

# Solar Radiation Measurements:

## A Workshop For

The National Association of State Universities  
and Land Grant Colleges

By

Tom Stoffel & Steve Wilcox

Hydrogen & Electric Technologies & Systems Center

August 4, 2004



# Outline

- Introductions
- *Shining On, A Primer on Solar Radiation Data*
  - What are solar radiation measurements?
  - Why do we need solar radiation data?
  - What influences the amount of solar radiation?
  - How do we use solar radiation data?
  - How accurate do the data need to be?
- How are we meeting our solar radiation data needs?
- Where can you obtain solar radiation data?
- Pop Quiz
  - No acronyms!

# Introductions

Tom Stoffel & Steve Wilcox

Resource Integration Group

Measurement & Instrumentation Team

Geographic Information System Team

40+ years experience:

- Solar measurement station/network design
  - SRRL, HBCU, Saudi, DOE/ARM, NOAA, WMO/BSRN, GAW
- Radiometer calibration and characterization
  - BORCAL/RCC
  - IPCs, NPCs
- Solar data quality assessment
  - SERI-QC
  - DQMS

# What are Solar Radiation Measurements?

Energy from the Sun at the Earth's Surface

- Different parts of the sky
- Change with time (minutes, hours)
- Change with time (seasons, years, decades)
- Change with location



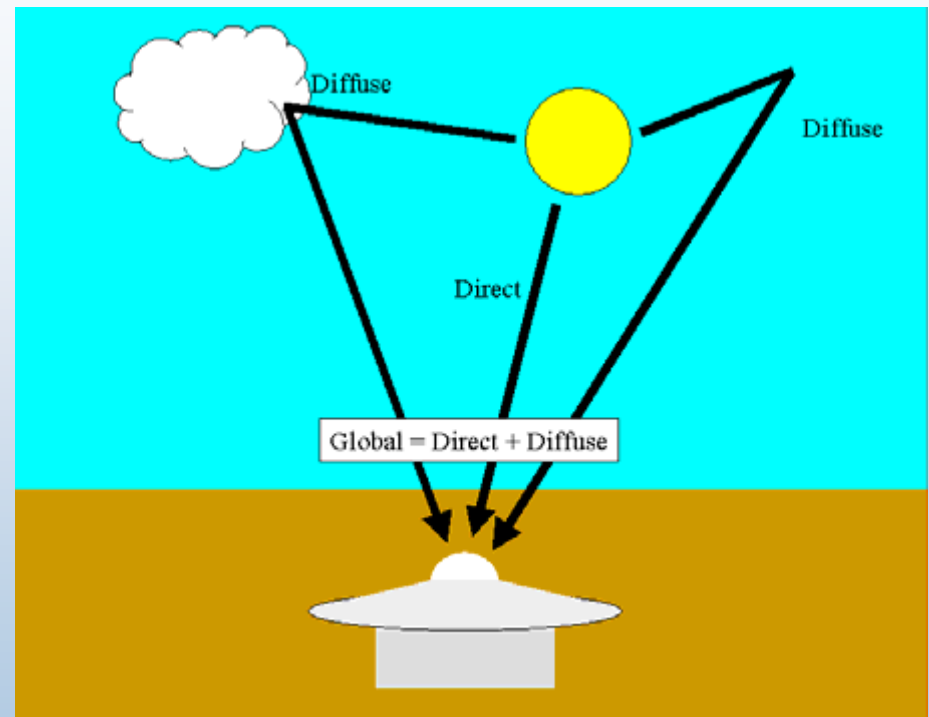
# What are Solar Radiation Measurements?

Light from the sky dome

- Direct from the sun
- Everywhere but the sun
- Entire sky

We call it

- Direct (beam)
- Diffuse (sky)
- Global (total)



