Photovoltaic Spectral Splitting Approaches for Space Systems

Michael F. Piszczor
Chief, Photovoltaic and Power Technologies Branch

Presentation to the ARPA-E Workshop on High Efficiency, High Concentration PV
March 26, 2012

Brief Introduction

- Early photovoltaic devices for space dominated by the drive to achieve higher efficiency and reduce degradation to space radiation
  - Silicon (Si) cells later transitioned into Gallium Arsenide (GaAs), development noted by extremely modest efficiency gains
- Transition to GaAs cells provided potential for substantial improvements in efficiency through development of multijunction solar cells that utilize solar spectrum more efficiently
  - Early development efforts suffered from the lack of a reliable, efficient tunnel junction to connect monolithically-grown devices
- As a result numerous cell and array designs were investigated
  - Mechanically-stacked solar cells (i.e. GaAs/GaSb @ Boeing)
  - Spectrum-splitting approaches (holographic concentrators, etc.)
  - DoD concentrator efforts focusing on survivability to natural and man-made threats
- Successful development of tunnel junctions has established multijuction GaAs-based cell technology as SOA for space PV

Why use Photovoltaic Concentrators in Space?

Photovoltaic (PV) concentrators offer many advantages similar to those for terrestrial applications. Potential advantages include

- Reduced cost due to reduced cell area
- Reduced mass (dependent upon specific designs)
- Decreased array stowed volume
- Increased radiation hardness
- Capability of high voltage operation within the space environment
- Inherent protection from natural and man-made threats
- Increased cell performance for outer planetary missions (reduced LILT effects)
- Increases in PV cell yield for designs using smaller cells
- Designs that could enable the first use of new high efficiency, high cost PV devices

But spacecraft designers must also consider

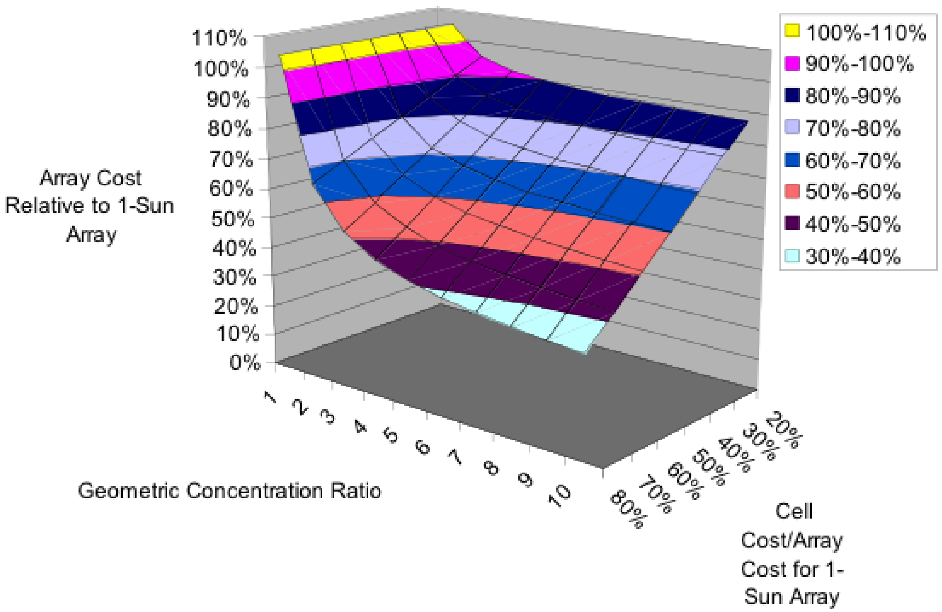
- Sun-pointing requirements
- Higher operating temperatures, thermal design & rejection
- Increased system complexity/decreased reliability
- Loss of mission during operational anomalies (concentrator arrays must be solar pointing to produce power)
- Cost associated with conc. elements, added structure, fabrication, testing, etc.
- Space environmental effects on concentrator & optical materials
- Lack of space flight heritage (different from planar solar array designs)

Space vs. Terrestrial Concentrator Designs

There are some significant differences between space and terrestrial concentrator designs

