Cylindrical and Flat Solar Collector Geometries: Theory and Experiment

The Performance and Optics of the "Solyndra" PV Panel

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Introduction

- Cylindrical solar cell tubes use thin-film CIGS technology:
  - Tracking not required
  - Ease of mounting, cooling, and cleaning
  - CIGS ~ 20% efficient
  - Wind loads reduced
  - Low roof penetration
- Significant media coverage of the technology:
  - How does it work?
  - Does it work well?
  - We are not interested in the politics (much)

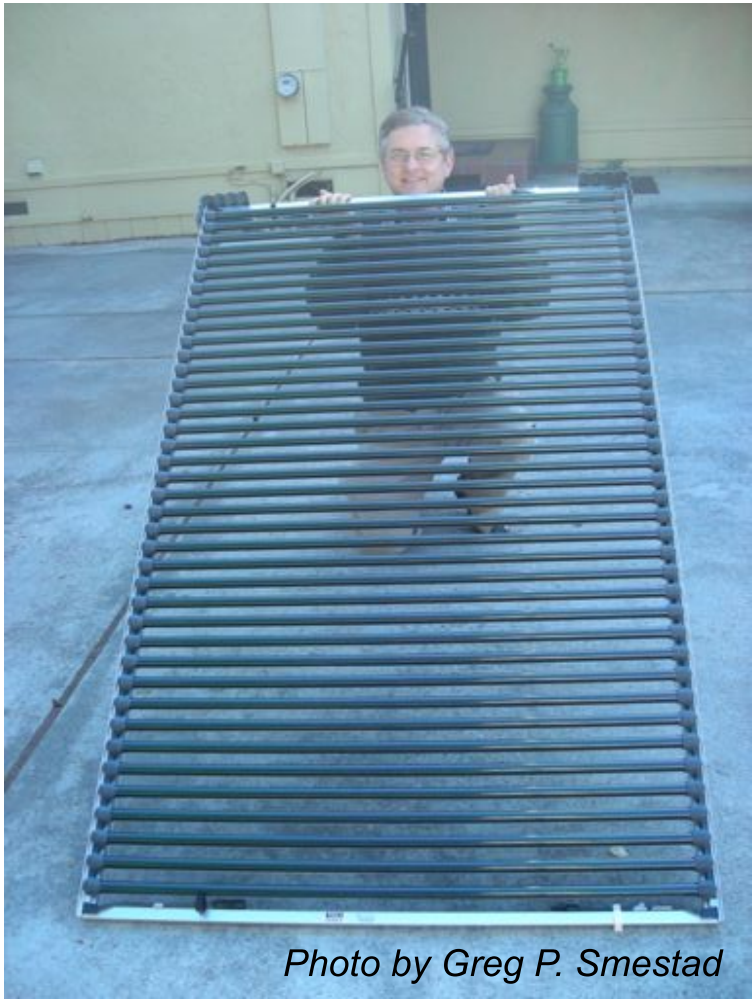
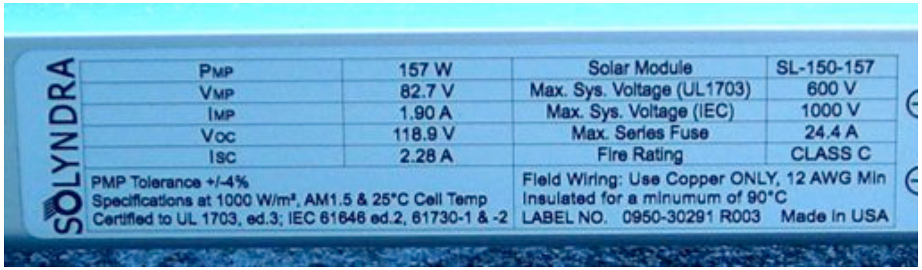


Photo by Greg P. Smestad

Motivation

Photos by Greg P. Smestad



SOLYNDRA

PMP	157 W	Solar Module	SL-150-157
VMP	82.7 V	Max. Sys. Voltage (UL1703)	600 V
IMP	1.90 A	Max. Sys. Voltage (IEC)	1000 V
Voc	118.9 V	Max. Series Fuse	24.4 A
Isc	2.28 A	Fire Rating	CLASS C

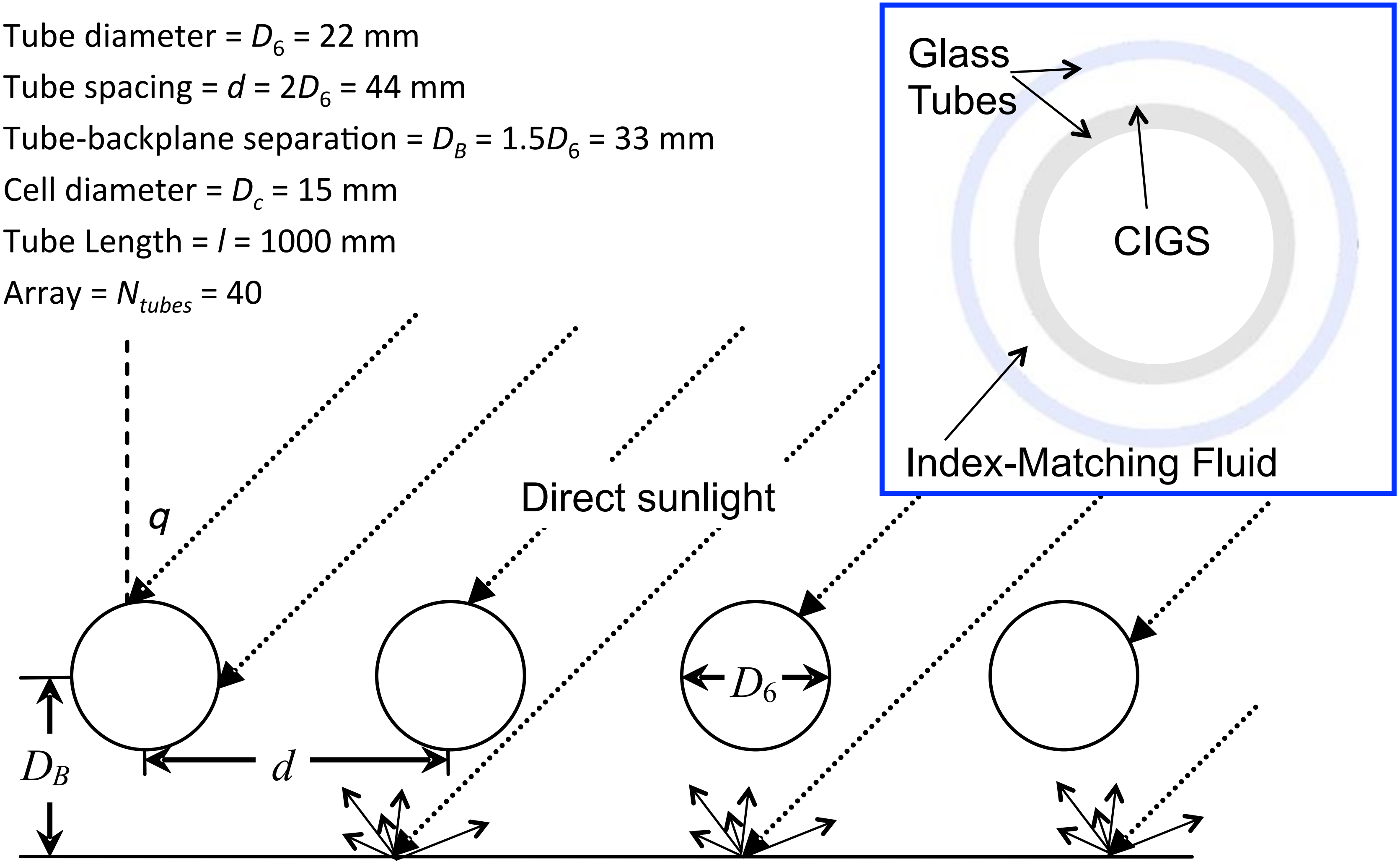
PMP Tolerance +/-4%
Specifications at 1000 W/m^2, AM1.5 & 25°C Cell Temp
Certified to UL 1703, ed.3; IEC 61646 ed.2, 61730-1 & -2

