion of the Study, which considered the alignment errors shown in Figure 4, and alignment budget shown in Table 1, the maximum amount of the available pointing budget used in any degree of freedom is about 20%; in other words, the wing is expected to point about 5 times more accurately than needed to keep the light spots on the solar cells. Of course the size of the cell is a variable that can be adjusted independent of the lens design, to provide a larger boundary to the focused light if needed.

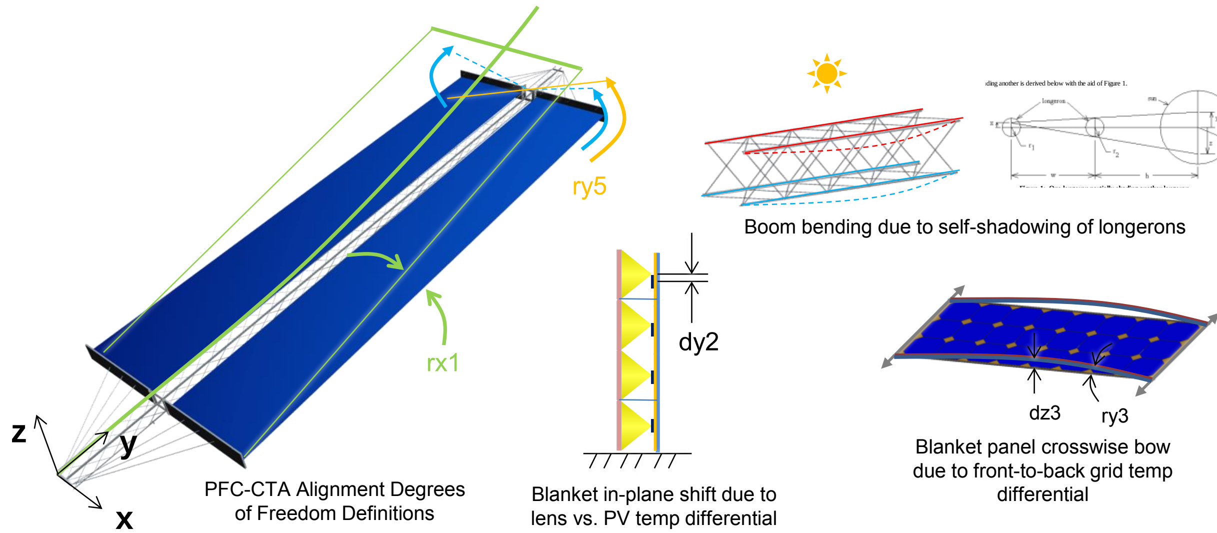
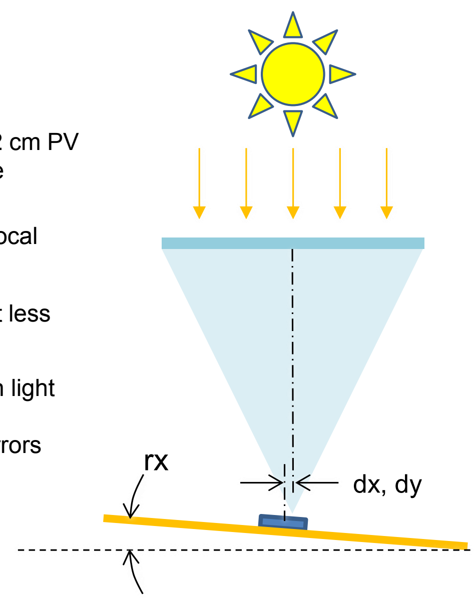


Figure 4. PFC CTA Alignment Definitions

Table 1. PFC Alignment Budget Determination

DoF	Description	Source
dx, dy	Lateral shift	PV collector is oversized vs. Lens "spot", e.g. 2 cm PV cell for 0.6 cm spot = ±0.7 cm (7 mm) tolerance
dz	Lens-Cell Focal Length	1% loss in collector efficiency for 5% error in focal length (.05*200mm = 10 mm)
rx	Lens tilt vs. Sun	Lens efficiency has no measureable drop-off at less than 2° error vs. sun line
dx, dy	Wing tilt vs. Sun	Blanket gross tilt creates a lateral shift between light spot and PV cell. 2° tilt --> 0.7 mm shift (lateral shifts due to angular errors included in rollup)



Risk I.D. 3: Given that the solar cells are subjected to many suns of light, there is the possibility that the cells will over-heat and be damaged

Thermal management is an obvious concern with any solar concentrator, and was addressed in this Study by a combination of analysis and design features. Detailed thermal analysis of the entire blanket system was performed. All blanket components were included in a 3-D Thermal Desktop model, and subjected to a variety of lighting conditions corresponding to various planetary locations as a familiar reference point for illumination conditions that vary from 0.7 AU (Venus, ~ 2 suns) to 10 AU (Jupiter, ~0.01 suns) . The fidelity of the solar cell modeling was given special attention, given the extreme environmental influences inflicted by the 200x range in solar flux input and the consequent changes in light conversion efficiency. SolAero was consulted to review the modeling assumptions and parameters. MOLLC provided light intensity and current concentrations as filtered by the color-mixing lens into each solar cell junction, over the 2 x 2 cm cell area in a 20 x 20 grid, sufficient to resolve thermal gradients related to the focused light spot. These inputs were imported as heat inputs in the solar cell blanket thermal model, which was meshed to an equivalent grid density. The resulting temperature profiles (over the cell area) were then provided to SolAero, which performed detailed power analyses for a wide range of AUs, based on a cell gridline design optimized (somewhat arbitrarily) for operation at Mars orbit.