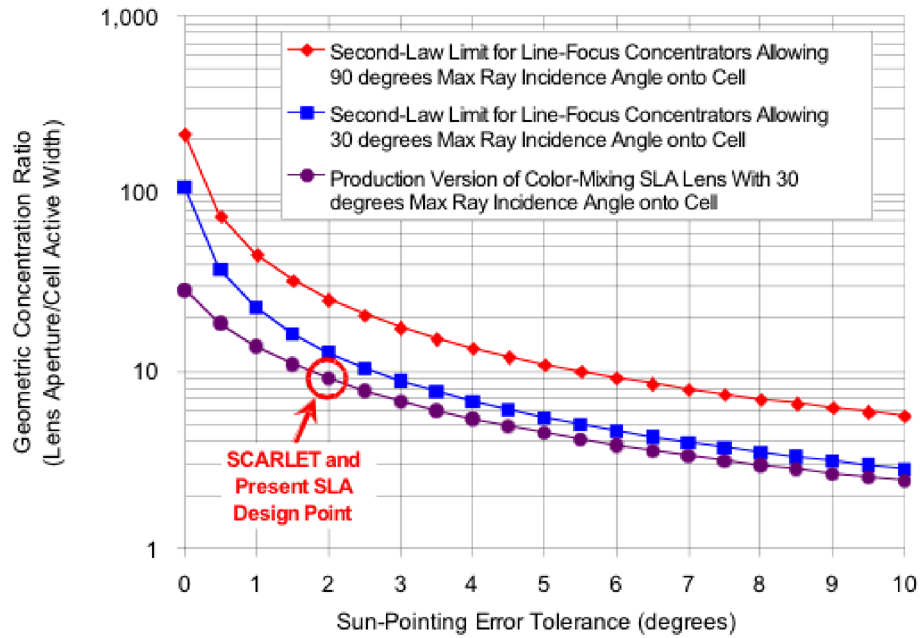
- Mass is a major performance parameter
- Long-term reliability under thermal, operational, etc. conditions is critical
- Array must stow compactly and deploy reliably
- Environmental conditions are unique & harsh (radiation, UV, AO, vacuum, etc.)
- **Operational sun-pointing requirements lead to lower concentration ratios**

<u>Example using Stretched Lens Array Design</u>



Relative Array Cost Compared to Planar Array

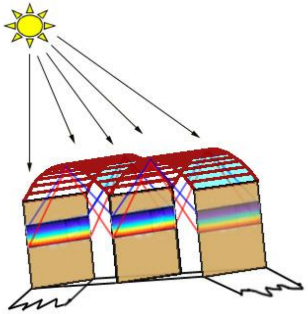
Concentration Ratio Versus Sun-Pointing Tolerance



Spectral Splitting and other Advanced Concentrator Concepts

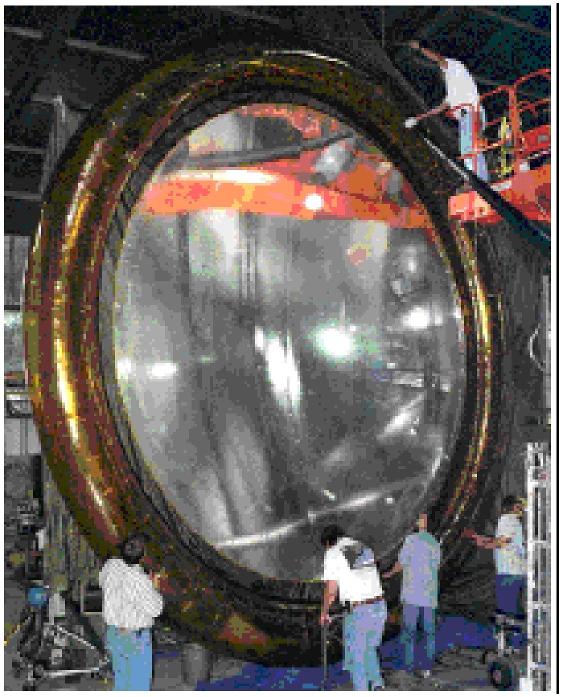
Multi Band Gap High Efficiency Converter (Rainbow) by JPL

Issues
- complexity
- optical losses
- control & dynamics
- materials
- etc.