Field Wiring: Use Copper ONLY, 12 AWG Min
Insulated for a minumum of 90°C
LABEL NO. 0950-30291 R003 Made in USA

- Better understand the cylindrical tube technology:
  - What is the theory behind performance?
  - Does it work better than non-tracking flat panels?
  - Can software modeling be used to accurate determine performance?
  - Can the technology be improved?
- Educational tool for undergraduate students at Santa Clara University

Characteristics of Cylindrical Tube Panels

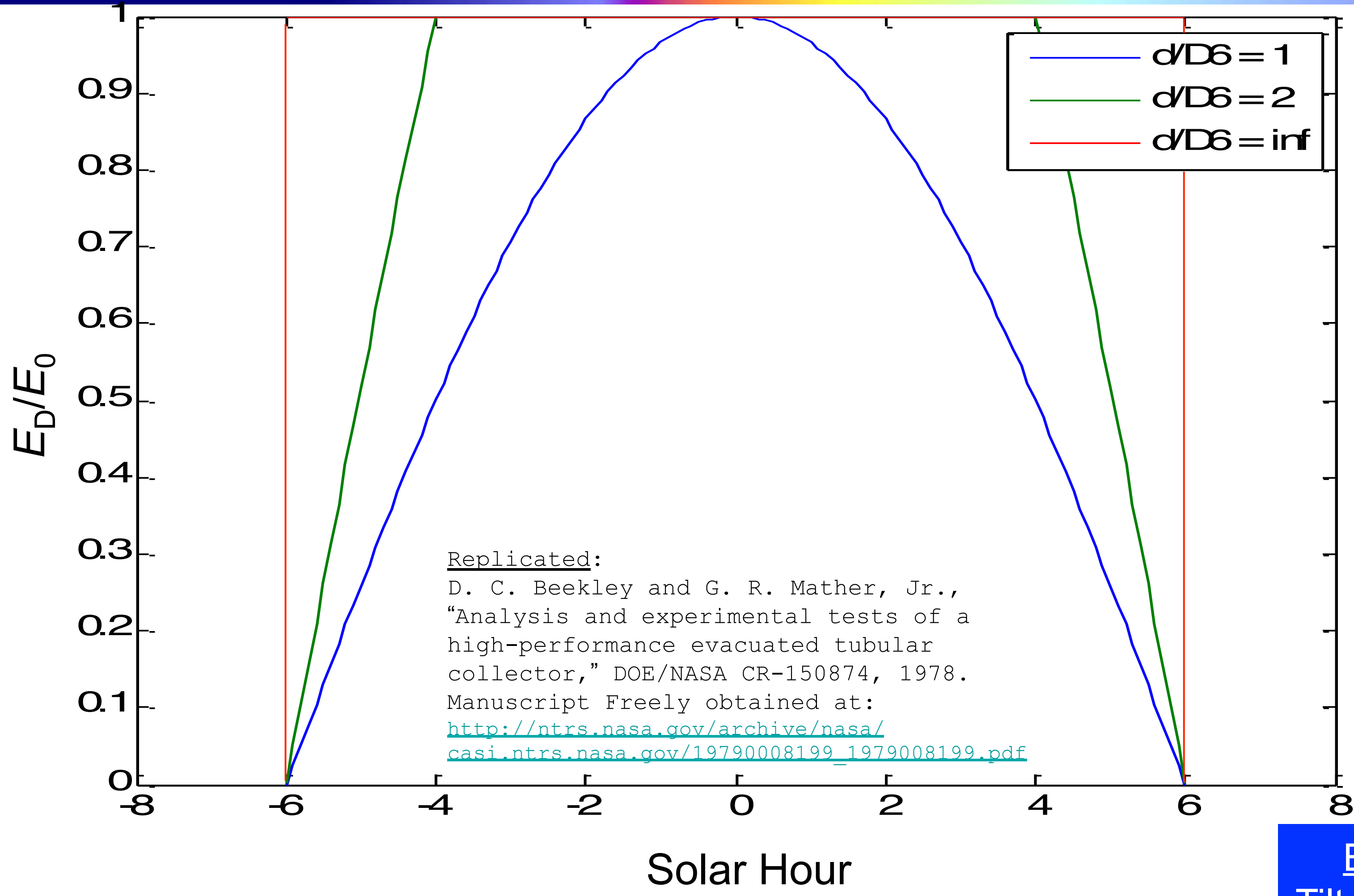
- Tube diameter = D_6 = 22 mm
- Tube spacing = $d = 2D_6$ = 44 mm
- Tube-backplane separation = $D_B = 1.5D_6$ = 33 mm
- Cell diameter = D_c = 15 mm
- Tube Length = l = 1000 mm
- Array = N_{tubes} = 40



Based on the research of evacuated tubes

THEORY

Driving Reason for Cylindrical Tubes

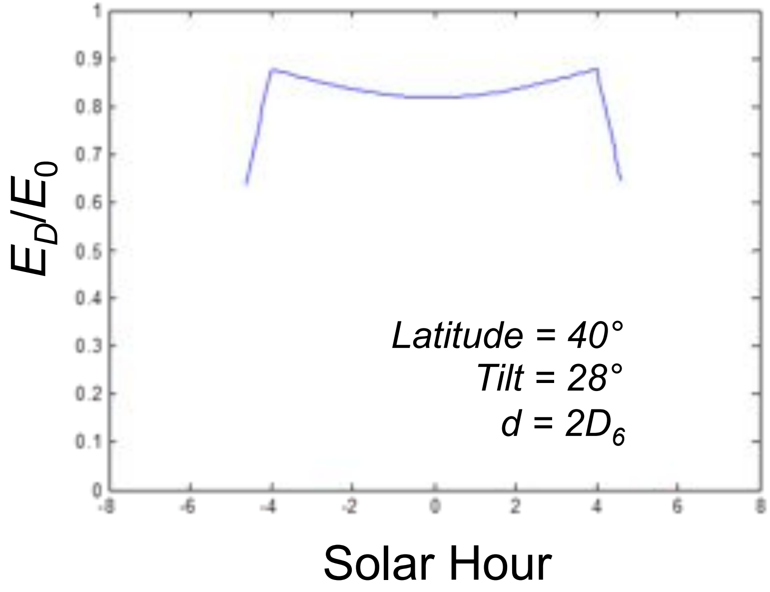


Replicated:
D. C. Beekley and G. R. Mather, Jr., "Analysis and experimental tests of a high-performance evacuated tubular collector," DOE/NASA CR-150874, 1978.
Manuscript Freely obtained at:
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19790008199_1979008199.pdf