The lens thermal and power modeling was informative and encouraging, indicating that the radiator design was indeed effective (and necessary) for spreading and rejecting waste heat from the cell. Furthermore, the analysis demonstrates that the PFC system, indeed likely any lightweight, spot-focusing concentrator cell, will likely require some form of active thermal management to be able to operate effectively over the extreme range of solar intensities. A solution developed for PFC-CTA is a simple mechanism to actively adjust the spacing between lens blanket and PV blanket, to intentionally de-focus the concentrated light spot for lower (e.g. Earth, Venus) orbits. The nominally ~100 kW array (2 wing) point-design system developed for this study would require only four small stepper motors to move nearly 300 m^2 of total surface area (lens blanket + PV blanket area) relative to each other. In contrast, a concentrator design based on locally supporting lenses over each individual cell would require 13,560 actuators (the approximate number of cells and lenses in our point-design wing), or complicated mechanical synchronization, to move all of these lenses. PFC-CTA supports the flat tensioned blankets by a limited number of tapes terminating at each ends on the panels. The simple adjustment mechanism would need to be actuated only a few times over the course of a typical mission, to pre-determined lens-to-cell distances. A dynamic feedback control system is not necessary, since the light intensity vs. orbit is known, the spacecraft operators know beforehand when to adjust the focus. Our preliminary evaluation has determined that defocus settings optimized for Venus, Earth, and orbits higher than Mars, would provide robust protection against over-heating, while a nominally focused setting provides optimal off-pointing tolerance and light transmission efficiency to maximize power production at higher orbits when light intensity is most limited.

A brassboard prototype of the spacing mechanism was built and tested during the Base Phase, to validate the expected high actuation efficiency. It was verified that the torque needed to move the blankets is very small, and the drive mechanism can likewise be small and lightweight. The spacing mechanism is expected to be robust in launch vibration, as the components are lightweight and do not support any external loads when the blanket is stowed.

The ability to de-focus the lenses is a truly enabling feature for PFC-CTA, as it is a simple yet effective throttle for the solar cell temperature to avoid over-heating, and also for enabling optimum operation - maximum power out when most needed – or *all throughout* the extremely wide range of solar intensities, from Venus to Saturn (and beyond), with essentially *standard, state-of-the-practice (TRL 9) PV cells*. A brassboard of this simple mechanism has been built to demonstrate its functionality (TRL 4) and will be refined and tested further in Option 1 to increase TRL to 5.

Also, during the Optional phases Orbital ATK intends to study, in parallel with the above defocus mechanism, options to achieve more effective heat spreading across the PV cell and into the radiator, which could potentially eliminate entirely the need for active defocusing even at lower orbits. This is the tradeoff that must be made, adopting more effective (yet lower TRL and likely heavier) PV configurations in exchange for the simplicity of eliminating the defocus mechanism. For the Base Phase, the PFC team consciously decided to baseline the design around flight-proven, “standard” PV cell configurations – materials and dimensions because we had intended from the outset that PFC-CTA be essentially agnostic to PV configurations, to ensure that the PV supplier base be unconstrained and to eliminate the dependence of PFC-

CTA's viability on advancing the TRL of PV cells having integral heat spreaders. Still, this is a trade worth considering, and certainly merits a preliminary investigation such as re-running thermal models which include heat spreading features such have been demonstrated on terrestrial solar arrays and which show promise for use in space flight.

Risk I.D. 4: Given that stowed PFC lens blanket has not been tested, there is the possibility that a PFC blanket is damaged by stowage and/or dynamic (vibration) environments

Surviving the harsh dynamic launch environment is a well-known challenge for all spacecraft components, especially large, lightweight structures with high expansion ratios. Add to the mix potentially delicate objects and this risk may appear to be extremely high. Fortunately, PFC-CTA incorporates a number of features that have been proven to survive launch dynamics, and additionally features, notably the composite grid frames discussed above, that react in- and out-of-plane stowed blanket loads, and eliminate stowed pressure contact between potentially sticky silicone lenses, lending confidence to the likelihood that the stowed blanket will survive launch and successfully deploy with zero degradation. These conditions can be extremely difficult to achieve and still maintain the sufficiently compact stowed volume sought for EESP type power systems. PFC EESP Option 1 includes plans to build a representative blanket stack and subject it to a simulated launch vibration environment to contribute to achieving TRL 5 for this Technology Element.

Risk I.D. 5: Given that they have not yet been tested, there is the possibility that PFC lenses and/or PV cells don't survive deployed environments

Outer space poses a notoriously challenging environment, potentially damaging or distorting materials and assemblies. The key environments related to PFC are radiation (UV and high energy), electric propulsion ion plume, and wide thermal extremes (hot and cold).

Due to the extensive use of flight heritage materials and processes throughout the **CTA platform**, these deployed environments have been validated with all the same, or very similar, materials and configurations. This lends confidence to applying a relatively low risk of successfully qualifying the first PFC-CTA system for space flight.