Global is the sum of direct and diffuse

# What are Solar Radiation Measurements?

## Direct Normal

Measured by a *Pyrheliometer* on a sun-following tracker



## Global Horizontal

Measured by a *Pyranometer* with a horizontal sensor



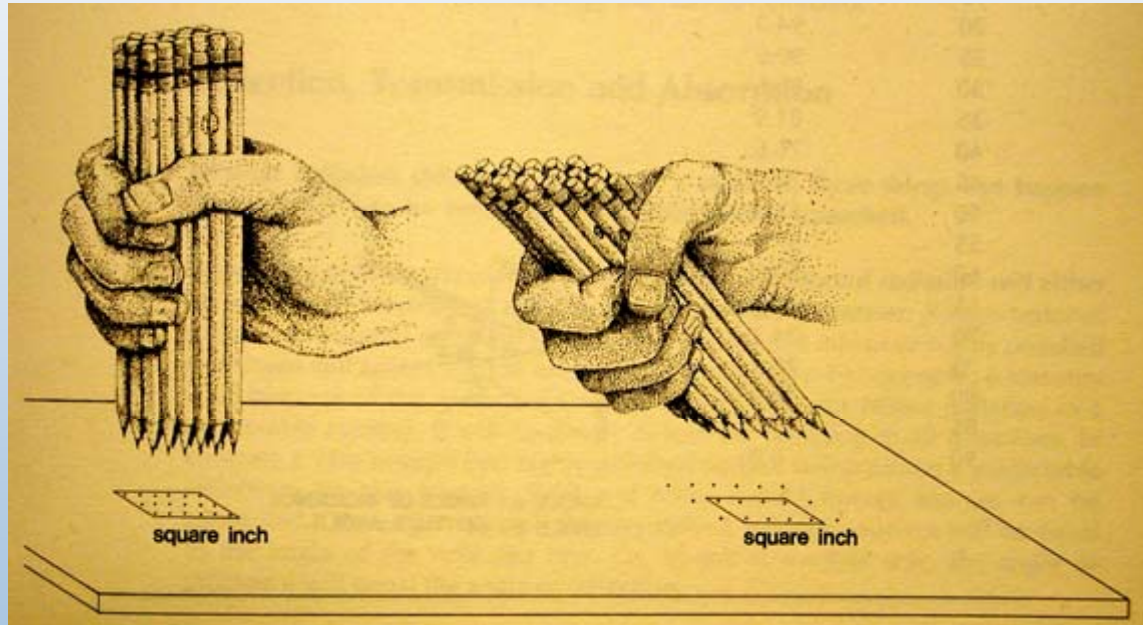
## Diffuse

Measured by a shaded *Pyranometer* under a tracking ball



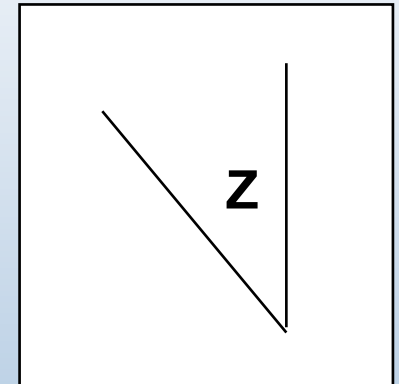
# Solar Irradiance Components

$$\text{Global} = \text{Direct Normal} * \cos(Z) + \text{Diffuse}$$



18 dots

8 dots



$$\cos(Z) = 8/18$$

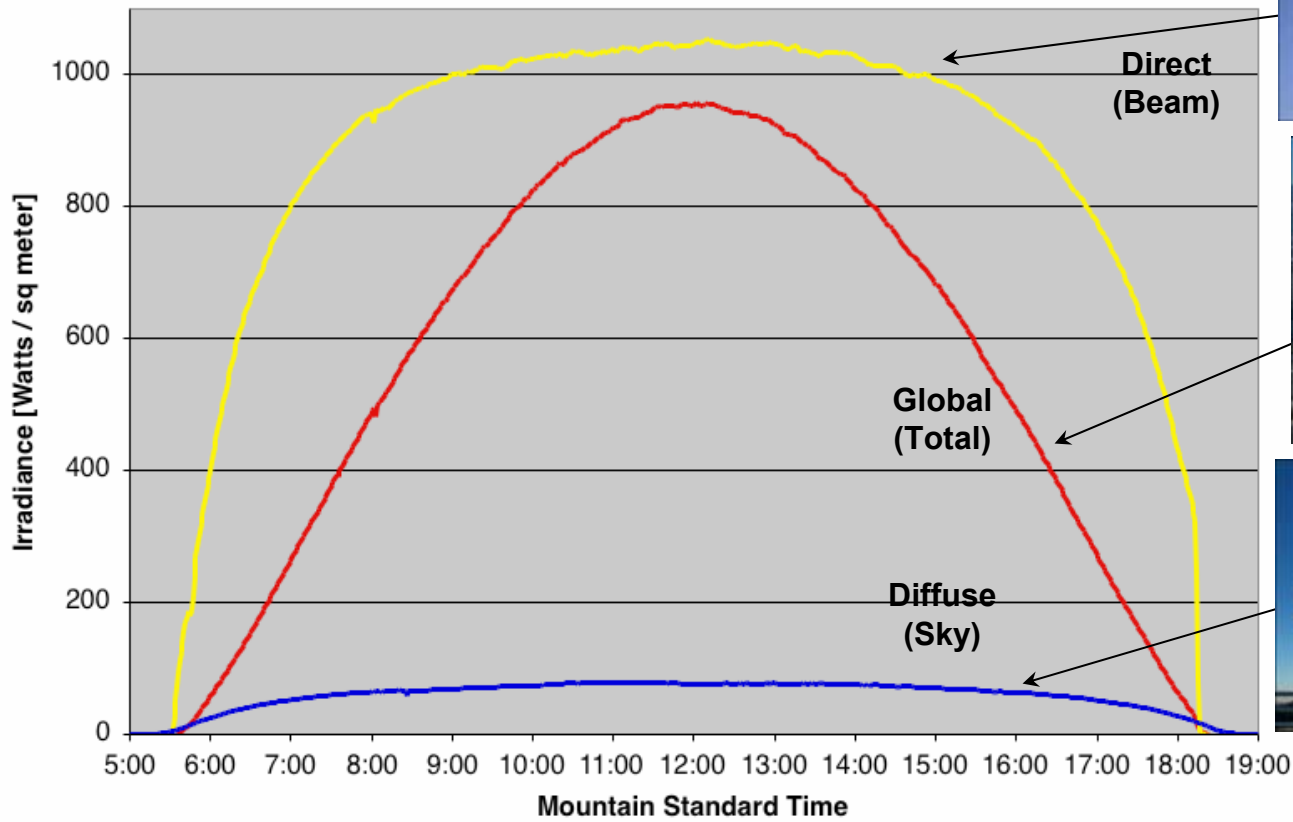
$$Z = \cos^{-1}(0.4444)$$

$$Z = 63.6^\circ$$



# Clear Sky

**Solar Irradiance Measurements**  
Golden, Colorado 9 April 2003



<http://www.nrel.gov/srri>



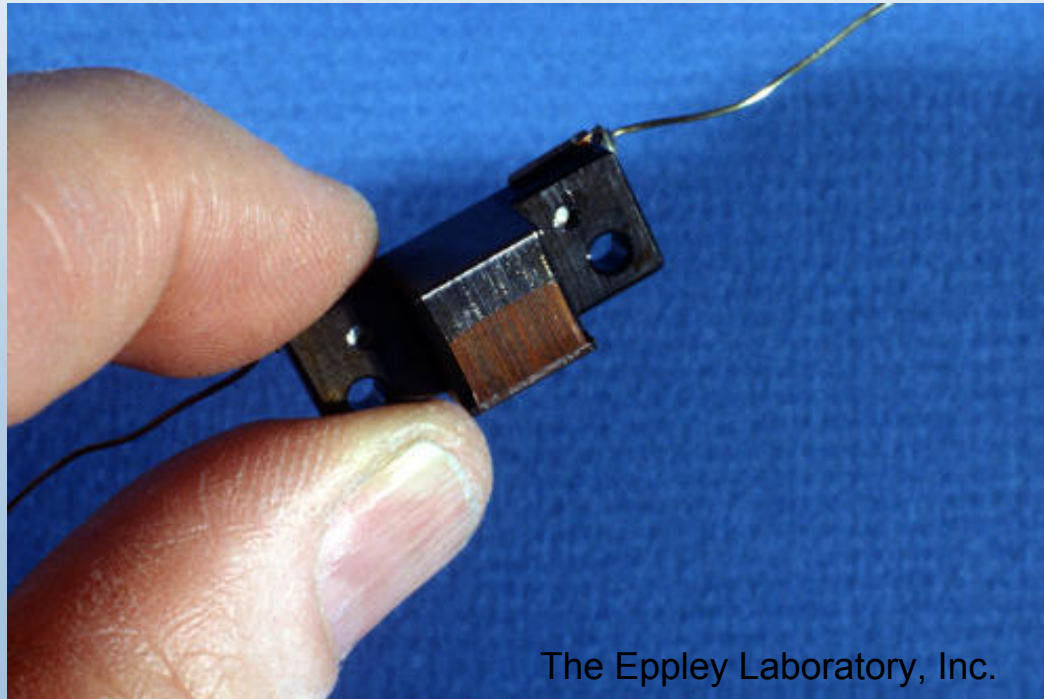
# Thermopile Detectors

*How do the radiometers work?*

**Thermo-electric detectors:**

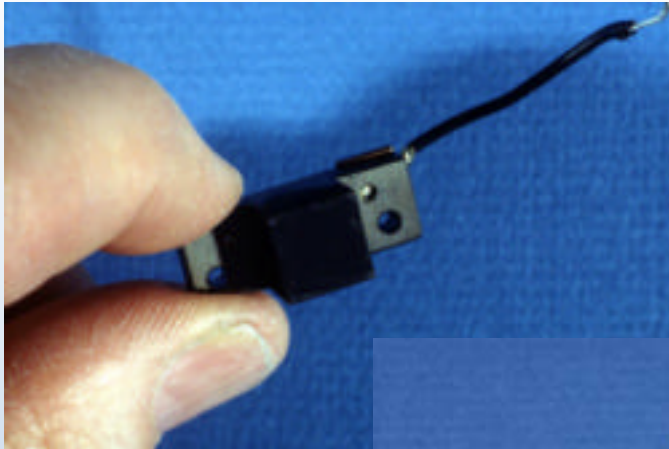
**Two metals + Heat = Electrical Current**

**Copper-Constantan wire wound *Thermopiles***



The Eppley Laboratory, Inc.

# Thermopile Detectors

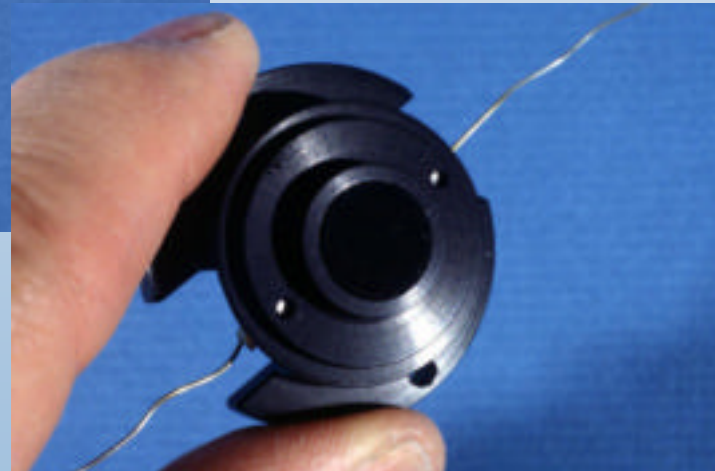


## Pyrheliometer

1st Class \$, Flat Spectral Response, "Slow"



## Pyranometer



The Eppley Laboratory, Inc.

# Photoelectric Detectors

Fast, Low-Cost, with Reduced Spectral Response:



[www.kippzonen.com](http://www.kippzonen.com)



[www.licor.com](http://www.licor.com)

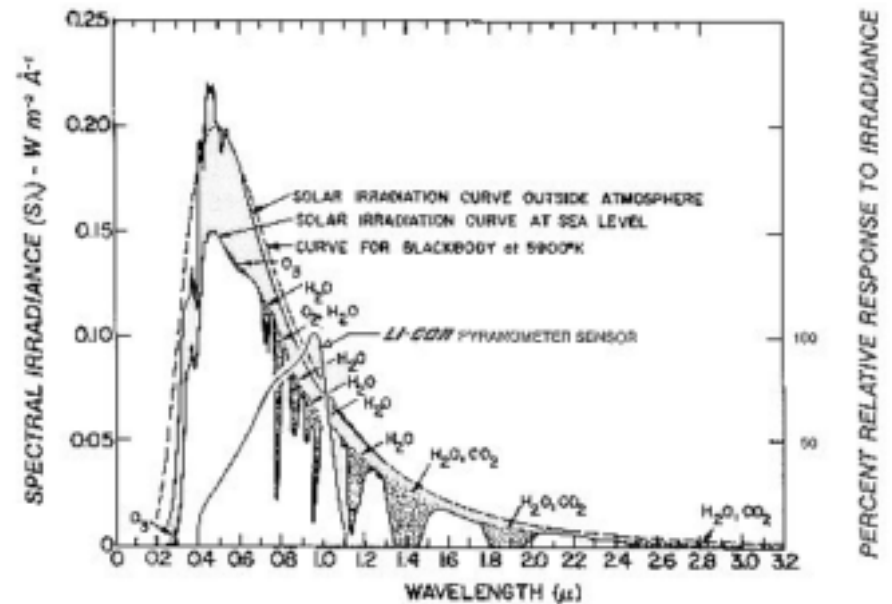
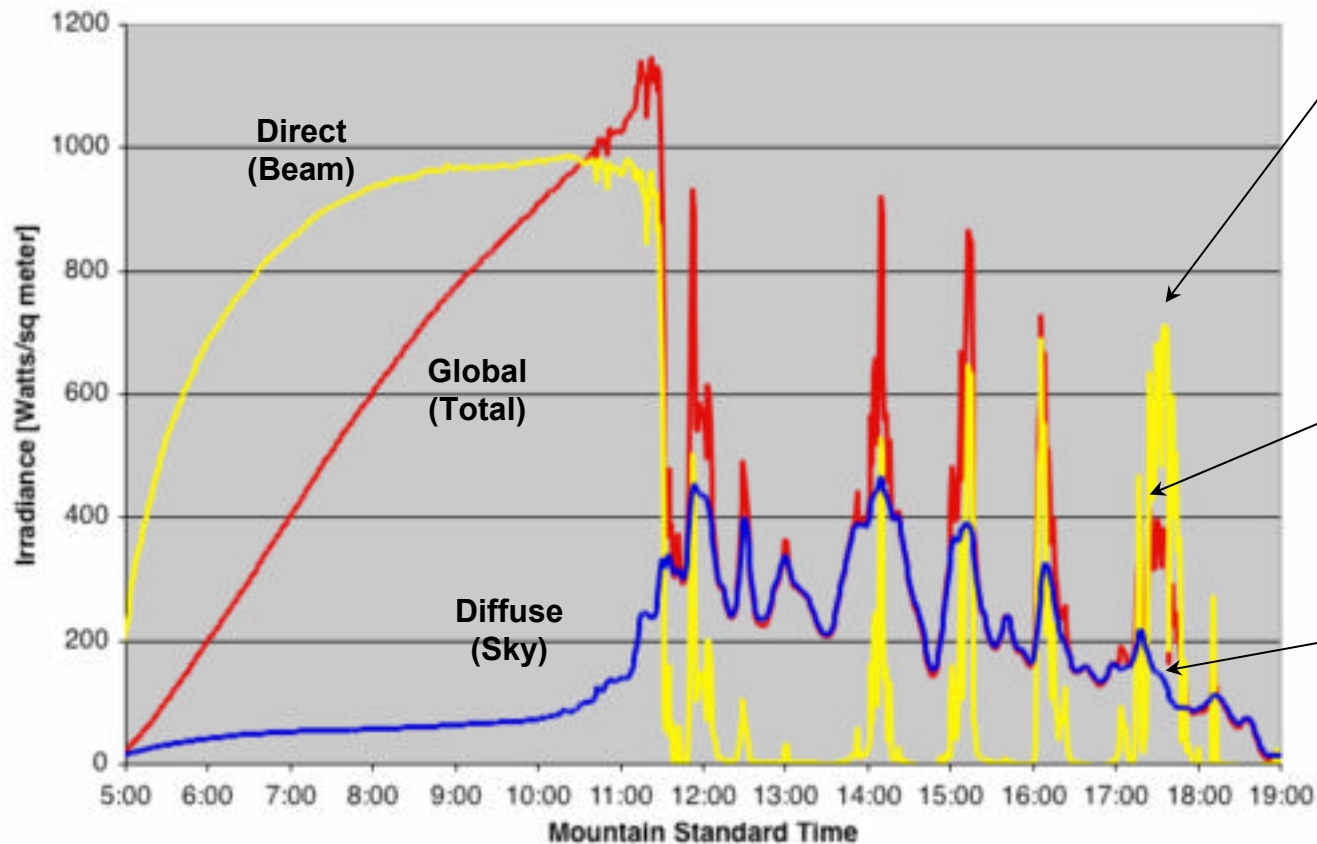


Figure 4. The LI-200SA Pyranometer spectral response is illustrated along with the energy distribution in the solar spectrum (8).