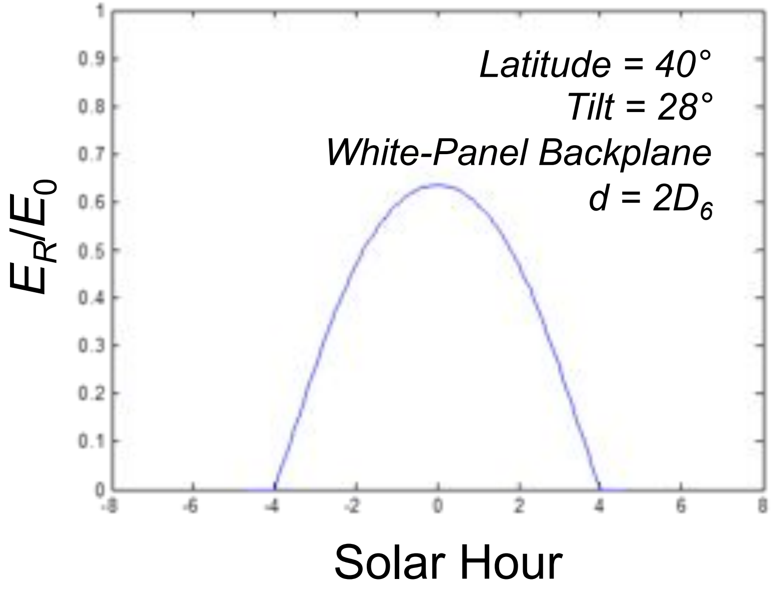
Equinox
Tilt = Latitude

Irradiance Ratio on Cylindrical Tubes

Direct on Cylindrical Tubes



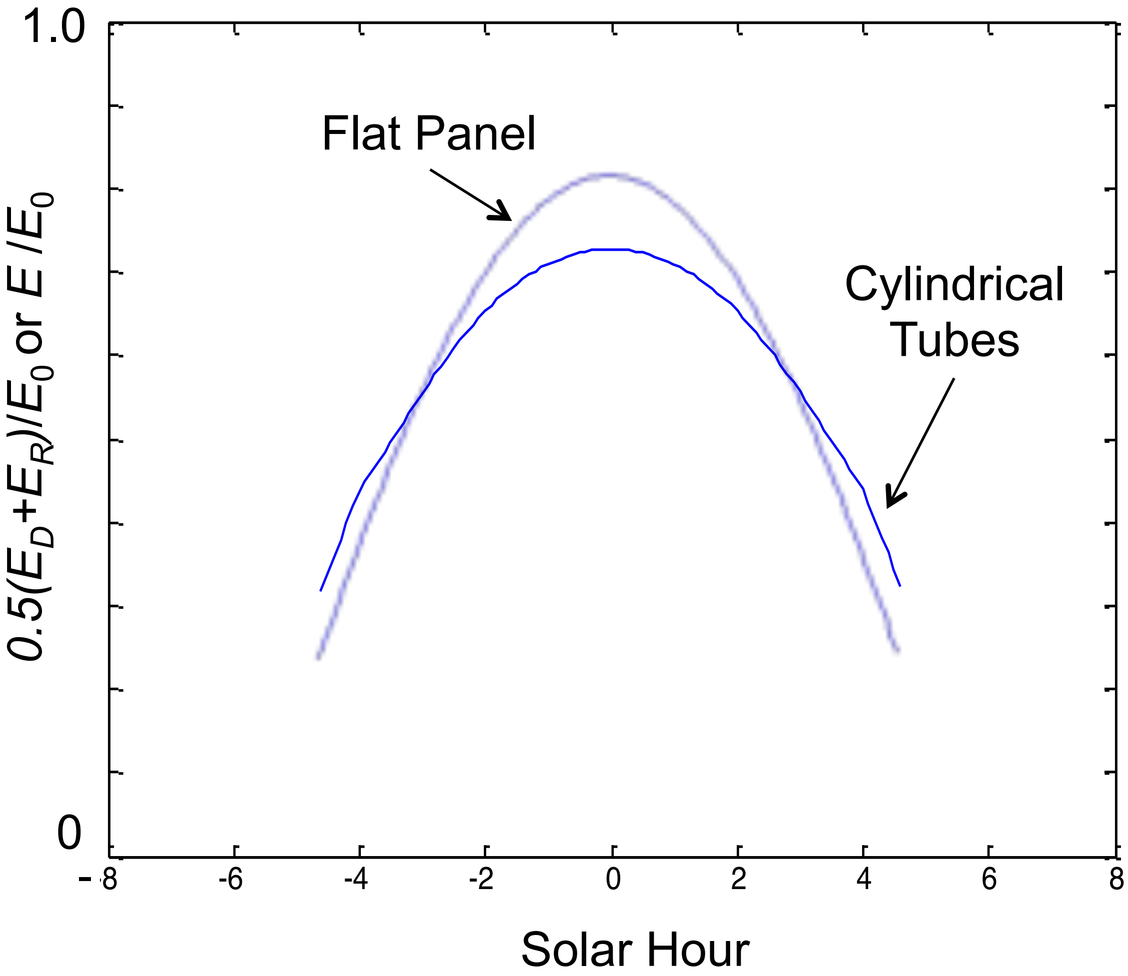
Scatter on Cylindrical Tubes



E_D = irradiance on tilted cylindrical tubes from direct sunlight
E_R = irradiance on tilted cylindrical tubes from backplane scatter
E_0 = irradiance on flat panel normal to direct sunlight
E = irradiance on horizontal flat panel from direct sunlight

http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19790008199_1979008199.pdf

Comparison: Cylindrical Array & Flat Panel



The theory indicates flat panels should be better around noon, while the tubes are better in early and late hours

http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19790008199_1979008199.pdf