The **lens blanket assembly** is also constructed of materials that have been extensively flown in space. However, it is clear that the lens materials are implemented much differently than typically; for example, silicone optics have been flown on multiple occasions, but none to-date in the precisely same configuration as the PFC baseline: square, flat silicone lenses, no glass superstrate, mesh reinforcement, mounted within composite grid frames. Therefore, we have looked closely at how this system performs in the relevant space environments, principally, the thermal extremes (stress and strain) and radiation (mechanical and optical degradation).

Thermal: A detailed thermal model of the deployed lens and PV blankets has been assembled, including all pertinent geometry and material properties. This model was used to predict temperatures of all the components at a wide range of operating conditions. Thermal survivability has been investigated by thermal cycling of brassboard lens panels, as well as of brassboard radiator panels populated with radiators and mesh reinforcement. A trade matrix of candidate mesh options was developed and samples of promising lens construction (Figure 5) were built by MOLLC and assembled into a lens grid array (Figure 6) and tested to +125/-170C for five cycles. Mesh A and Mesh B successfully withstood this thermal-cycling demonstrating promise and making them leading candidates for further evaluation in Option 1.

Related to thermal survivability is potential susceptibility of concentration optics to degradation by condensation of volatile solids outgassing from other spacecraft components, especially those on the solar array. This problem has plagued reflective concentrator arrays flown to date[4], while refractive concentrators, notably SCARLET and PASP+, have not experienced this type of degradation, and is therefore not expected to pose a threat to PFC-CTA.