# Partly Cloudy Sky

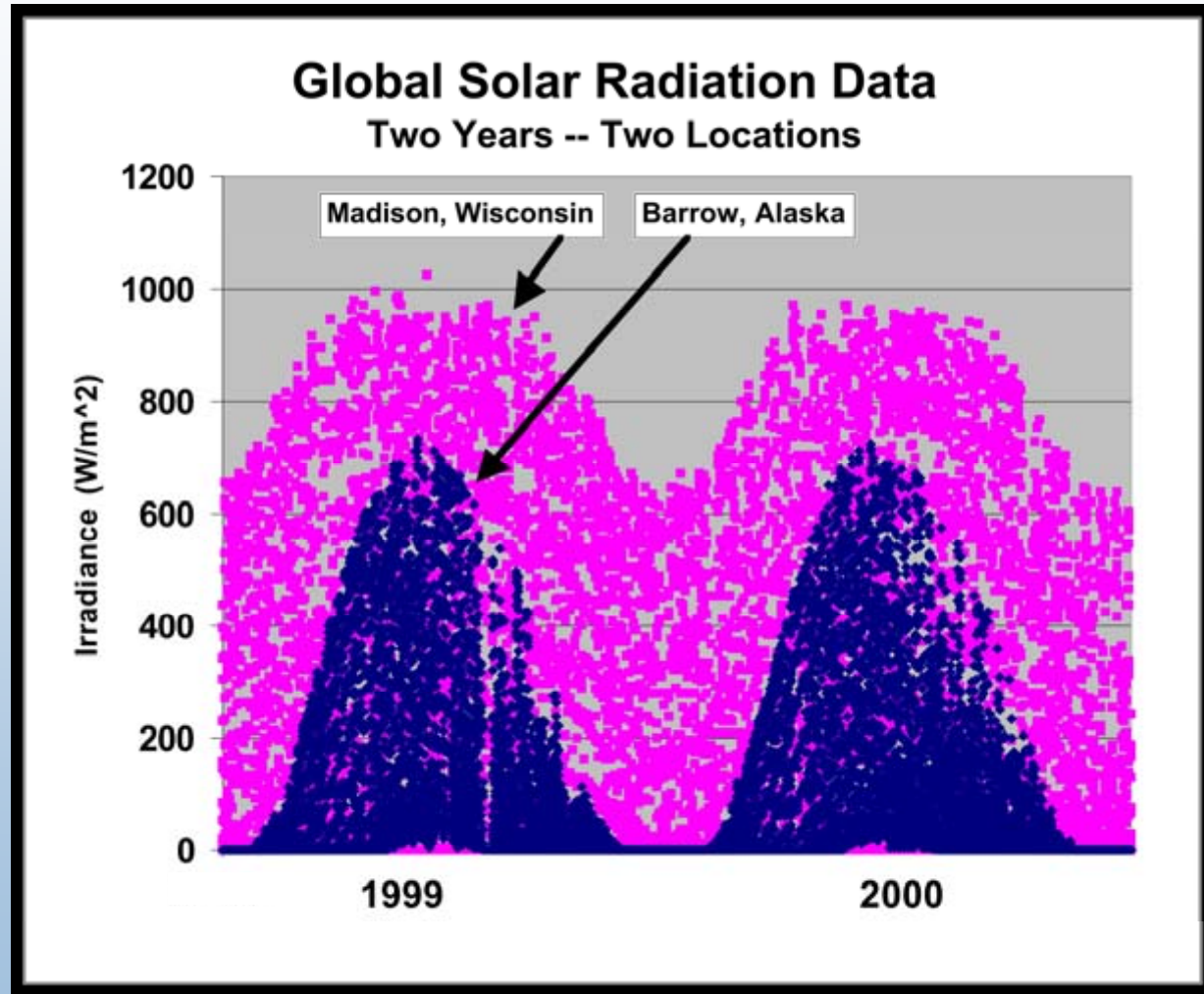
Solar Irradiance Measurements  
Golden, Colorado 3 July 2004



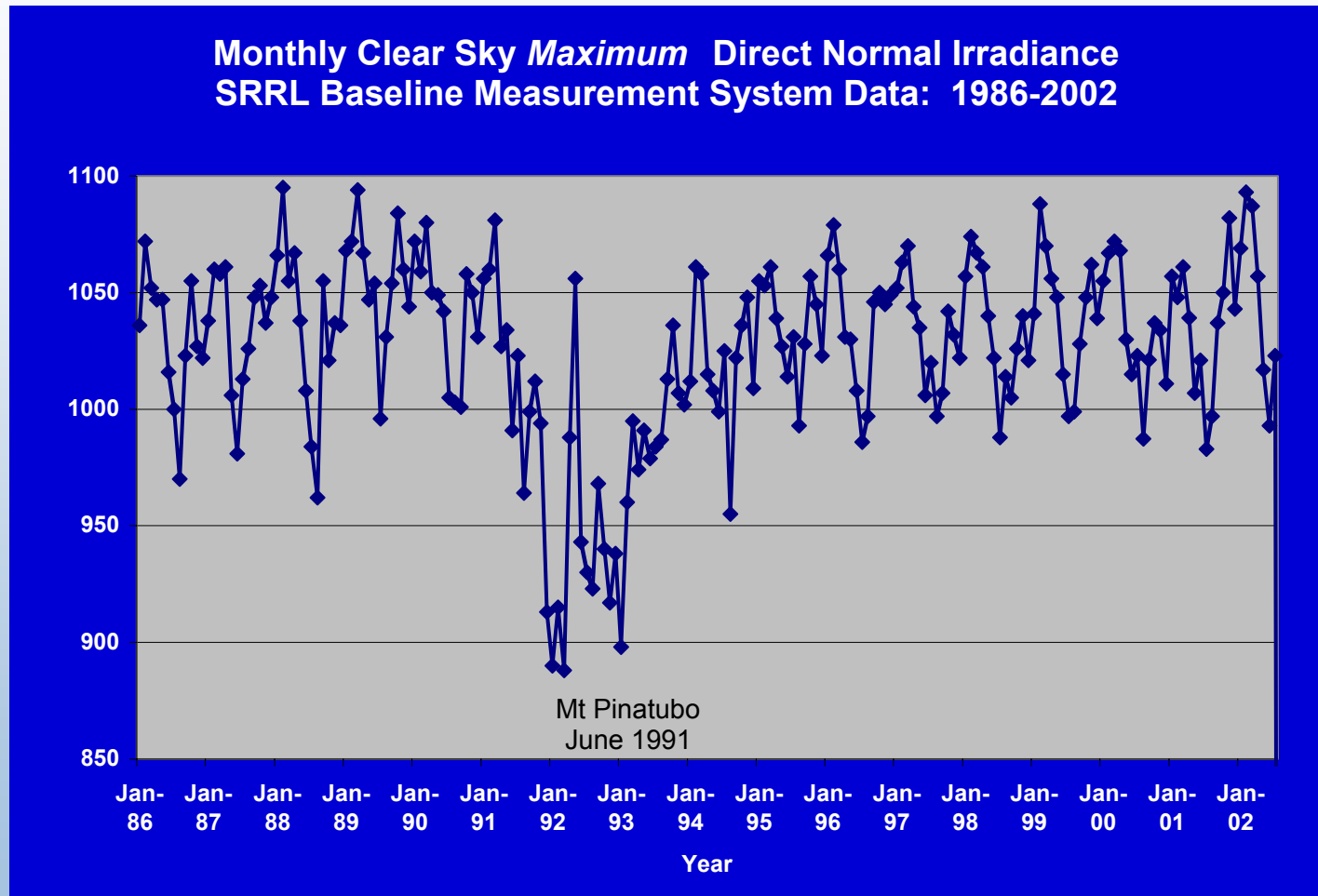
<http://www.nrel.gov/srri>



# Changes with Time & Location: Annual Cycle

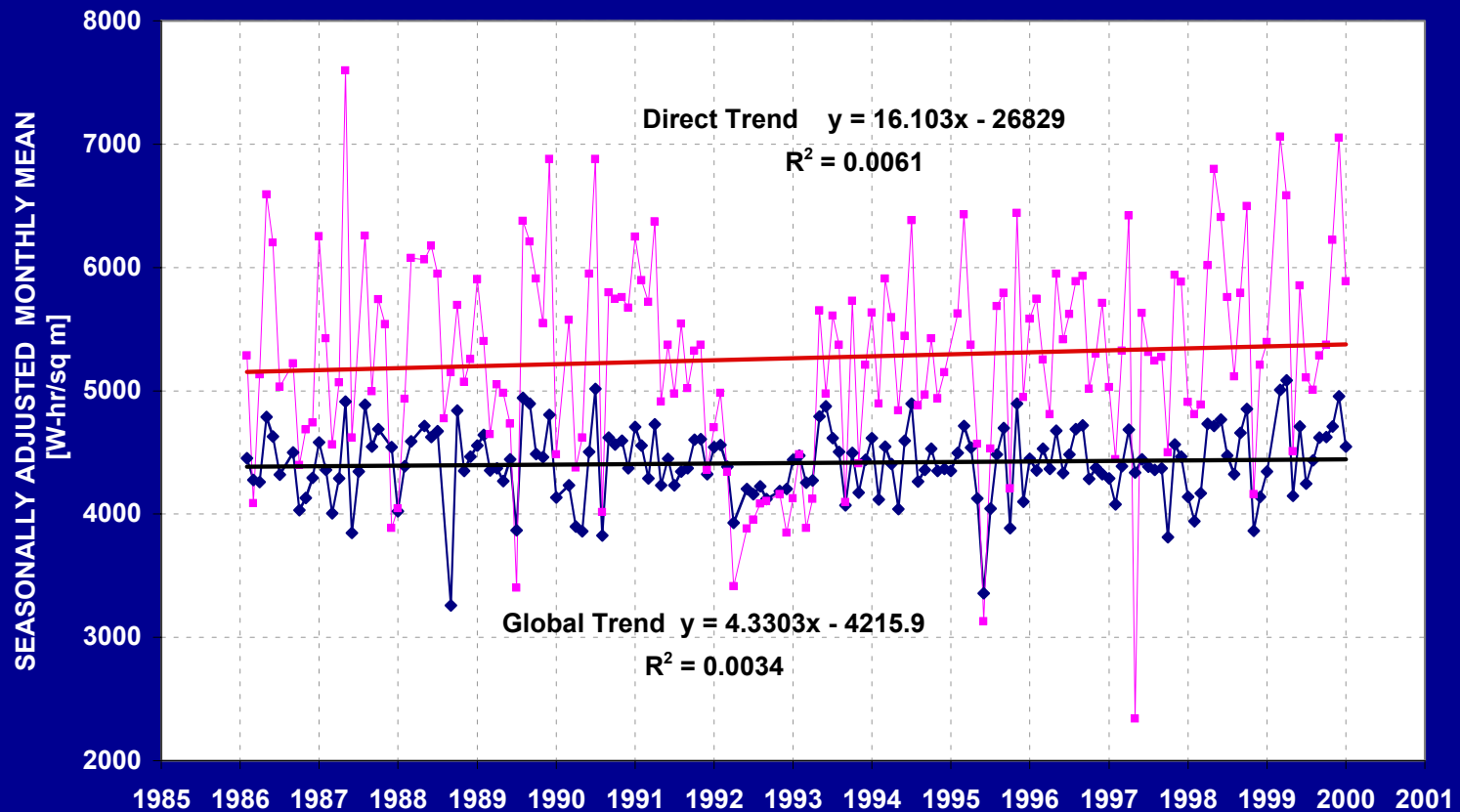


# Changes with Time: Inter-annual



# Changes with Time: Inter-annual

**MONTHLY MEAN DAILY TOTALS**  
**Solar Radiation Research Laboratory 1986-2000**





# Spectral Distribution of Solar Radiation

Broadband Solar Radiation:

280 nm - 3,000 nm

(99% of “shortwave” irradiance at the surface)