Measurements and comparisons to theory

EXPERIMENT

They Look Like Flat Panels…

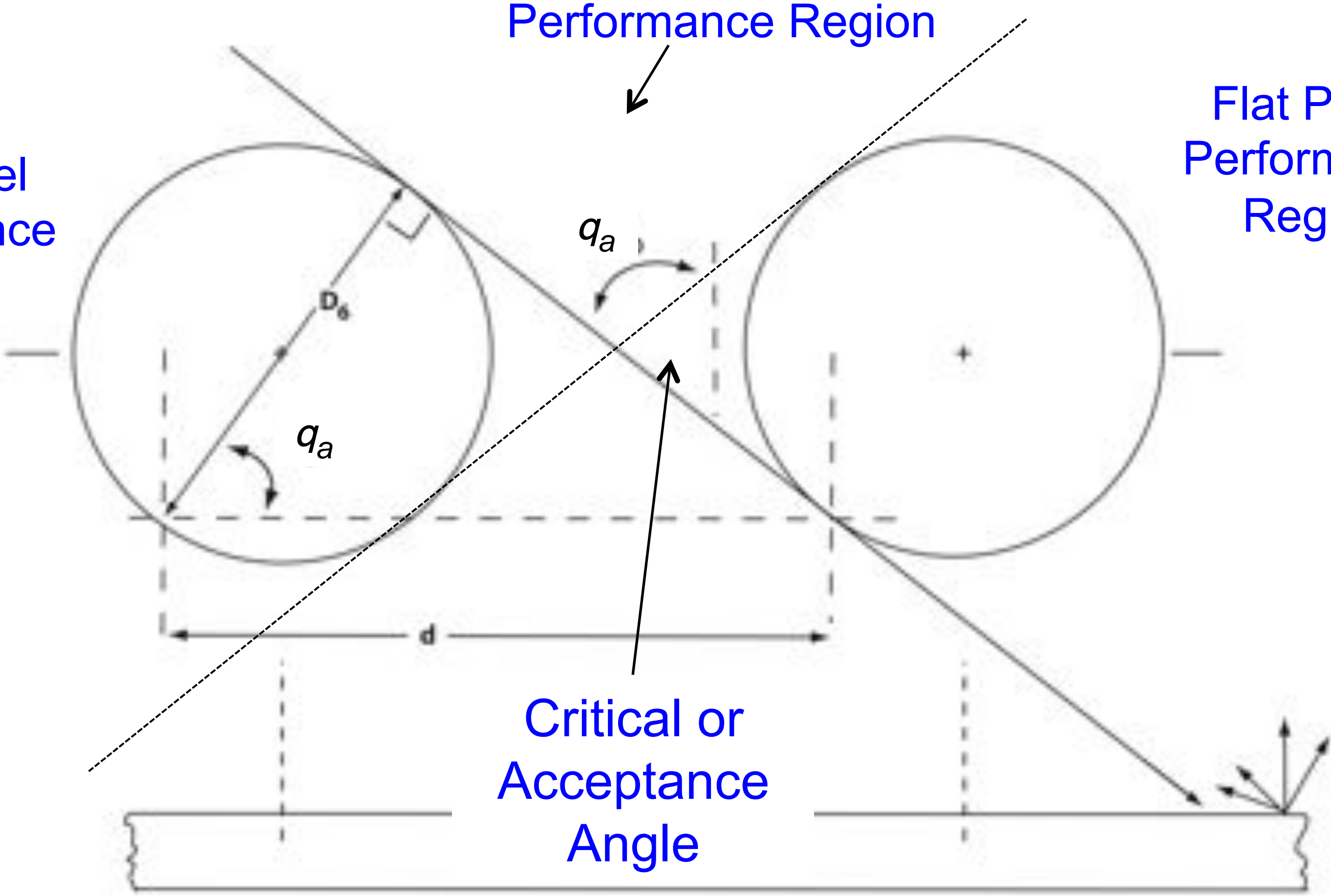

Greater than the critical angle

Photo by Greg P. Smestad

…and They Look Like Blinds

Photos by Greg P. Smestad

Edge-Ray Geometry of Cylindrical Tubes



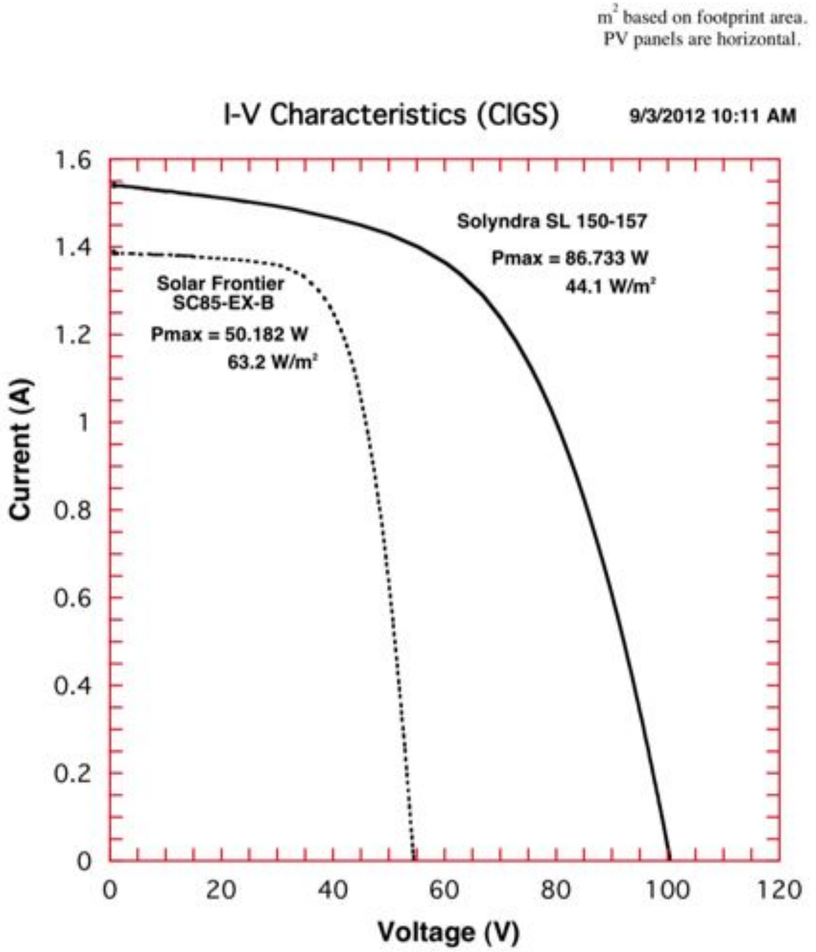
Cylindrical Tubes Performance Region

Flat Panel Performance Region

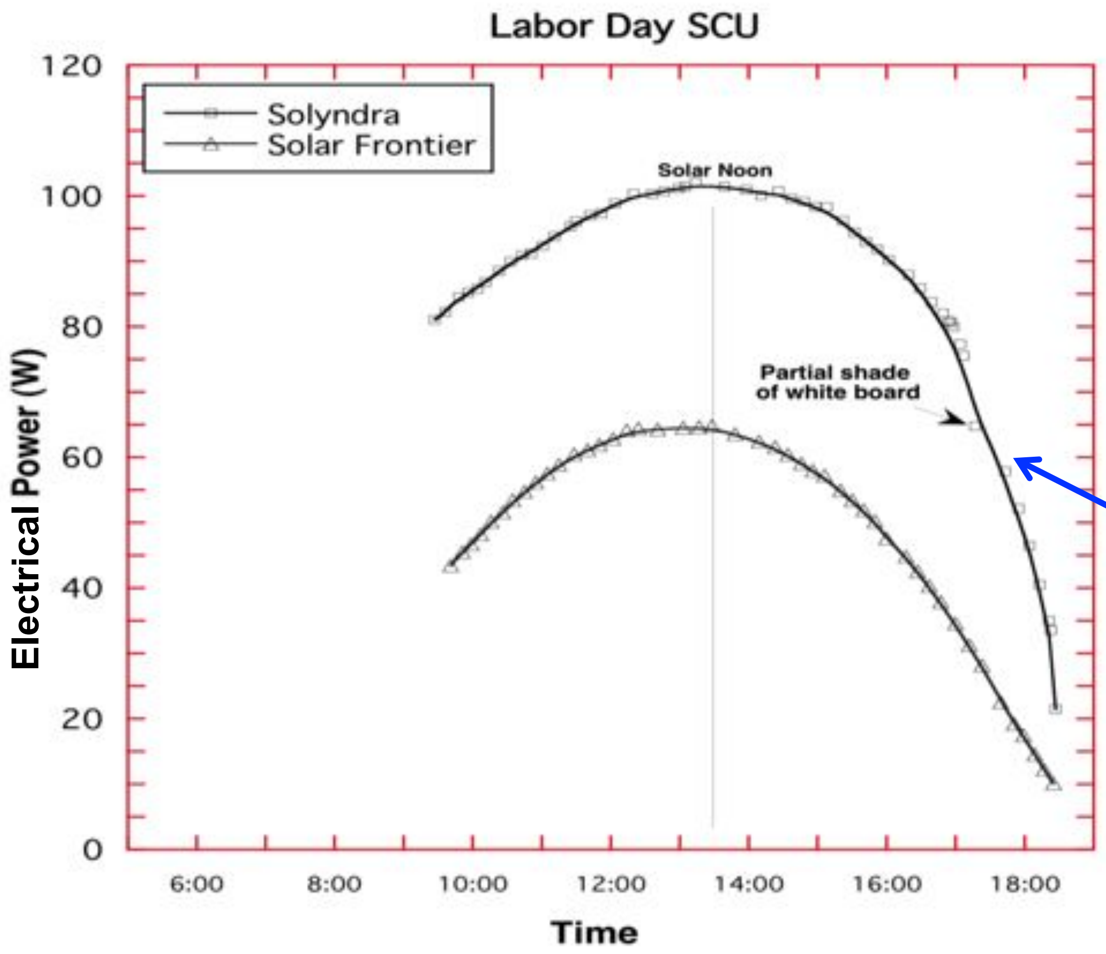
Flat Panel Performance Region

Critical or Acceptance Angle

Measured IV Curves for Solar Panels



Comparing PV Module Power



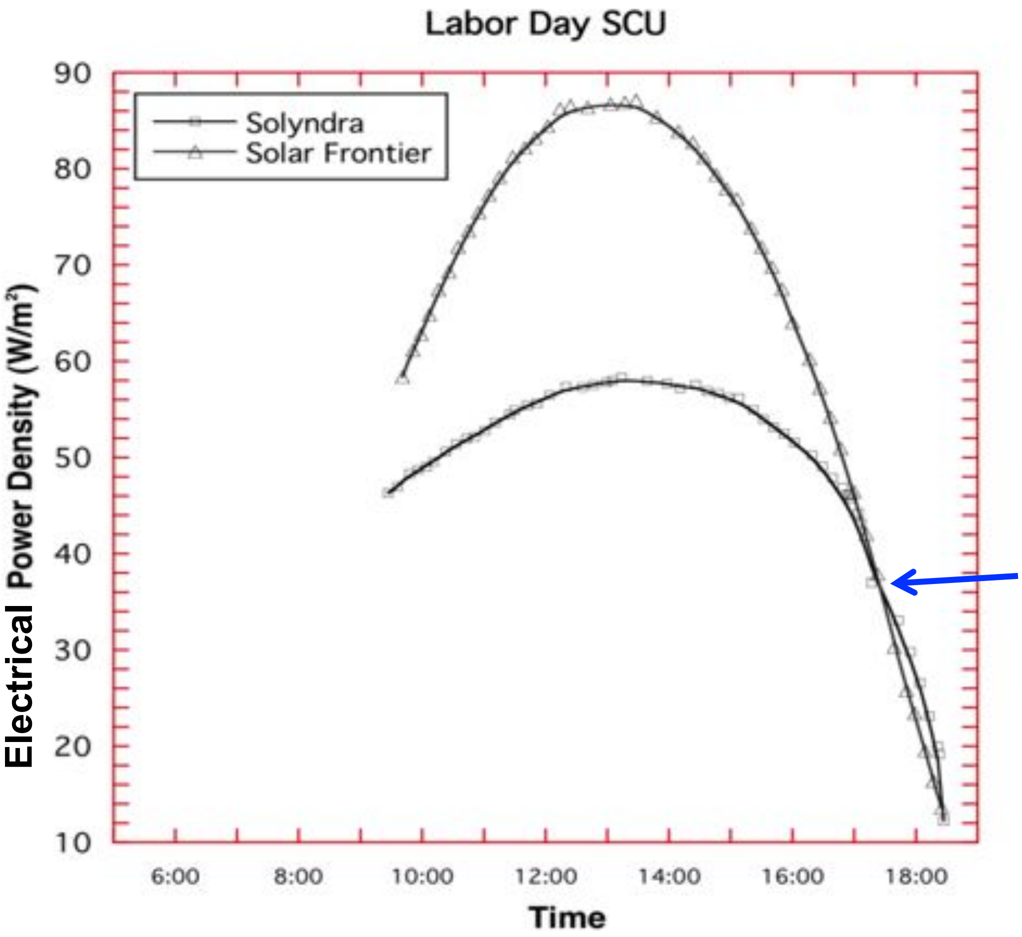
First glance: cylindrical tube panel (Solyndra) performs better than flat panel (Solar Frontier)