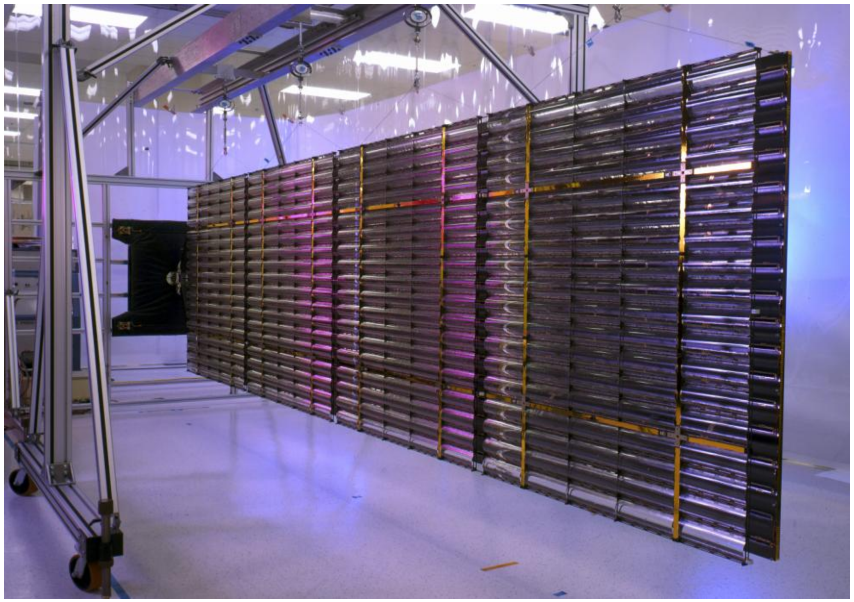
20X spectrum splitting approach to achieve system efficiencies > 50%

Dense PV Array Concepts: Thin film reflectors redirect sunlight to small PV arrays



Lightweight Inflatable Conc. developed by SRS & AFRL

NASA Deep Space 1
SCARLET Concentrator Flight History

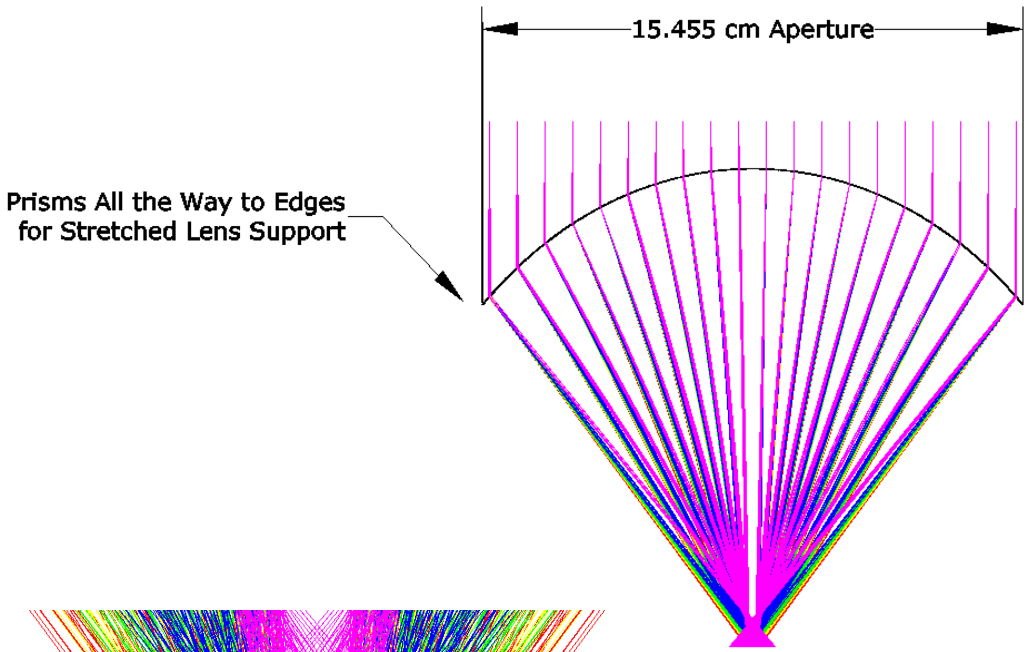


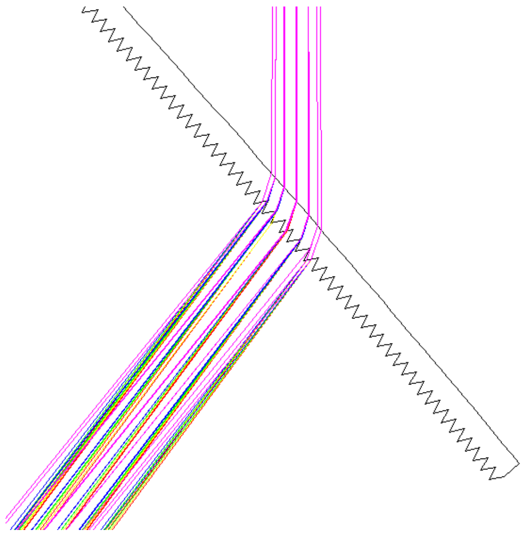
SCARLET: Solar Concentrator Arrays with Refractive Linear Element Technology