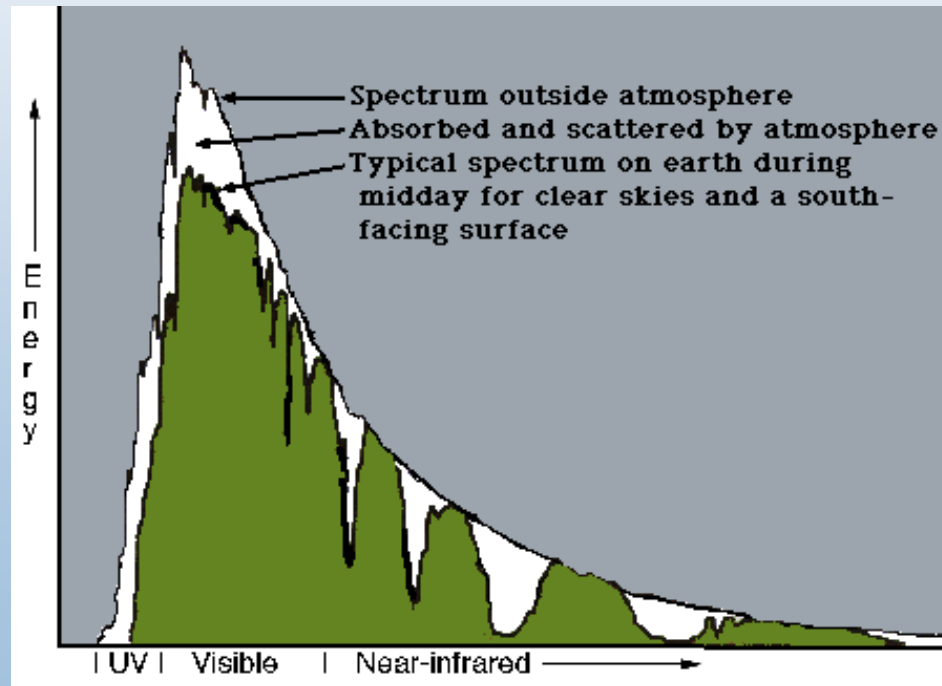


QuickTime™ and a  
TIFF (Uncompressed) decompressor  
are needed to see this picture.

# Spectral Irradiance

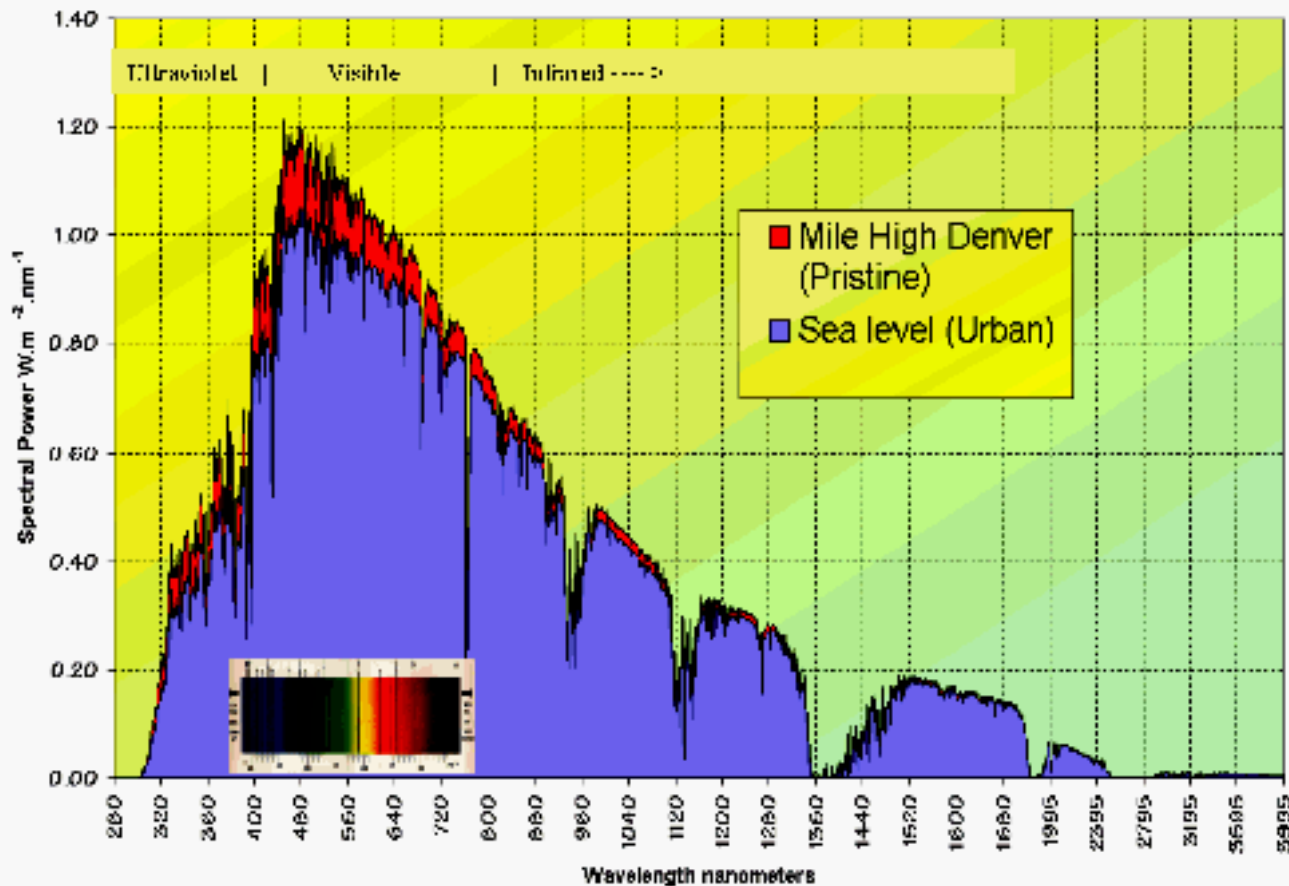
## Basic Solar Spectral Regions:

- Ultraviolet.....200 - 400 nm
- Visible.....400 - 700 nm
- Infrared.....700 - 3000 nm

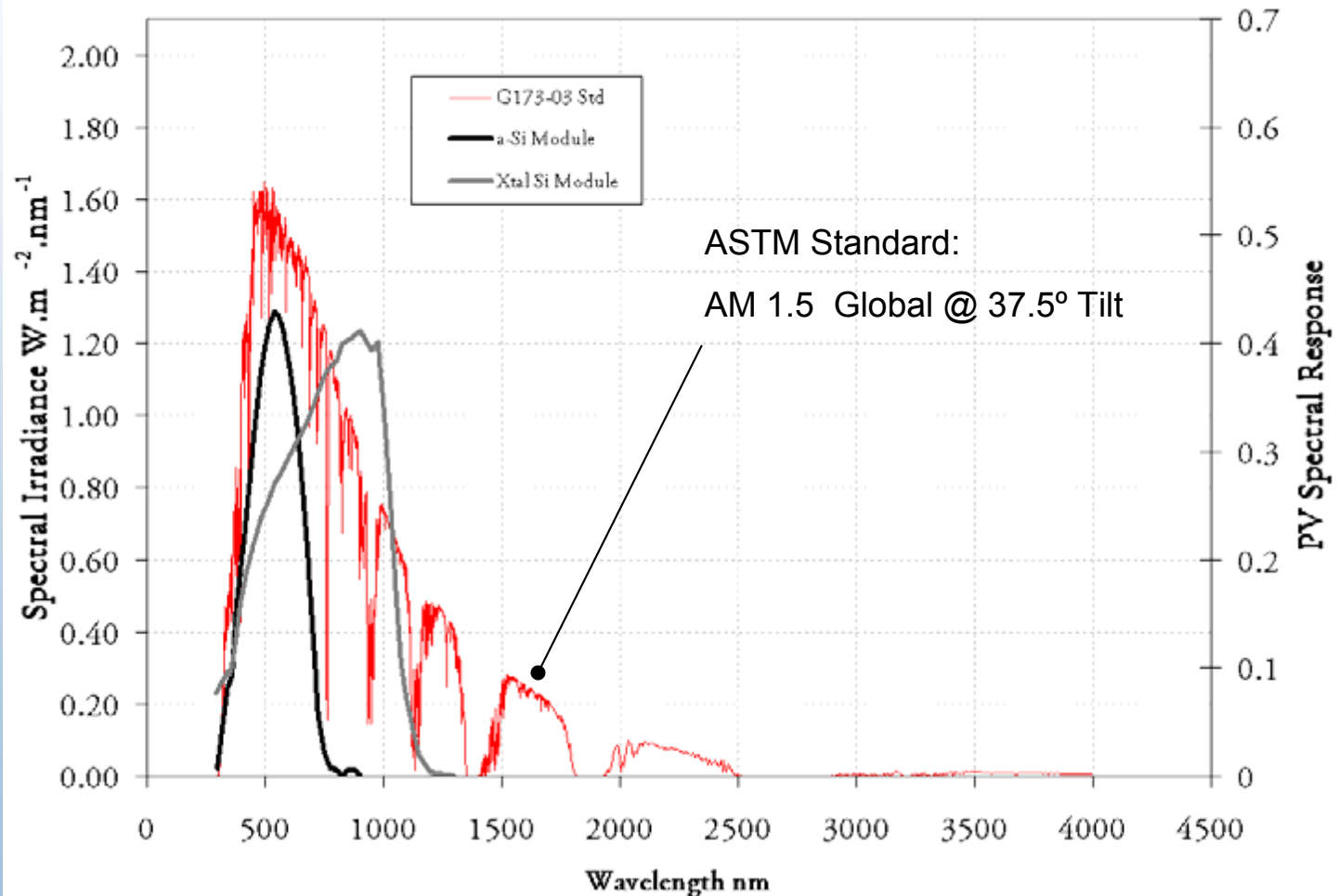


# Follow the Photons!

Comparison of Sea Level and Denver Clear Sky Spectra  
Modeled for typical 10 AM, 2 PM conditions in Summer