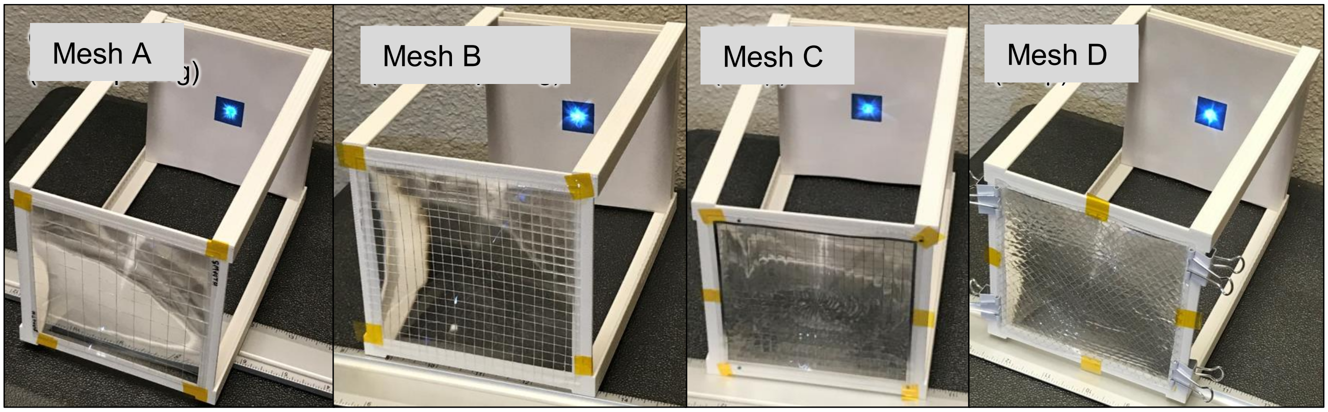


Figure 5. Lens Samples Produced with Various Embedded Meshes

Table 2. Lens Reinforcement Trade

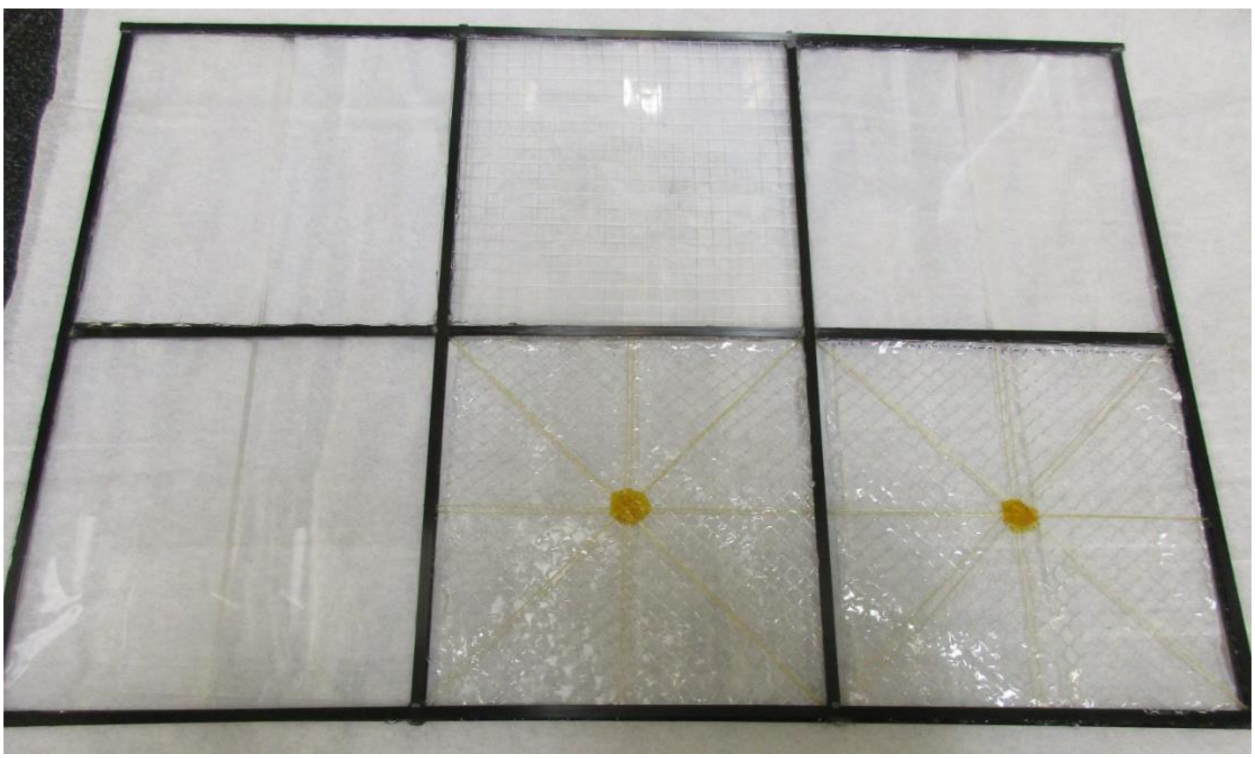


Figure 6. Brassboard Lens Grid with Variety of Options

Radiation: The refractive concentrators used for PFC-CTA have been under development by NASA and MOLLC and other organizations for more than three decades (see Figure 7). The lenses have proven to be robust in the simulated space environment (ground testing) by many organizations, including NASA Glenn, NASA Marshall, Orbital ATK, Boeing, Auburn University, and others.

Ground testing has included monatomic oxygen exposure, space solar ultraviolet (UV) exposure, micrometeoroid exposure, electron exposure, proton exposure, thermal cycling, etc. In addition, multiple flight tests have shown the lenses to be robust in various orbits, including the high-radiation PASP+ mission (USAF and NASA) in 1994-1995, the deep space DS1 mission (NASA/JPL) in 1998-2001[5], low earth orbit (LEO) testing on the International Space Station (multiple MISSE experiments with durations up to 4 years), and the high-radiation TacSat 4 mission[6,7] (NRL/MDA/NASA) in 2011-2012.

All of the lenses held up well in all of these missions and flight tests, except for a mechanical failure issue on TacSat 4, which has since been diagnosed and solved. The silicone lenses are robust when equipped with a UV-rejection coating that reflects away vacuum ultraviolet (VUV) light, or, alternatively, with a UV-absorbing ceria-doped glass superstrate. Many papers have been published showing these results[8].

More recently, additional testing has been performed for proton and electron exposure for missions including 15 years on geostationary orbit (GEO) and 1 year on the TacSat 4 orbit. The basic silicone lens material was originally selected based on its half-century successful flight heritage as the cover glass adhesive on one-sun arrays in space and unique properties[9,10,11].

The latest lenses (line-focus and point-focus) developed by MOLLC for NASA in 2014-2017[12,13] include strengthening elements (either embedded mesh or transparent superstrates) and are the lightest, most robust lenses yet offered. Based on this extensive ground test and space flight heritage, Orbital ATK is confident that robust point-focus lenses can be produced to populate the PFC-CTA solar array.

Given this extensive heritage of the lens configuration, and the variety of promising mechanical reinforcement options, the attainment of TRL 5 for the lens blanket Technology Element by the conclusion of Option 1 is expected by performing thermal cycle and radiation tests on high-fidelity lens grid modules.

Dense Plasma from Electric Propulsion Ion Plume: While certainly a “relevant environment” for any SEP solar array, this subject is not considered a key risk to PFC development. Orbital ATK[14] and others[15,16],have investigated this subject in detail, and developed solutions to mitigate these effects which will be incorporated on PFC-CTA, including complete cell and interconnect encapsulation and a plume-compatible lens outer surface.