Second glance: we need to normalize for differences in solar cell active area

Third glance: there is the characteristic kink in the curve due to critical angle phenomenon

3 September 2012
Latitude = 37.3492°
Longitude = -121.9381°
Altitude = 20 m
White-Panel Backplane

Not So Fast: It is Power Density



First glance: flat panel (Solar Frontier) performs better than cylindrical tube panel (Solyndra)

Second glance: we are gaining some power from the open regions in the panel, but not doubling

Third glance: the kink is still there due to critical angle phenomenon

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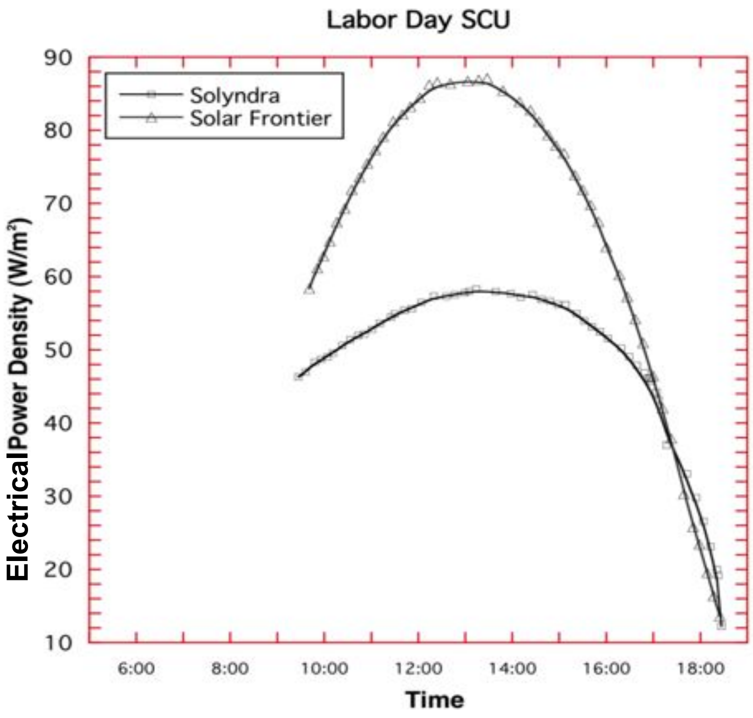
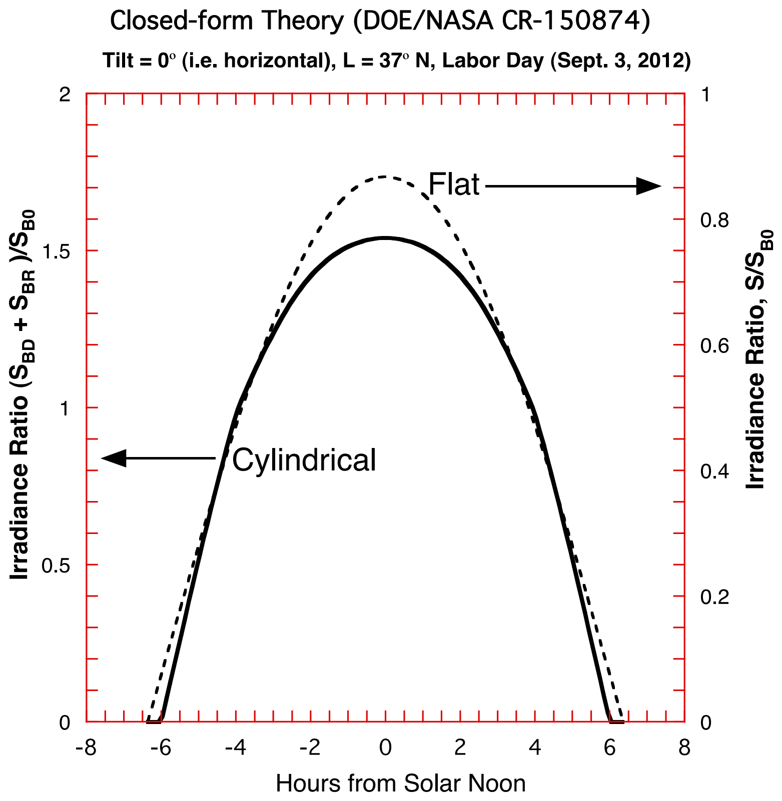
White-Panel Backplane