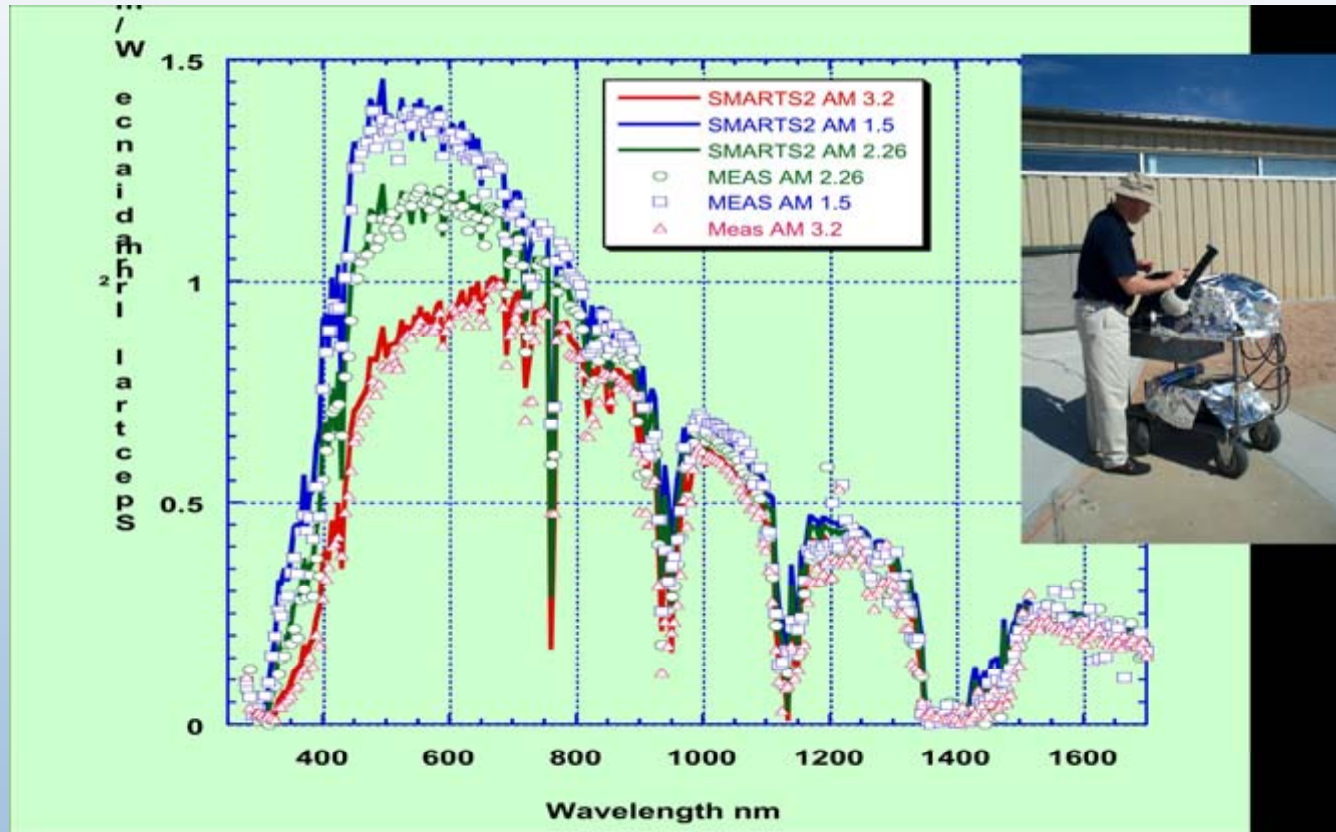


# Photovoltaic Responses



# Simple Model for Atmospheric Radiative Transfer of Sunshine

## SMARTS



# SMARTS

<b>Extraterrestrial Spectrum</b> (Card 7a)		<b>Default Atmosphere</b> <b>Atmosphere</b> (Card 3)		<b>Gaseous Absorption and Pollution</b> (Card 6)																																	
<b>Aerosol Model</b> (Card 8)	<b>Turbidity</b> (Card 9)	<b>Albedo</b> (Card 10)	<b>Circumsolar</b> (Card 13)	<b>Scanning/Smoothing</b> (Card 14)																																	
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<b>Illuminance</b> <b>Extra Illu</b> (Card 15)		<b>Output</b> (Card 12)																																			
<b>Solar Position</b> (Card 17) <ul style="list-style-type: none"> <li><input type="radio"/> Input Zenith and Azi</li> <li><input type="radio"/> Input Elevation and Az</li> <li><input type="radio"/> Input relative Air Ma</li> <li><input type="radio"/> Input Year, Month, D</li> <li><input type="radio"/> Input Month, Latitud</li> </ul>		<b>Output</b> (Card 12) <ul style="list-style-type: none"> <li><input type="radio"/> Create .OUT file only, no spectral results</li> <li><input type="radio"/> Create .OUT file only, with spectral results</li> <li><input checked="" type="radio"/> Create .OUT and .EXT files, include spectral results in .EXT file only</li> <li><input type="radio"/> Create .OUT and .EXT files, include spectral results in both files</li> </ul>																																			
Not <div>             Record Number              1 of 1           </div>		Spectral range to be printed (nm) <table border="1"> <tr> <th>Minimum</th> <th>Maximum</th> <th>Interval (step)</th> </tr> <tr> <td>280</td> <td>4000</td> <td>.5</td> </tr> </table>			Minimum	Maximum	Interval (step)	280	4000	.5																											
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280	4000	.5																																			
		<b>Spectral Results</b> <i>Note: Output order is as shown below and cannot be specified.</i> <table border="0"> <tr> <td><input type="checkbox"/> Extraterrestrial irradiance</td> <td><input type="checkbox"/> Global horizontal photon flux</td> <td><input type="checkbox"/> Ozone optical thickness</td> </tr> <tr> <td><input type="checkbox"/> Direct normal irradiance</td> <td><input type="checkbox"/> Diffuse horizontal photon flux</td> <td><input type="checkbox"/> Optical thickness from all trace gases</td> </tr> <tr> <td><input type="checkbox"/> Diffuse horizontal irradiance</td> <td><input type="checkbox"/> Direct normal photon flux</td> <td><input type="checkbox"/> Water vapor optical thickness</td> </tr> <tr> <td><input type="checkbox"/> Global horizontal irradiance</td> <td><input type="checkbox"/> Rayleigh transmittance</td> <td><input type="checkbox"/> Uniformly mixed gas optical thickness</td> </tr> <tr> <td><input type="checkbox"/> Direct horizontal irradiance</td> <td><input type="checkbox"/> Ozone transmittance</td> <td><input type="checkbox"/> Aerosol optical thickness</td> </tr> <tr> <td><input type="checkbox"/> Direct tilted irradiance</td> <td><input type="checkbox"/> Transmittance from all trace gases</td> <td><input type="checkbox"/> Aerosol single scattering albedo</td> </tr> <tr> <td><input type="checkbox"/> Diffuse tilted irradiance</td> <td><input type="checkbox"/> Water vapor transmittance</td> <td><input type="checkbox"/> Aerosol asymmetry factor</td> </tr> <tr> <td><input type="checkbox"/> Global tilted irradiance</td> <td><input type="checkbox"/> Uniformly mixed gas transmittance</td> <td><input type="checkbox"/> Zonal surface reflectance</td> </tr> <tr> <td><input type="checkbox"/> Experimental direct w/circumsolar</td> <td><input type="checkbox"/> Aerosol transmittance</td> <td><input type="checkbox"/> Local ground reflectance</td> </tr> <tr> <td><input type="checkbox"/> Experimental diffuse irradiance</td> <td><input type="checkbox"/> Beam radiation transmittance</td> <td><input type="checkbox"/> Atmospheric reflectance</td> </tr> <tr> <td><input type="checkbox"/> Circumsolar within radiometer</td> <td><input type="checkbox"/> Rayleigh optical thickness</td> <td></td> </tr> </table>			<input type="checkbox"/> Extraterrestrial irradiance	<input type="checkbox"/> Global horizontal photon flux	<input type="checkbox"/> Ozone optical thickness	<input type="checkbox"/> Direct normal irradiance	<input type="checkbox"/> Diffuse horizontal photon flux	<input type="checkbox"/> Optical thickness from all trace gases	<input type="checkbox"/> Diffuse horizontal irradiance	<input type="checkbox"/> Direct normal photon flux	<input type="checkbox"/> Water vapor optical thickness	<input type="checkbox"/> Global horizontal irradiance	<input type="checkbox"/> Rayleigh transmittance	<input type="checkbox"/> Uniformly mixed gas optical thickness	<input type="checkbox"/> Direct horizontal irradiance	<input type="checkbox"/> Ozone transmittance	<input type="checkbox"/> Aerosol optical thickness	<input type="checkbox"/> Direct tilted irradiance	<input type="checkbox"/> Transmittance from all trace gases	<input type="checkbox"/> Aerosol single scattering albedo	<input type="checkbox"/> Diffuse tilted irradiance	<input type="checkbox"/> Water vapor transmittance	<input type="checkbox"/> Aerosol asymmetry factor	<input type="checkbox"/> Global tilted irradiance	<input type="checkbox"/> Uniformly mixed gas transmittance	<input type="checkbox"/> Zonal surface reflectance	<input type="checkbox"/> Experimental direct w/circumsolar	<input type="checkbox"/> Aerosol transmittance	<input type="checkbox"/> Local ground reflectance	<input type="checkbox"/> Experimental diffuse irradiance	<input type="checkbox"/> Beam radiation transmittance	<input type="checkbox"/> Atmospheric reflectance	<input type="checkbox"/> Circumsolar within radiometer	<input type="checkbox"/> Rayleigh optical thickness	
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Hour (local standard time, deci Latitude (deg, +N, Longitude (deg, +E, Time Zone (+E,		Units: Irradiance in $W m^{-2} nm^{-1}$ ; Photon Flux in $10^{-3} cm^{-2} s^{-1} nm^{-1}$																																			
		<div>             Select All             Deselect All             Enter             Cancel           </div>																																			

Available from NREL: <http://rredc.nrel.gov>

# Why Do We Need Solar Radiation Data?

- Agriculture
  - Astronomy
  - Atmospheric Science
  - Climate Change
  - Health
  - Hydrology
  - Materials
  - Oceanography
  - Photobiology
  - Renewable Energy
- Photosynthesis
  - Solar Output Variation
  - Numerical Weather Prediction
  - Energy Balance
  - UV effects on skin
  - Evaporation
  - Degradation
  - Energy Balance
  - Light and Life
  - Sustainability

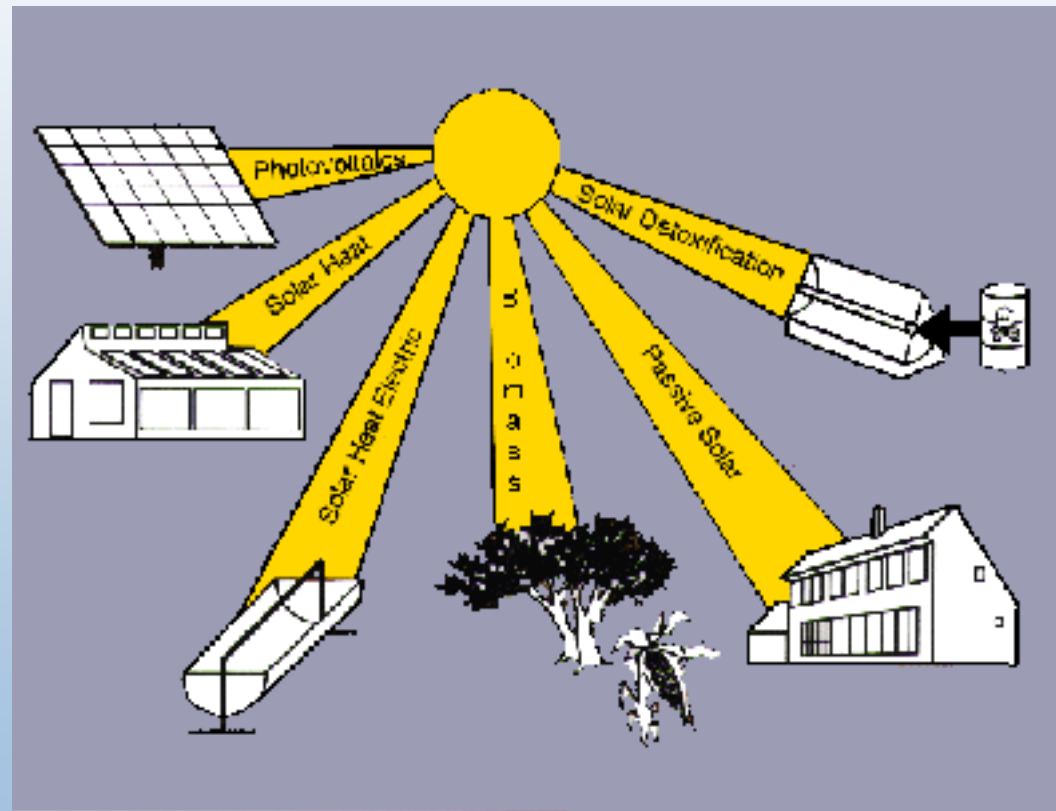


# Why Do We Need Solar Radiation Data?

## Renewable Energy

The amount of solar energy reaching the earth's land areas in 1 hour is enough to supply the U.S. energy needs for 1 year (~100 Quads/yr)