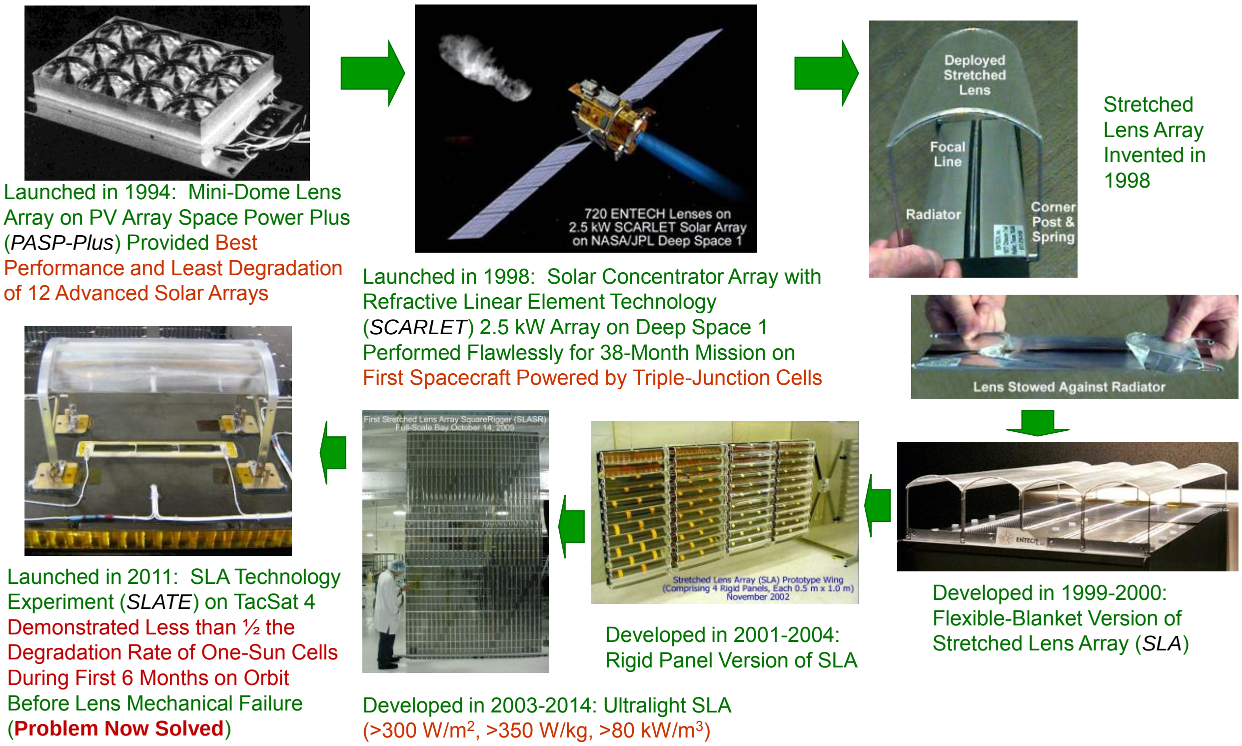


Figure 7. PFC Team's Concentrator Solar Experience Examples

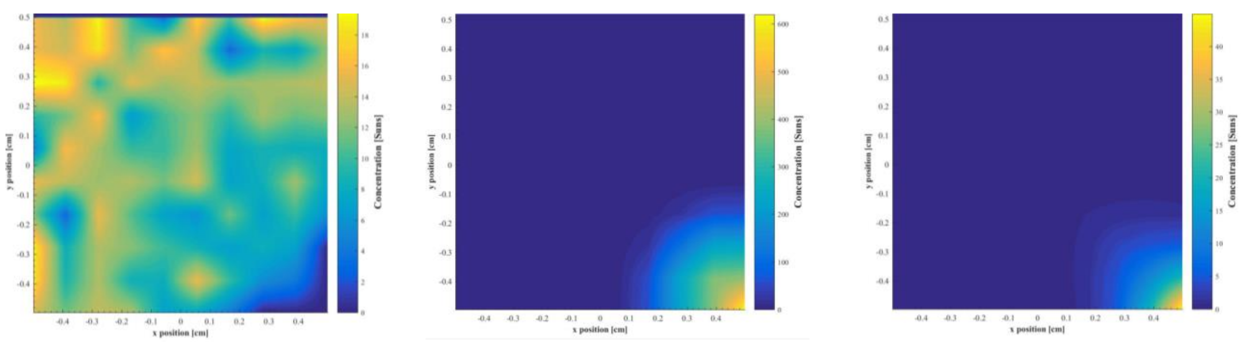
Thermal Analysis

As mentioned above, thermal analysis was a key activity of this base phase study. Temperature predictions for all the relevant components were used to guide the design (materials, finishes), and determine predicted performance (alignment, power production). A detailed Thermal Desktop model of the PFC-CTA blanket was developed, with model inputs and parameters corresponding to current best estimates of dimensions, materials, and properties for all relevant components. This model was run through a variety of solar intensities (orbits) and lens defocus positions. Key component temperatures were utilized by sub-system math models to determine the resultant thermal distortions that could affect system pointing. Detailed maps of temperatures over the surface of the PV cell were provided to SolAero for them to perform a grid spacing optimization (at one operating point) and power analysis of their state of the art triple junction cell at the various orbits. Table 3 summarizes the cases evaluated and estimated power production for the 3.1-m "point design" PFC-CTA wing. Figure 8 shows the illumination on a 1/4th cell area for three selected cases.

As discussed above, one key finding of the thermal analysis was that there must be some form of active thermal management to allow the PFC 25X GCR array to fly at sub-1 AU orbit, e.g. for a Venus flyby mission assuming standard PV cells are to be used. PFC-CTA is uniquely capable of achieving this with a minimum of added complexity by defocusing the entire array of lenses with a small number of actuators and simple mechanism. The effect of defocusing the lenses is made clear by the plots of Figure 8 and Figure 9, and the point focus lens shown in Figure 10.