Comparison of Theory and Experiment

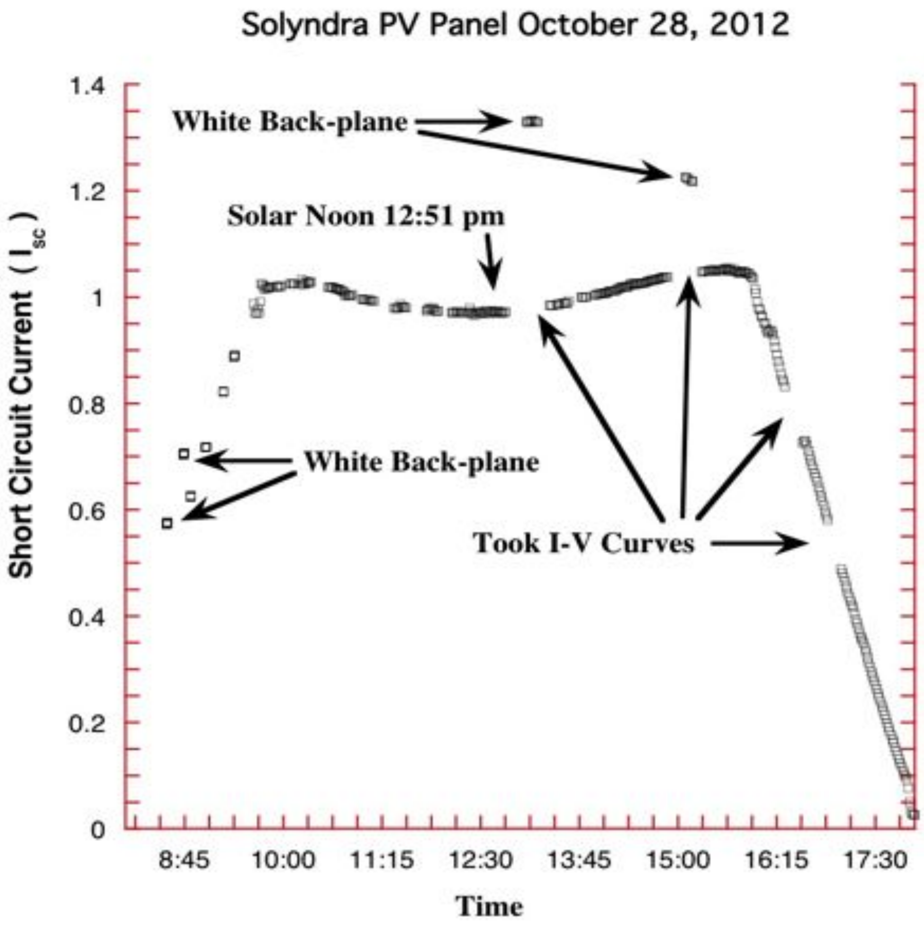
Experimental: Electrical Power Density



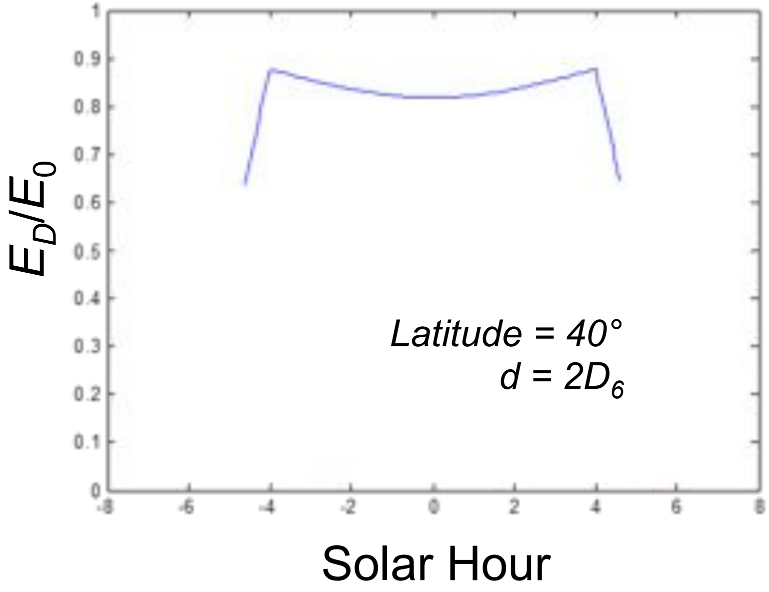
Theory: Irradiance Ratio



Cylindrical Tube Array Comparison to Theory


Solyndra PV Panel October 28, 2012

Theory: direct on cylindrical tubes



28 October 2012 (AM1.5 Conditions)
Latitude = 37.3492°
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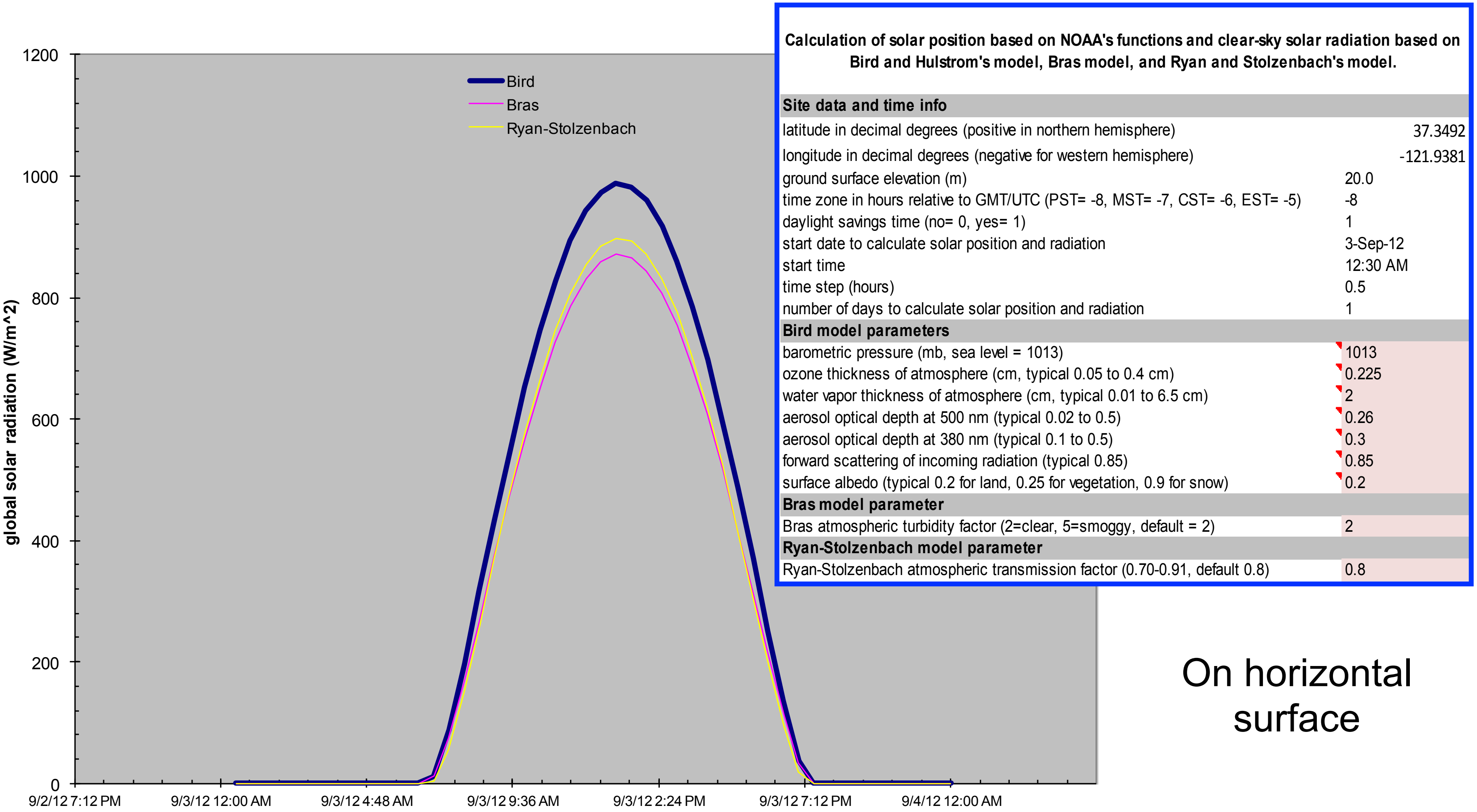
Altitude = 20 m
Black Velvet Backplane