- Photovoltaics
- Solar Heat-thermal
- Solar Heat-electric
- Solar Fuel-biomass
- Passive Solar Lighting
- Building HVAC
- Solar Detoxification



# What Influences the Amount of Solar Radiation?

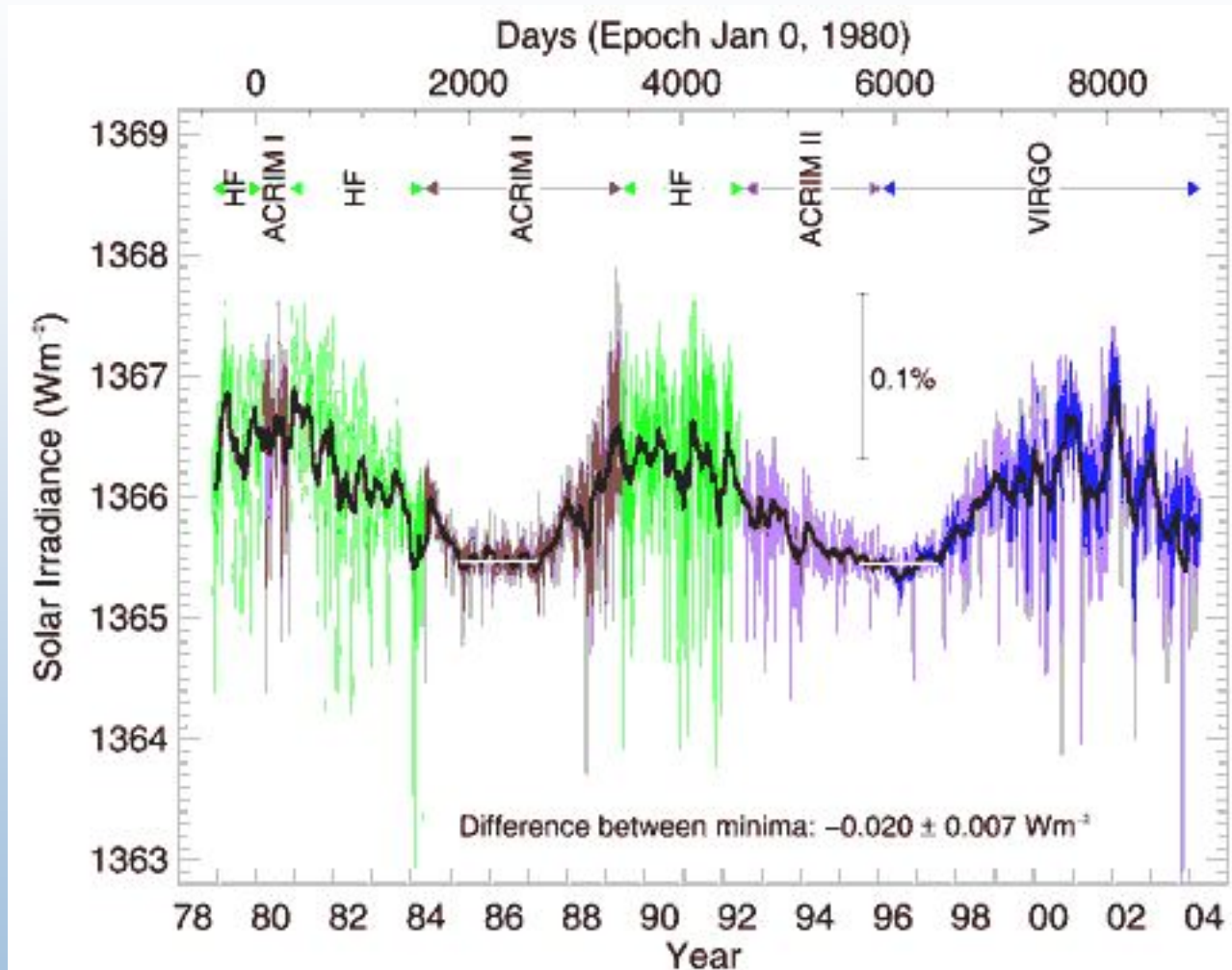
- Solar output
- Earth-Sun distance
- Clouds
- Water vapor
- Air pollution
- Smoke from forest fires
- Volcanic ash
- Location
- Time of day
- Season



11 year solar cycle  
3.5% annual variation  
Dominant factor  
Selective absorber  
40% less direct  
Natural or man-made  
Global effect for years

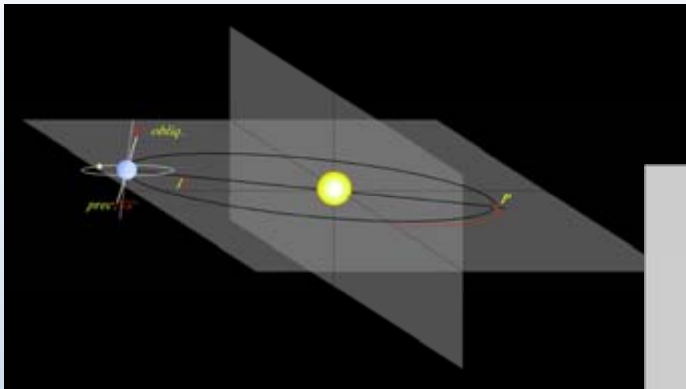
Solar position

# Solar “Constant”



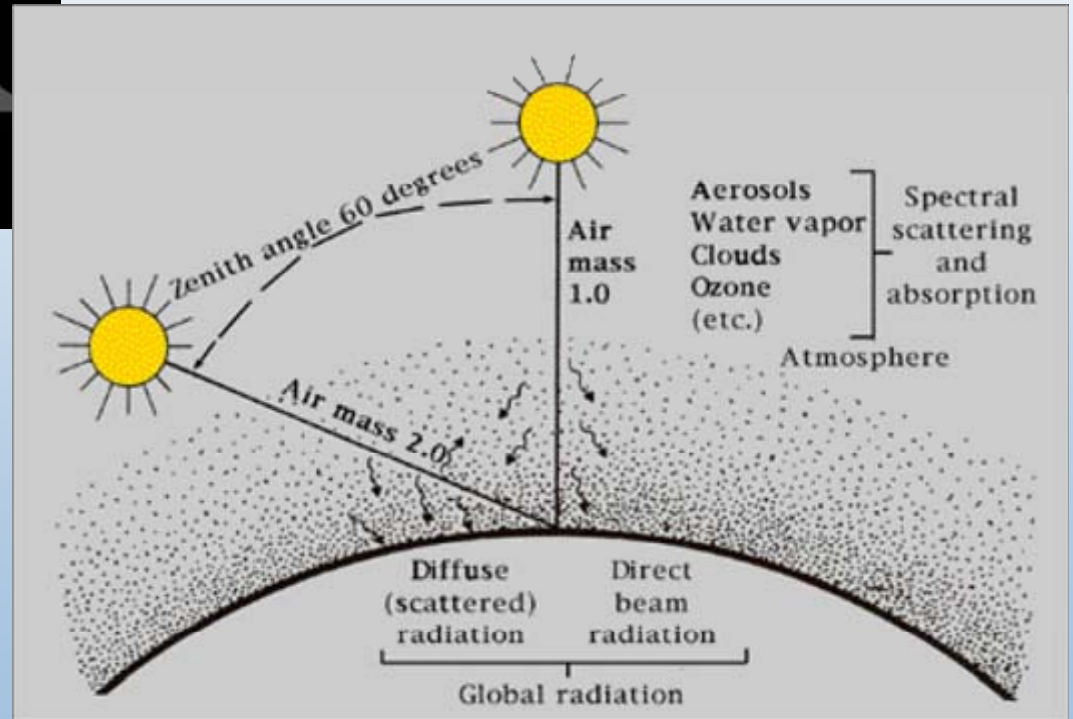
World Radiation Center, Davos, Switzerland  
<http://www.pmodwrc.ch/>

# What Influences the Amount of Solar Radiation?



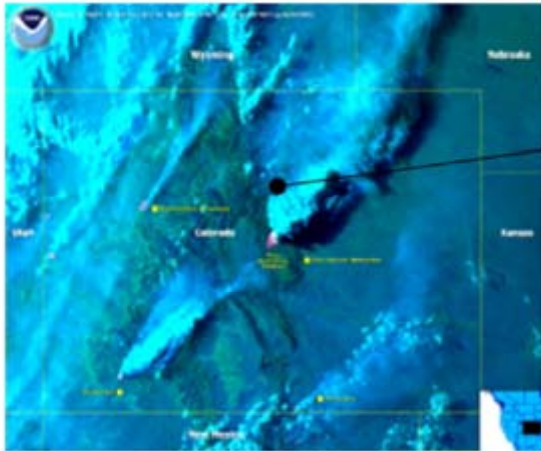
## Earth's Orbit:

- Earth-Sun distance
- Relative tilt
- Time of day



# What Influences the Amount of Solar Radiation?

## SRRL Measures Effects of Forest Fires on Solar Radiation



← NOAA Satellite Image

NREL

SRRL "SKYCAM" Image →  
June 10, 2002



Fuzzy Sun and Shadows:  
Increased scattering yields Higher-than-normal  
Circumsolar Radiation

### Changes in Direct "Beam" Irradiance

-A- Morning Haze Before Shift in Wind:

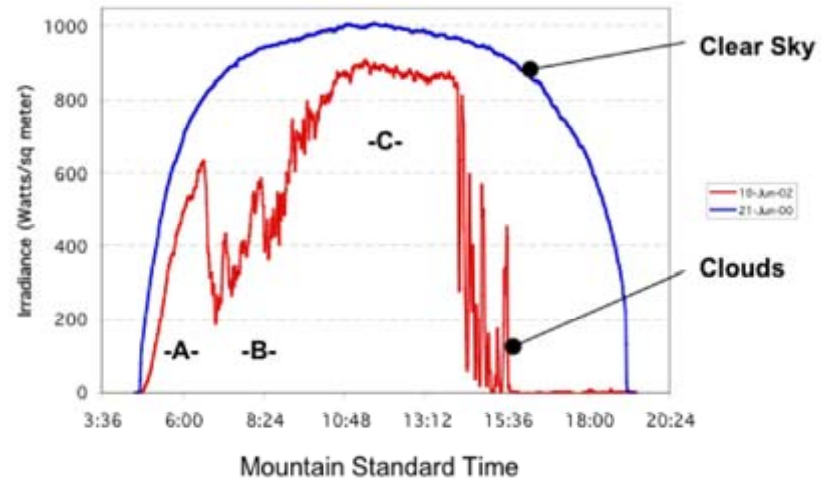
75% of Clear Sky (7:00)