Table 3. Thermal Modeling Cases & Summary Results

Location	AU	"suns"	% of NFL	% light hitting cell	Spot size on cell (Øcm)	Predicted Temps and Gradients (C)					Eff (%) Rel. to 1367 W/m^2	Point-Design Wing Power (kW)
						Lens & Grid	Lens Grid Front/ Back Gradient	PV Peak	PV Grid	PV Grid Font/ Back Gradient		
Venus	0.72	1.93	72	50%	2	34.6	1.0	161.8	110.6	0.3	24.4%	37.5
Earth	1.00	1.00	72	50%	2	-23.0	0.4	82.4	56.0	0.2	28.8%	22.9
Earth*	1.00	1.00	94	100%	1.4	-22.0	0.6	180.5	57.6	0.2	22.8%	36.3
Mars	1.50	0.44	94	100%	1.4	-68.0	0.3	52.7	-4.0	0.1	30.7%	21.7
Jupiter	5.20	0.04	100	100%	0.6	-161.0	0.1	-109.0	-125.0	0.1	38.0%	2.2
Saturn	9.60	0.01	100	100%	0.6	-195.0	0.1	-160.2	-165.0	0.1	39.7%	0.7



Earth, 72% FL, ¼ cell area *Earth, 94% FL, ¼ cell area* *Jupiter, 100% FL, ¼ cell area*