Validation and optimization

SOFTWARE MODELING

Source Setup: NREL Solar Model

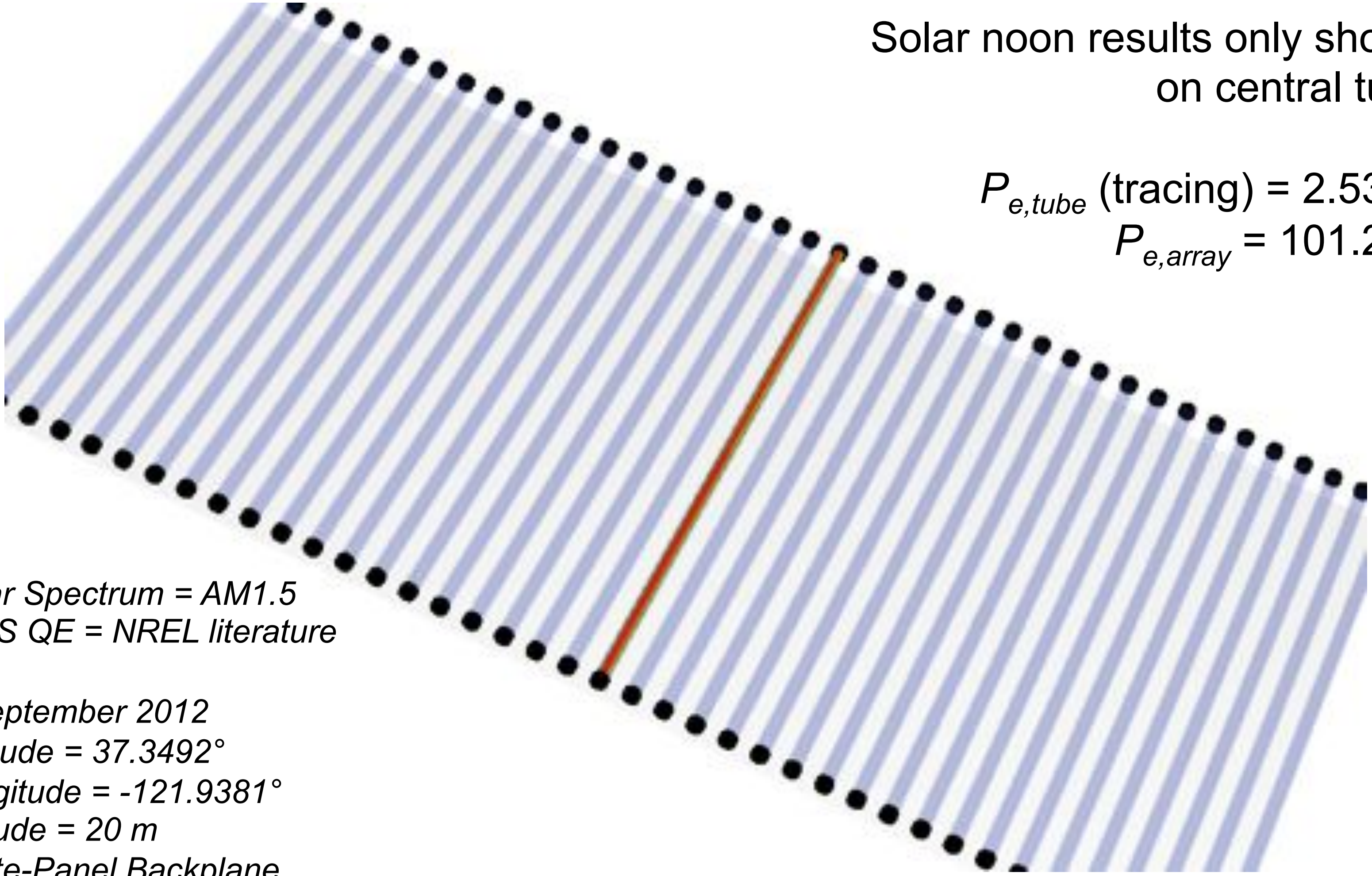


Calculation of solar position based on NOAA's functions and clear-sky solar radiation based on Bird and Hulstrom's model, Bras model, and Ryan and Stolzenbach's model.

Site data and time info	
latitude in decimal degrees (positive in northern hemisphere)	37.3492
longitude in decimal degrees (negative for western hemisphere)	-121.9381
ground surface elevation (m)	20.0
time zone in hours relative to GMT/UTC (PST= -8, MST= -7, CST= -6, EST= -5)	-8
daylight savings time (no= 0, yes= 1)	1
start date to calculate solar position and radiation	3-Sep-12
start time	12:30 AM
time step (hours)	0.5
number of days to calculate solar position and radiation	1
Bird model parameters	
barometric pressure (mb, sea level = 1013)	1013
ozone thickness of atmosphere (cm, typical 0.05 to 0.4 cm)	0.225
water vapor thickness of atmosphere (cm, typical 0.01 to 6.5 cm)	2
aerosol optical depth at 500 nm (typical 0.02 to 0.5)	0.26
aerosol optical depth at 380 nm (typical 0.1 to 0.5)	0.3
forward scattering of incoming radiation (typical 0.85)	0.85
surface albedo (typical 0.2 for land, 0.25 for vegetation, 0.9 for snow)	0.2
Bras model parameter	
Bras atmospheric turbidity factor (2=clear, 5=smoggy, default = 2)	2
Ryan-Stolzenbach model parameter	
Ryan-Stolzenbach atmospheric transmission factor (0.70-0.91, default 0.8)	0.8

On horizontal surface

Software Geometry of Single Panel



Solar noon results only shown on central tube

$P_{e,tube}$ (tracing) = 2.53 W
$P_{e,array}$ = 101.2 W

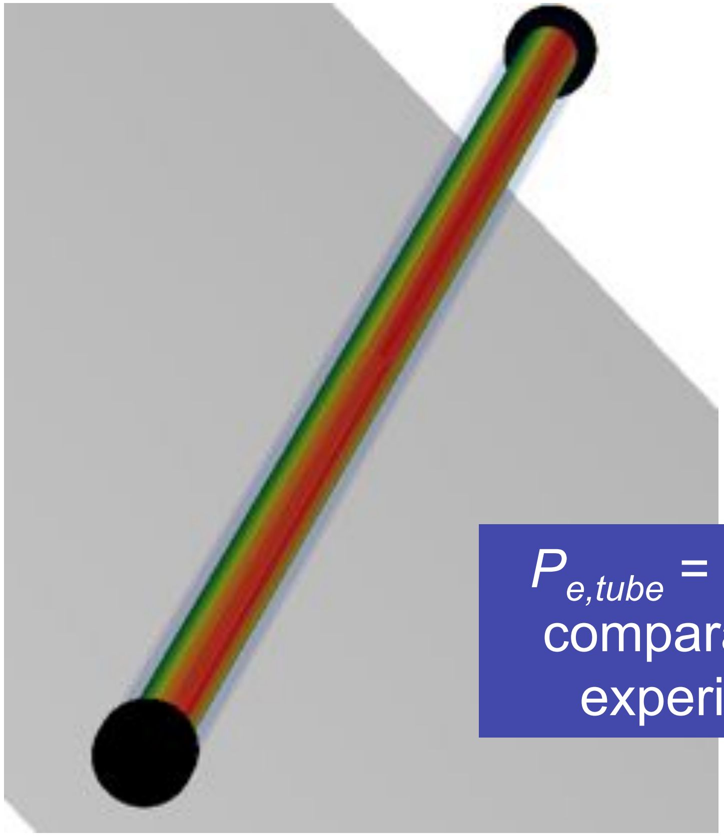
Solar Spectrum = AM1.5
CIGS QE = NREL literature