-B- Thick Smoke Cloud:

23% of Clear Sky (7:30)

-C- Midday Haze:

90% of Clear Sky





# How Do We Use Solar Radiation Data?

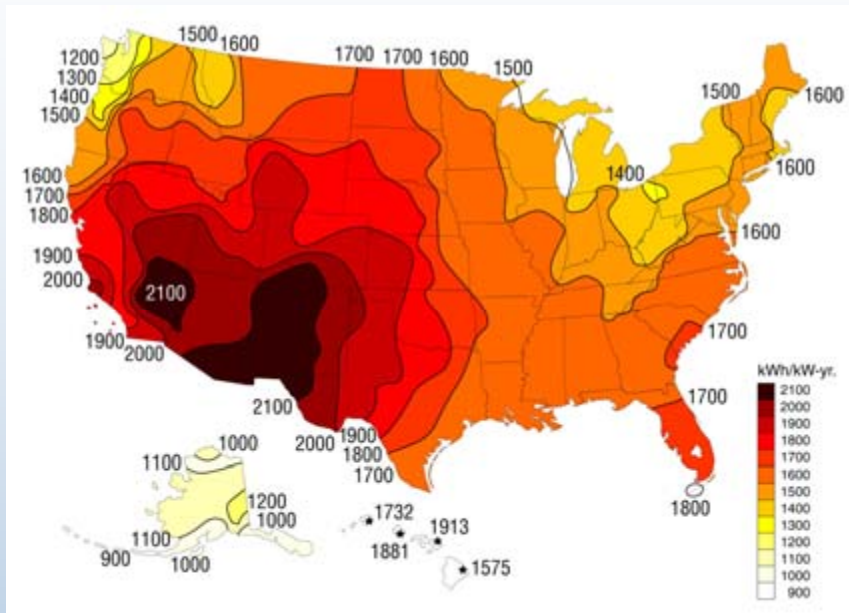
- Technology Selection
- Siting
- System Design
- Performance Monitoring



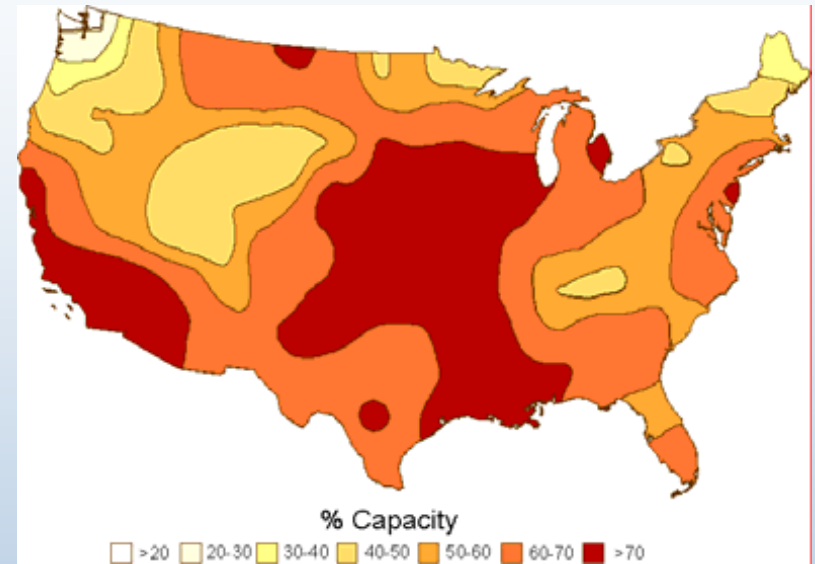
Flat Plate and  
Concentrating Collectors



## PV Energy kWh/kW-yr



## Effective Load Carrying Capacity

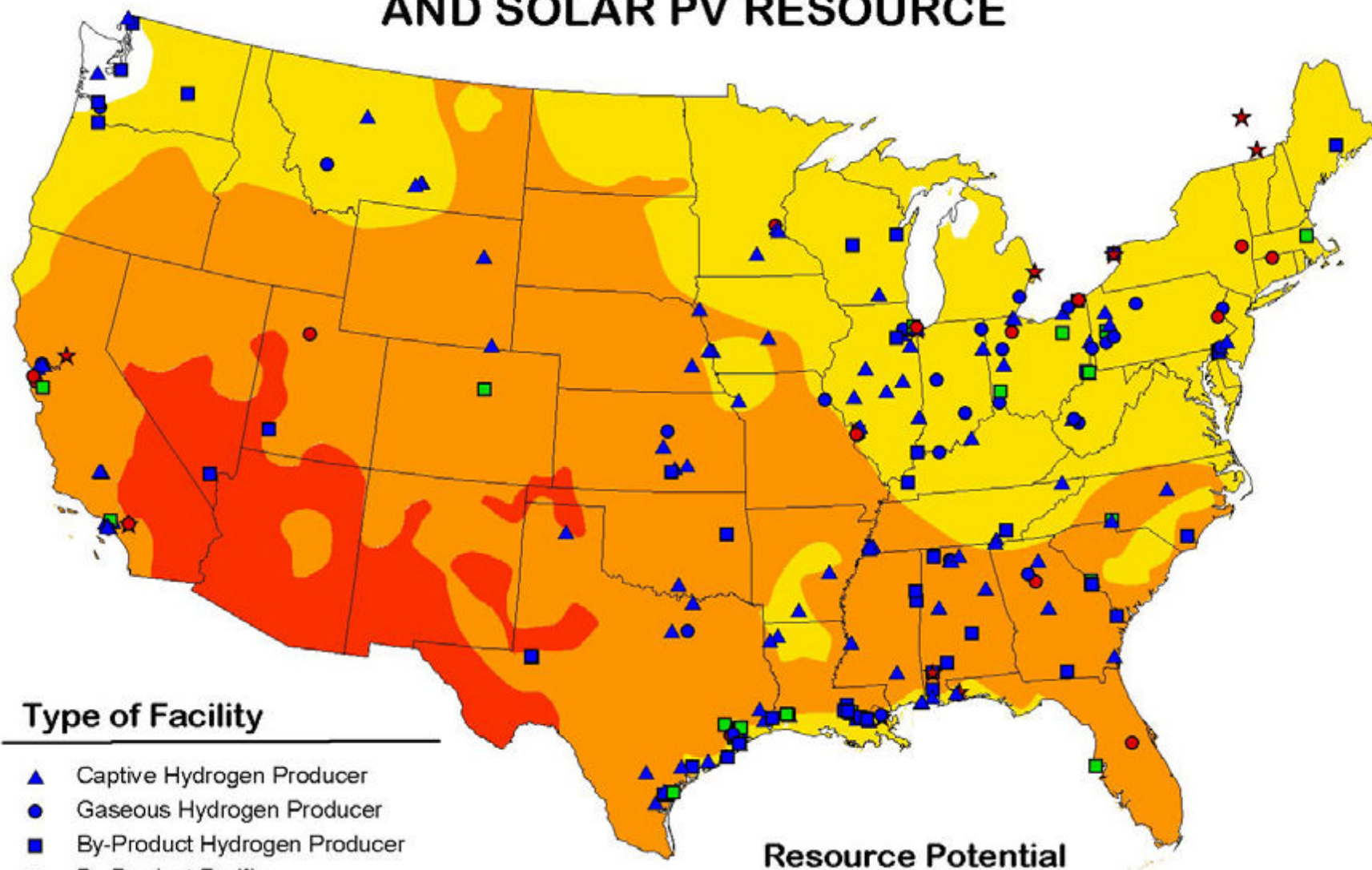


Source: Christy Herig (NREL) and Richard Perez (SUNY/Albany)

- PV can provide peak shaving in many parts of U.S.
- During off-peak periods, PV capacity can be applied to hydrogen generation



# HYDROGEN FACILITIES AND SOLAR PV RESOURCE



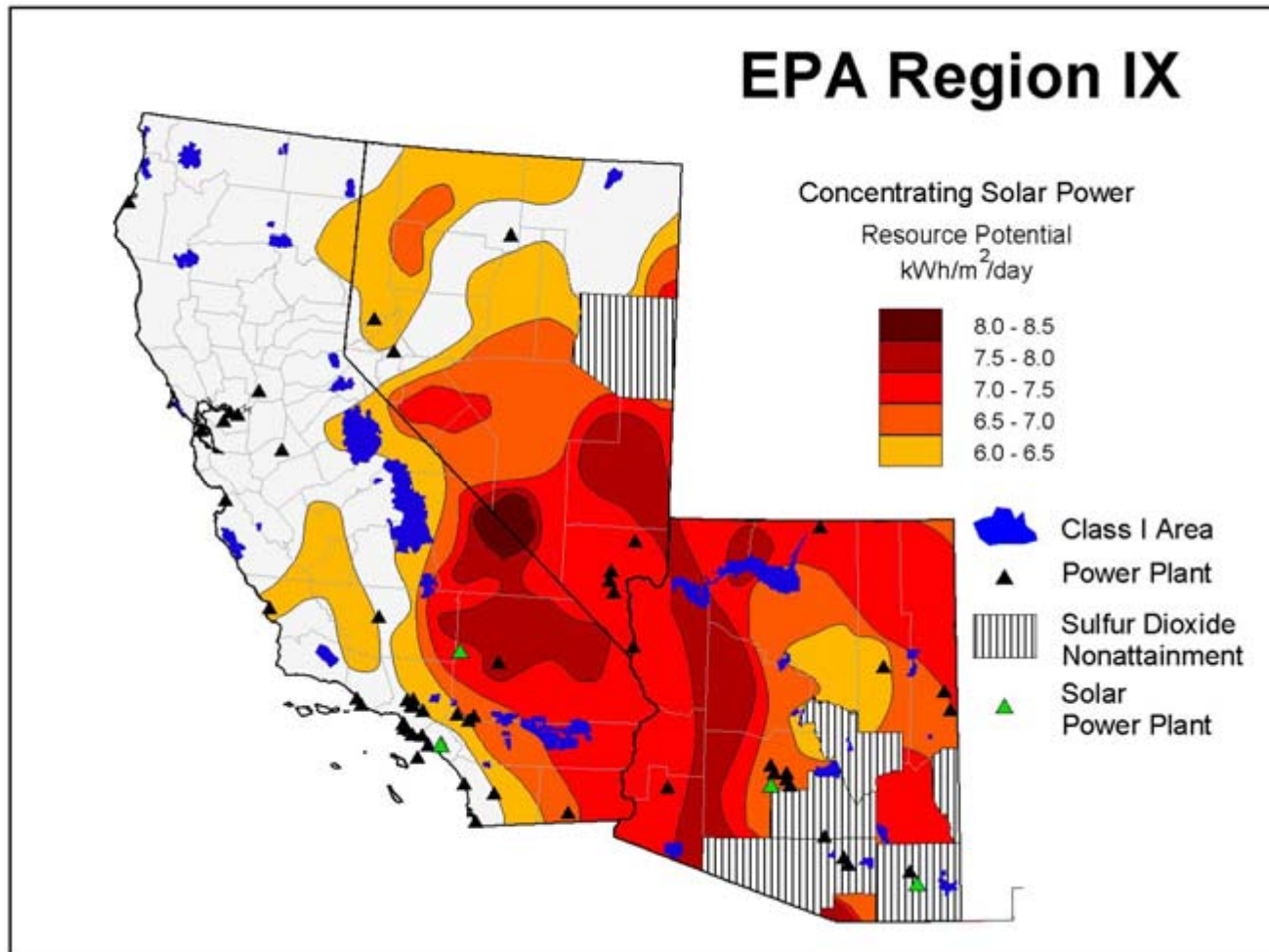
## Type of Facility

- ▲ Captive Hydrogen Producer
- Gaseous Hydrogen Producer
- By-Product Hydrogen Producer
- By-Product Purifier
- ★ Liquid Hydrogen Producer
- Satellite Terminal
- Undetermined