Figure 8 . Cell Illumination Examples

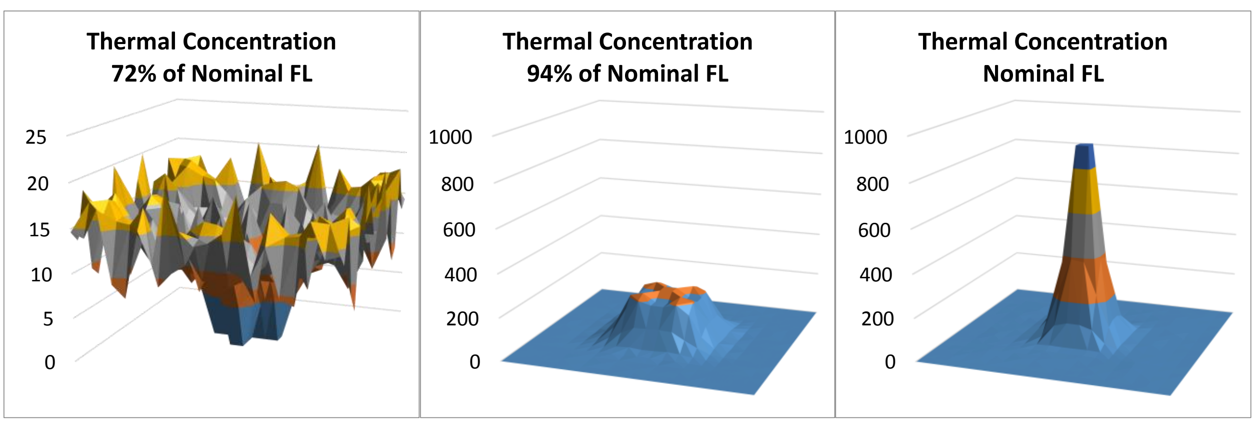


Figure 9. Light Spot on Solar Cell at Nominal and De-Focused Positions

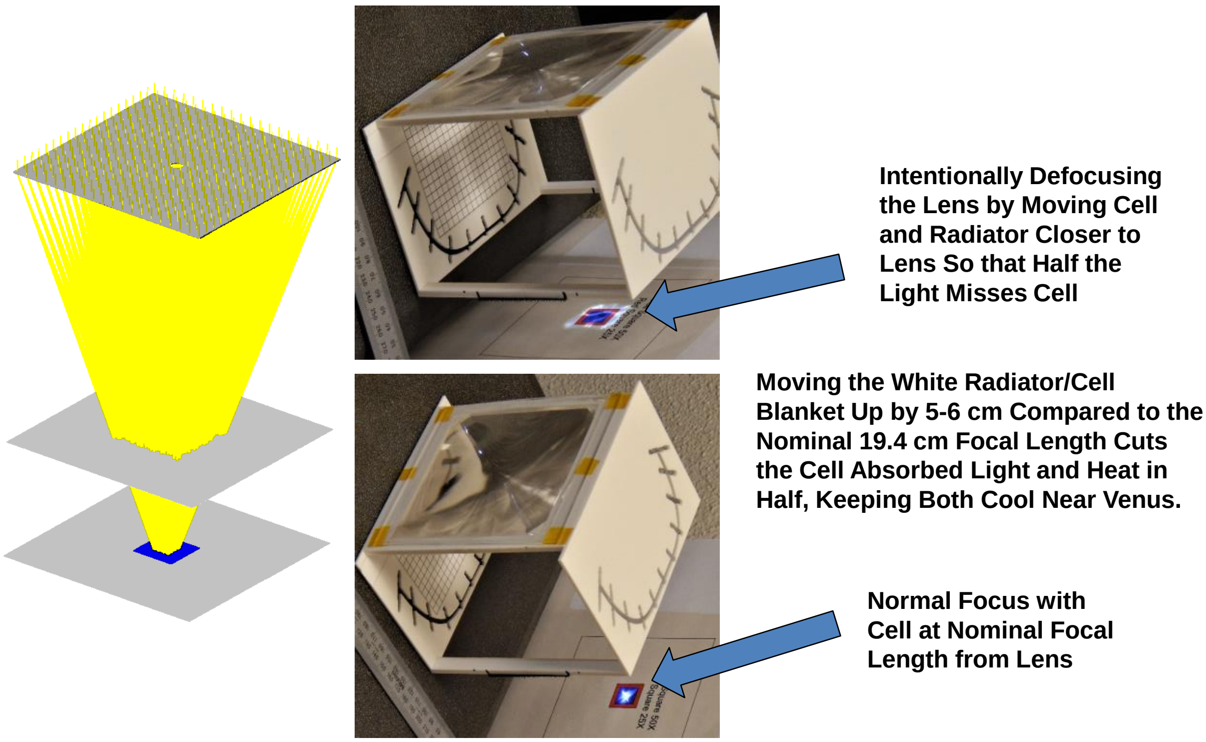


Figure 10. Effects of Lens De-focusing on Light Intensity Hitting Cell

System-Level Performance Analysis

A system sizing spreadsheet has been developed and updated by Orbital ATK to incorporate all relevant solar array parameters, constraints (e.g. stiffness, strength, maximum dimensions), and goals/objectives (e.g. max W/kg or kW/m^3) to allow the user to quickly perform “one-click” system optimization and sizing of the wing. The spreadsheet provides all the relevant dimensions, including mast components (longeron and diagonal width and thickness), blanket panels (facesheet and core thickness), blanket tension, etc.

These initial parameters are then easily imported to the master system CAD model, which assigns parameters to component dimensions, which in turn updates entire solar array wing. This is an incredibly powerful tool for quickly providing a high-fidelity design baseline for mission planners (spacecraft systems engineers) to optimize and iterate potential mission architectures to different aspect ratios (for example, a dual-manifest launch configuration), orbital trajectories (optimizing power production at a particular orbit/intensity), stiffness, strength, etc.

This tool has been exercised to produce a comparison between a “one-sun” CTA system and a PFC-CTA system at 25X geometric concentration ratio (GCR), which is the current study baseline. An example of the tool’s utility in optimizing for a wide range of goals is the $/W-to-orbit metric, which conceivably may be a driving requirement, especially for a very high-powered mission. Thanks largely to the more than 50% reduction in blanket areal mass offered by PFC, coupled with significantly lower PV (solar cell) costs (1/25th the PV area of a 1-sun array), the $/W metric is approximately 1/3 of the one-sun array cost, and other critical metrics (W/kg, kW/m^3) are also radically improved.

Scaling trends can also be explored in depth, where specific power on a kW/m^3 basis or W/kg basis can be shown to trend slightly down as wings grow, as is expected assuming structural requirements (stiffness, strength) are held constant. Tradeoffs between stowage efficiency (kW/m^3) vs. mass efficiency (W/kg) can also be made, as shown in Figure 11.

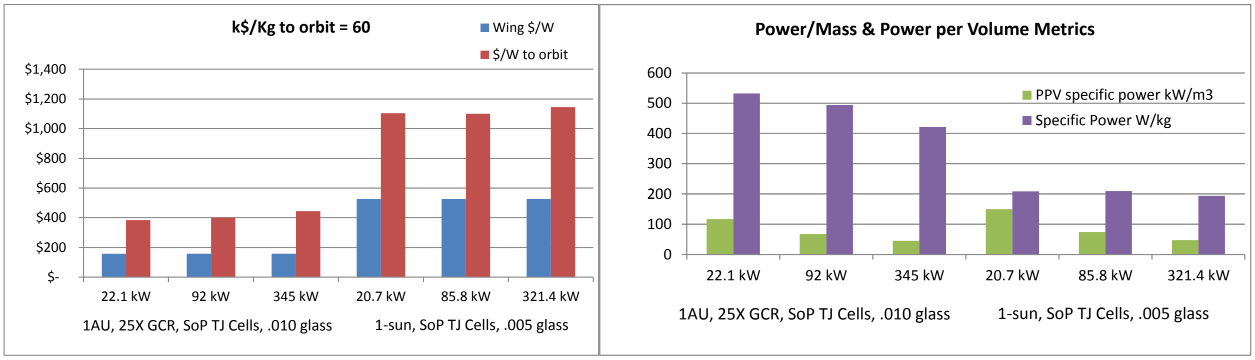


Figure 11. System Sizing Output Examples

High optical concentration solar arrays have been studied in depth by NASA scientists and engineers, and a concise summary of current thinking is offered by Geoff Landis in a recent paper[17]: ““The net calculation, incorporating intensity, LILT, and radiation effects, suggests that for a 1-year mission at Europa, concentrator systems at a concentration of ~25 could produce on the order of 50% higher end-of-life power for the same array mass. For a mission further into the radiation belts (e.g., Io), or longer assumed lifetimes, the advantage increases. Whether this increase in power is worth the added complexity and pointing requirements of a concentrator system is a question for the spacecraft systems engineer.” These projections are consistent with the findings made by the PFC-CTA study.

A summary of the projected PFC-CTA performance vs. the requirements set forth in the EESP NASA Research Announcement (NNH15ZOA001N-15GCD-C3) is provided in Table 4. Despite their aggressive, “Game-Changing” quality, all goals are readily achieved by PFC-CTA, many by a significant (~2X) factor.