3 September 2012
Latitude = 37.3492°
Longitude = -121.9381°
Altitude = 20 m
White-Panel Backplane

Ray-Tracing Results

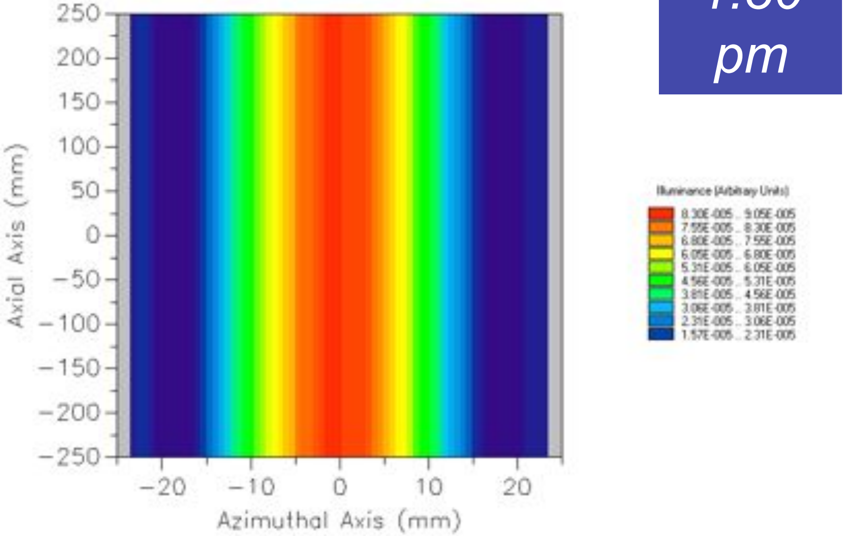
1.30 pm

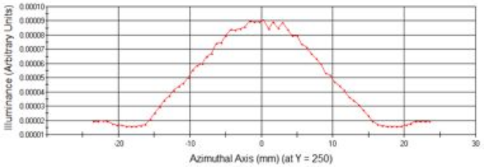
3D Visualization



$P_{e,tube}$ = 2.53 W comparable to experiment

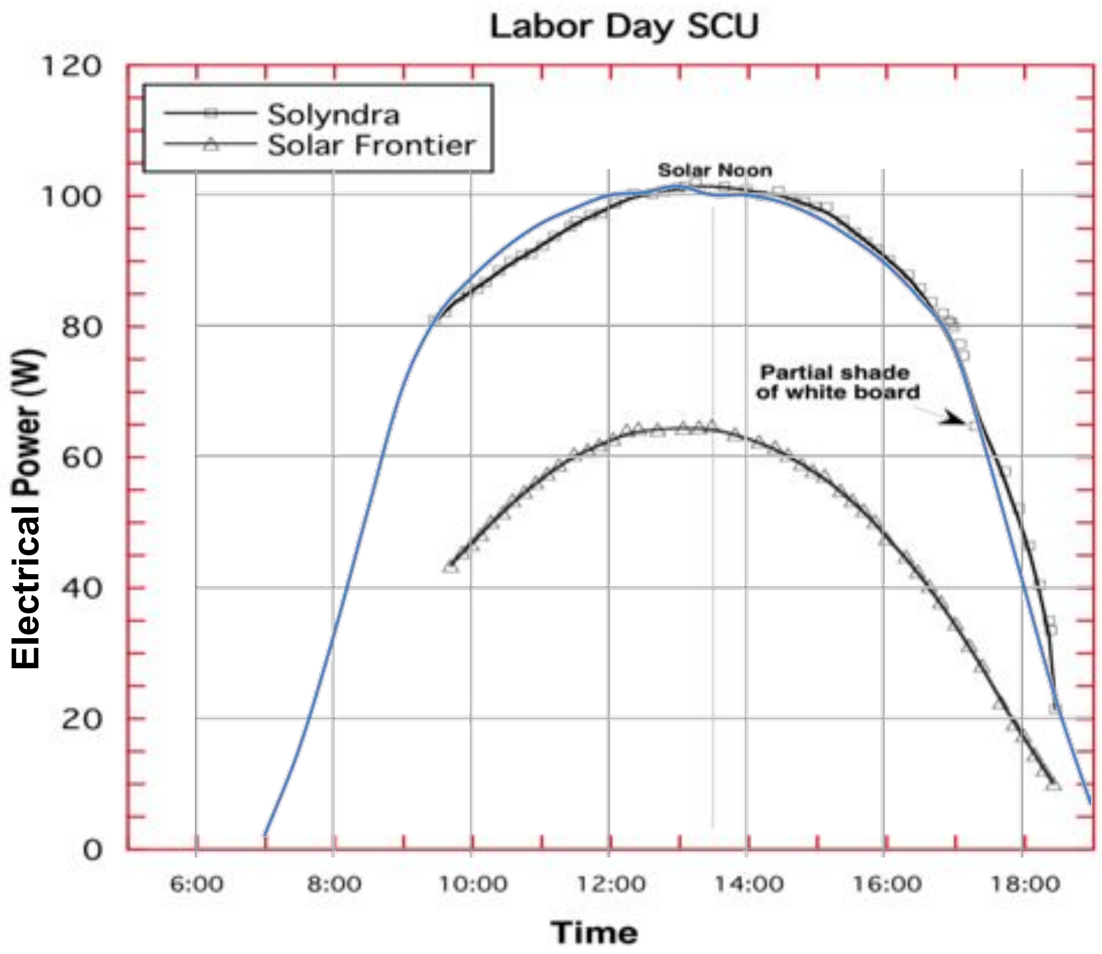
2D Chart





Note: irradiance on back surface of tube

Modeled Electrical Power Generation



Comparison of Solyndra cylindrical tube panel: experiment and ray trace model – good agreement.

Variations due to solar source assumptions, such as atmospheric conditions

Indicates that software ray-tracing model validates virtual design method.

3 September 2012
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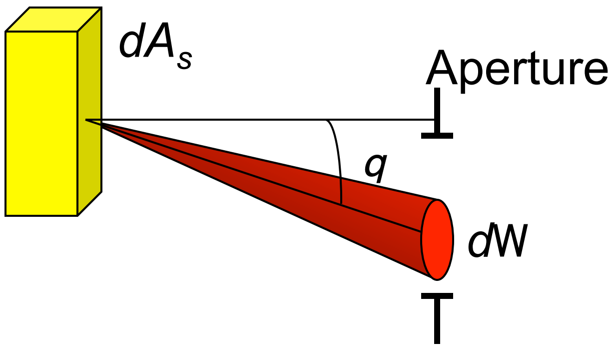
Altitude = 20 m
White-Panel Backplane

Étendue

- French Word:
  - Verb: extended
  - Noun: reach
- Étendue is a geometric factor:



$$\boxed{\mathscr{E} = n^2 \iint\limits_{\text{aperture}} \cos\theta \, dA_s \, d\Omega}$$

- It describes the flux propagation characteristics of an optical system:

<u>Arbitrary Source Radiance</u>

$$\Phi = \iint\limits_{\text{aperture}} L(\mathbf{r}, \hat{\mathbf{a}}) \cos\theta \, dA_s \, d\Omega,$$

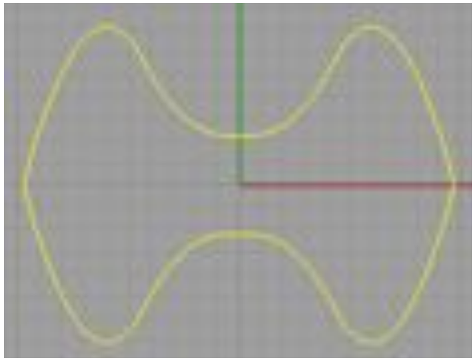
<u>Lambertian Source Radiance</u>

$$\Phi = L_s \iint\limits_{\text{aperture}} \cos\theta \, dA_s \, d\Omega$$

$$= \frac{L_s \mathscr{E}}{n^2}$$

Preliminary Optimization Studies

- Optimized configuration of the system:
  - Results indicate $d = 2D_6$ and $D_B = 1.5D_6$ are optimal
  - Tilt angle (s) = Latitude (L), optimizes performance by making response more uniform over year
  - Different merit function can be used to optimize performance for a given time of the day/year:
    - Afternoon to handle cooling needs
    - More equitable over the year such that winter performance drives design
- Preliminary results show that a shape that helps trap incident radiation is better:



  - Cross section of "tube" using NURBS. Optimized with ray tracing software
  - The recesses trap light
  - This gives light a "second chance
  - Shape depends greatly on merit function
- Note that performance will approach a flat panel

Future studies

CONCLUSIONS

Conclusion and Future Research

Conclusions

- Cylindrical tubes only offer minor improvements (morning and evening hours)
- Decreased performance around solar noon
- Effective ray trace modeling can be done
- Étendue drives the design:

$$\boxed{\xi = n^2 \iint_{\text{aperture}} \cos\theta \, dA_s \, d\Omega,}$$

To ignore it can be hazardous!

- System can be improved (slightly) with software optimization – Not enough time to go into the details here

Future research

- More optimization cases:
  - Modification of merit function
  - More study of "tube" shape
- Include National Weather Service data taking into account local sky conditions (i.e., in Santa Clara)
- Specular edge ray concentrator between tubes, but this step "violates" the simplicity of the tubular array geometry

A Silver Lining: Education

What to do with 15 Million Tubes?

www.solideas.com/GlassTubes.html