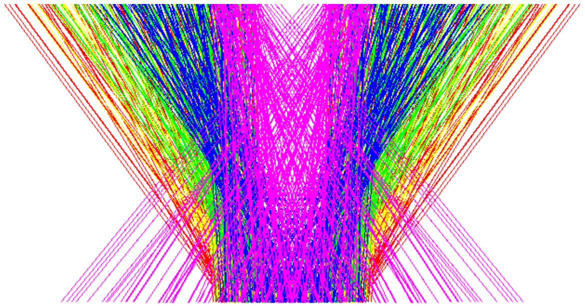
- Flight Results
  - no deployment or performance problems
  - array operated as predicted

- First operational refractive concentrator
  - launched Oct. 1998 on NASA Deep Space 1
  - comet rendezvous mission
  - used as primary power for solar electric propulsion
- Distributed refractive design
  - 7.5X concentration
  - 2.5 kW array
  - used GaInP/GaAs DJ cells

Entech Solar Thin Lensfilm (250 microns) Design Using Symmetrical Refraction Approach





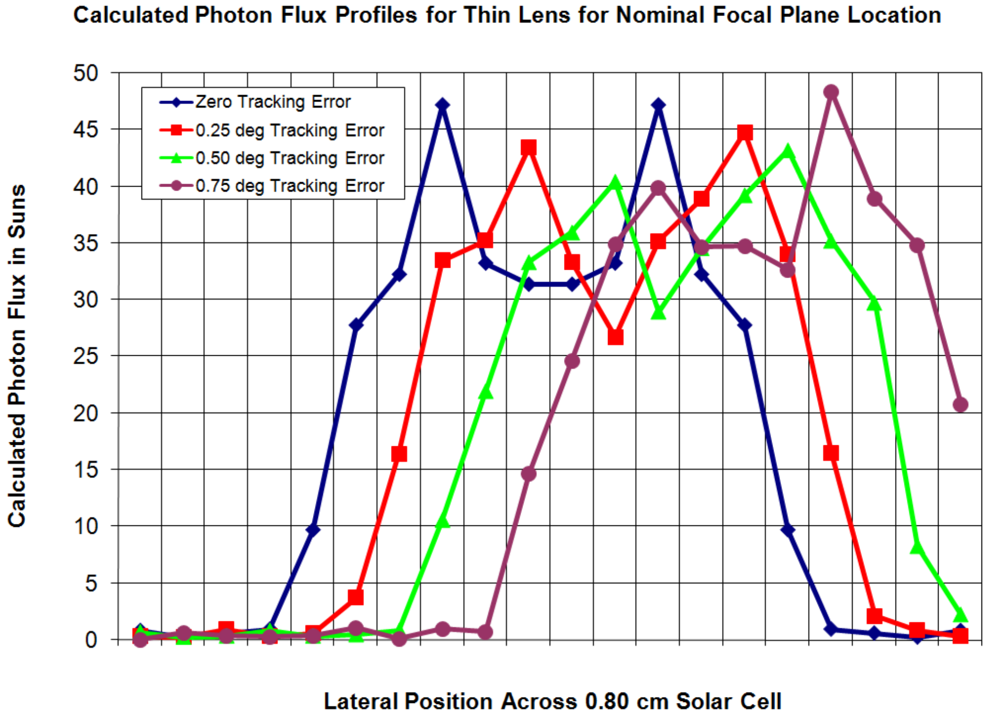


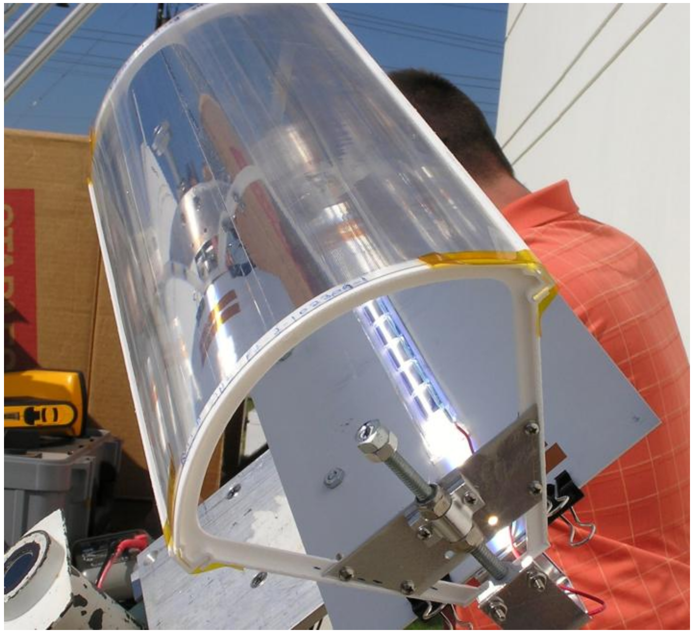
Edge Blow-Up Shown Above and Focal Region Blow-Up Shown on the Left