Table 4. PFC-CTA Performance vs. NRA Goals/Requirements

Array System Goal (for conclusion of Option II)	**PFC-CTA Performance (as of conclusion of Base Phase)**
35% BOL cell efficiency measured at 5 AU and -125°C	Predicted cell average operating temp is -109C, 38% efficiency at 5 AU (vs. 29.1% at 1 AU) using SoP 3J cells. IMM cells on PFC-CTA are expected to provide >40%.
28% EOL at the blanket (or equivalent) level, given mission conditions characterized in Table 1	Conservatively assuming 10% efficiency loss at EoL, net 34% (with SoP 3J cells). Refinement pending radiation analysis in Option 1.
8-10 W/kg measured at EOL inclusive of the array structure and deployment mechanism, given mission conditions characterized in Table 1	Preliminary estimate (pending Option 1 detailed radiation analysis) Assuming 29% efficient cells with 10% system losses, system is at 18 W/kg at 5 AU **(2x better than goal)**
Packaging density of at least 60 kW/m3(2), calculated at power level predictions for BOL in near earth orbit (1345 W/m2)	Assuming 29% efficient cells with 10% system losses, system is at 97 kW/m3 **(1.6x better than goal)**
Demonstrate ability to integrate proposed technology into a solar array structure that can be stowed and survive launch conditions.	**Yes,** Blanket design derived from flight-proven UltraFlex. Option 1 will perform blanket subsystem vibration testing. Two separate Phase-2 SBIRs developing CTA architecture (hardware fabrication in work), second of which will include wing-level vibration testing.

Array System Goal (for conclusion of Option II)	**PFC-CTA Performance (as of conclusion of Base Phase)**
Technology capable of operation over the range of 100 – 300 V.	**Yes**, protection from arcing in plasma by cell encapsulation Sparse PV cell spacing and small cell area facilitates robust structure grounding and insulation of cells.
Technology capable of operation in the presence of plasma exhaust fields equivalent to Xe plasma having an energy level (Te) of 2 eV and a number density of 1e8/cm3	**Yes,** Option 1 study to determine if ion plume has negative effect on lens efficiency or strength. PV blanket similar to those previously demonstrated operating in dense plasma.

Table 5. Relevant Environments and Maturity of Key PFC Elements

Item(s)	**Stowed Dynamics**	**Deployed Dynamics**	**Deployed Environments**
Mast, blanket panels, mecha-nisms	High-fidelity EDU developed under two, Phase-2 SBIRs. Vibration testing is planned for 4Q 2017.	Mast is preloaded, determinate structure. Full-scale EDU's will provide ground test validation of high-fidelity FEA.	Pointing accuracy is key performance attribute (besides survival). Continuous, unidirectional composite elements, un-strained when stowed and deployed, in conjunction with determinate, preloaded latches, promise extremely predictable system-level behavior.
Lens Panels	Blanket design with composite grid frames is inherently robust. Vibration testing of stowed blanket coupon is planned for Option 1.	Composite grid frames have been sized to guarantee that local panel modes are much higher than blanket system. Thermal analysis indicates that crosswise bowing is trivial.	**Thermal:** Thermal cycling and analysis of brassboard coupons indicated need for different lens support method. Many options available to investigate. **Radiation:** Results from coupon tests with similar to EESP target doses produce acceptable degradation. **Plume:** Will be assessed in detail in Option 1 & 2.
PV Panels	(similar to lens panels)	(similar to lens panels)	**Thermal:** Thermal extremes predicted for PFC are encompassed by flight heritage conditions. **Radiation:** Results from coupon tests with similar to EESP target doses produce acceptable degradation. **Plume:** Will be assessed in detail in Option 1 & 2.

Activities Related to PFC-CTA Development

Table 6. PFC-CTA-Related Activities

Lead (partner)	Funding, Title	Time-frame	Key Activities
AD (OA)	NASA, CTA Phase 2 SBIR	6/16 - 12/17	CTA EDU, key functional aspects less root hinge and tiedowns. Ground offloaded deployments only.
AD (OA)	AFRL, CTA Phase 2 SBIR	3/17 - 9/18	CTA EDU, adding root hinge, tiedowns.
OA (MOLLC)	NASA, EESP PFC-CTA Base Phase	10/16 - 4/17	Point Focus Concentrator: Pointing, thermal, system performance, etc. Brassboard fidelity prototypes & test hardware development.
MOLLC (SolAero)	NASA, Phase IIE	10/16 - 4/17	25X Point Focus lens developed including lens tooling. Lens samples delivered to NASA.
MOLLC (SolAero)	NASA, CCRPP (proposed)	6/17 – 6/18	Further development of 25X concentrator, mesh reinforcements, optical performance verification. Orbital ATK is an "investor" via EESP Option 1 & 2.
OA (NASA LaRC)	NASA, CIRAS (Tipping Point)	10/16 - 10/17	In-flight assembly technology demonstration program. Prototype CTA wings built to validate robotic installation and deployment.

Summary and Conclusion

Orbital ATK is excited about the promise of PFC-CTA, based on our success during the Base Phase in mitigating most of the key risks associated with the preparation of this technology for space flight infusion. The structural and packaging efficiency of CTA as a 1-sun solar array has shown to be similarly enabling for a high-concentration array, providing the accurate pointing and high stiffness required for high concentration. The fact that PFC-CTA achieves this breakthrough array level performance without the need for low-TRL PV technology (heat spreaders or IMM construction) makes it *accessible to near-term missions*, and the rapid rate at which the component elements is advancing along other fronts is further confidence that PFC-CTA will be “ready for action” by the completion of the EESP program options. Orbital ATK is very much looking forward to the opportunity to tackle the work remaining in the Optional phases, to see PFC-CTA become a reality to offer its enabling performance to an new generation of deep space missions which will help unlock the many secrets still hidden in the dark reaches of our solar system.

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