Entech Solar Symmetrical-Refraction Lens Offers:

- Minimum Reflection Loss, Maximum Transmittance
- Sharper Focusing
- Shorter F/#
- Exceptional Shape Error Tolerance
    - >200X Better than for Reflective Concentrators
    - >100X Better than for Flat Lenses

Entech Solar Lens Approach to Sun Pointing, Terrestrial Design





Prisms Are Optimized for 20X Concentration and $\pm$0.75 Degree Sun-Pointing Tolerance

Outdoor Measurements Confirm 90% Net Optical Efficiency at 20X

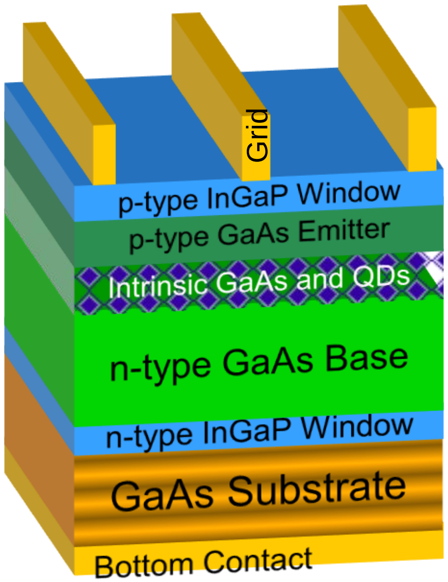
NanoStructured Photovoltaic Technology

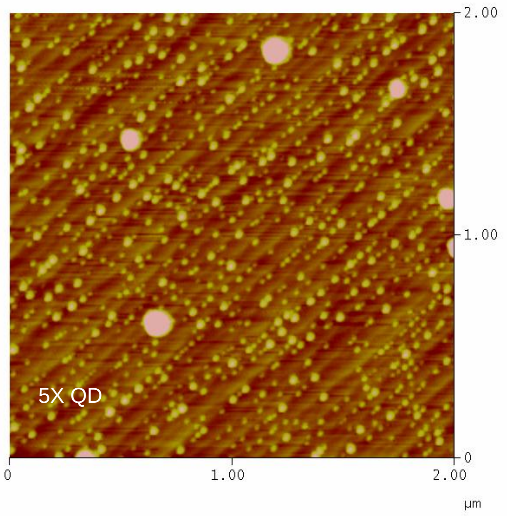
Quantum Dot Technology Has Potential to Exceed 40% Conversion Efficiency

- Intermediate Band due to QD coupling (IBSC)
  - A. Luque and A. Marti, Phys. Rev. Lett. 78, 5014 (1997).
- Enhanced photogeneration mechanisms and two-photon effects
- Reduced spectral sensitivity
- No current matching requirement
- Fundamental physics

Spectrum	Maximum Efficiency	E_{CI}	E_{IV}
6000 K Blackbody	46.70%	1.49 eV	0.92 eV
AM0	45.80%	1.38 eV	0.85 eV
AM1.5G	49.40%	1.50 eV	0.93 eV
	48.60%	1.36 eV	0.75 eV

- Absorption Spectrum Extension
- Low Eg Quantum Dots harvest photons lost due to transmission
- Demonstrated increased current generation
  - Linear increase with number of QD layers
- QD-enhanced GaAs p-i-n solar cell exceeds single junction efficiency (RIT-2010)
- Rich field of study with solid results to date





Summary

- Spectral-splitting "solar array" approaches have been overshadowed by the success in monolithic, GaAs-based multijuction cell technology
  – SOA, 3-junction GaAs-based cells (30% AM0 1 sun efficiency; 40+% under terrestrial, high concentration operation demonstrated)
  – Newer high-efficiency devices on the horizon; Inverted Metamorphic Multijunction (IMM) technology has been demonstrated, 5 & 6 junction development efforts underway, use of nanotechnology could further increase potential for higher efficiency at lower cost
  – Space technology rapidly making it's way into the terrestrial marketplace thru the use of very high concentration systems (500-1000X) that make this relatively expensive cell technology economically competitive with "traditional" terrestrial PV tech.
- Concentrator array designs will still provide an important role in meeting space mission requirements, emphasis on lower concentrations (i.e. 2 – 50X)

NASA