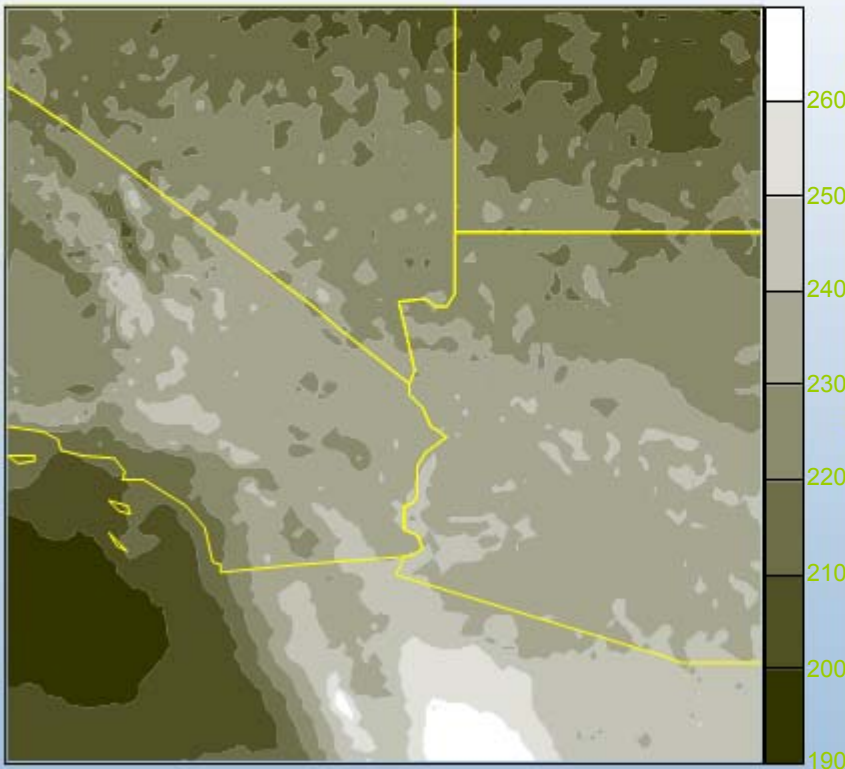
## Resource Potential

- Excellent
- Good
- Moderate

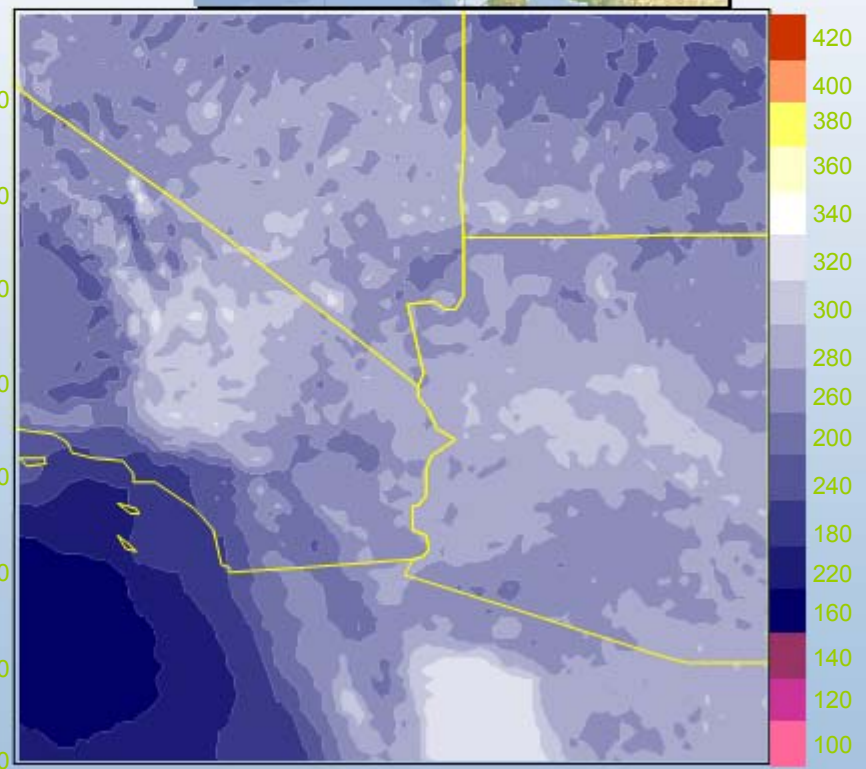
# An Integrated Analysis Utilizing GIS can Assist With Energy and Environment Planning Efforts



# Satellite-Derived Techniques Provide Improved Site-Time Coverage (SUNY/Albany)



GLOBAL IRRADIANCE (average W/sq.m)

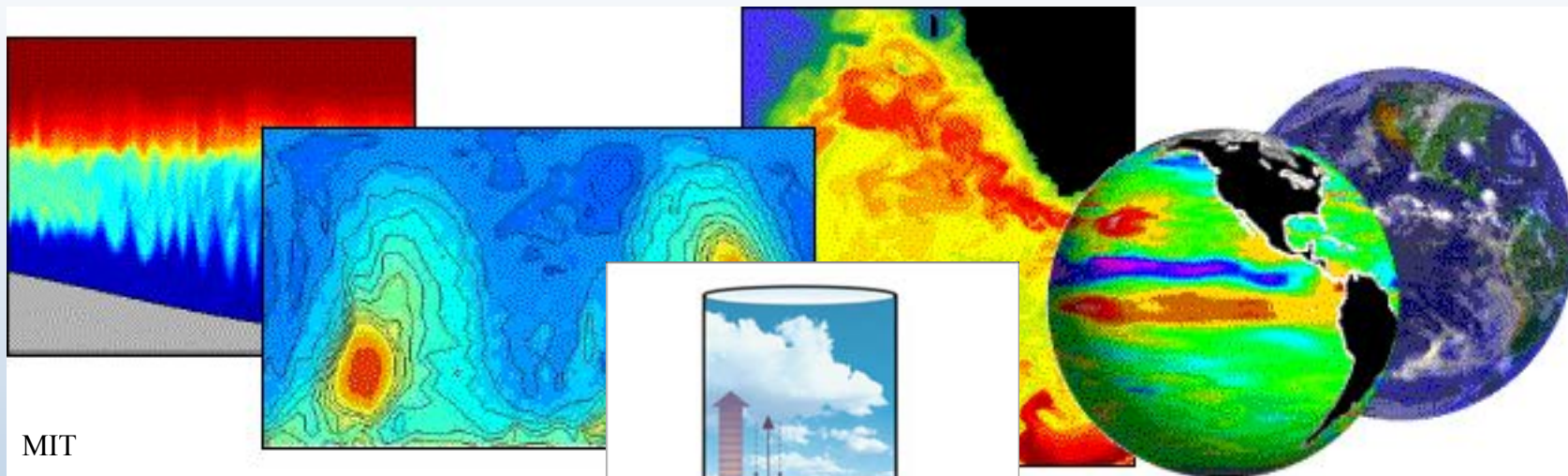


DIRECT IRRADIANCE (average W/sq.m)

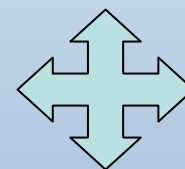
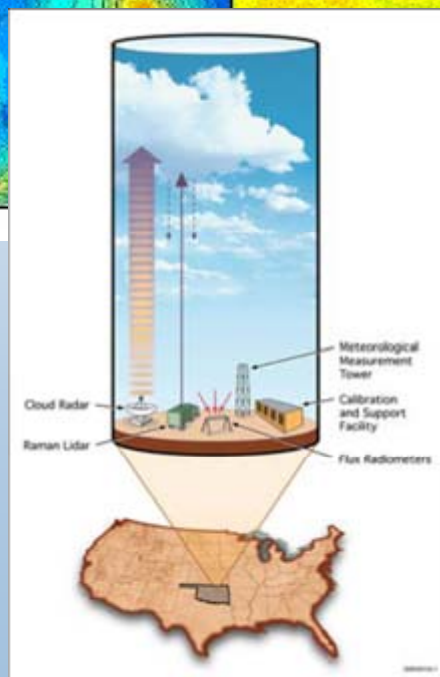


# How Do We Use Solar Radiation Data?

## General Circulation Model Development



MIT



**Radiant Fluxes?**

DOE/Atmospheric Radiation Measurement (ARM) Program

# How Accurate Do the Data Need to Be?

- What are the risks?
  - Cost/Benefit of Resource Assessment approach
- What is the application?
  - Daylighting & building thermal performance
  - Concentrating Collector Solar Power Plant
  - Cloud forcing analyses for climate change research
- What is the period of interest?
  - Measurement uncertainties decrease with longer averaging intervals (averaging can remove random errors)
  - Recent data more accurate than historical records (technology advancements)

# How Accurate Do the Data Need to Be?

What is possible?

## Measurement Uncertainty Estimates\*

	Pyrheliometer (Direct Normal)	Pyranometer (Global)
Calibration	$\pm 1.6\%$	$\pm 4.2\%$
Field Data (Best practice)	$\sim \pm 5\%$	$\sim \pm 5\%$

\*

Instantaneous data intervals

# How Will We Meet Our Solar Radiation Data Needs?

## Research Activities:

- Solar Radiation Research Laboratory
  - Metrology
  - Optics
  - Electronics
  - Data Acquisition
- Photovoltaic Program
  - Radiometric Measurements
- Climate Change
  - Broadband Radiometer Mentor
- Collaborations
  - WMO, UNEP, NCAR, NOAA, state & local govt, academia



# Solar Radiation Research Lab



- Baseline Measurements
- Radiometer Calibrations
- Instrument Development
- Station Operator Training



# Solar Radiation Research Lab



Baseline Measurements  
(98 data elements)

<http://www.nrel.gov/midc>



Rotating Shadowband Pyranometer



# Radiometer Calibrations



World Radiometric Reference

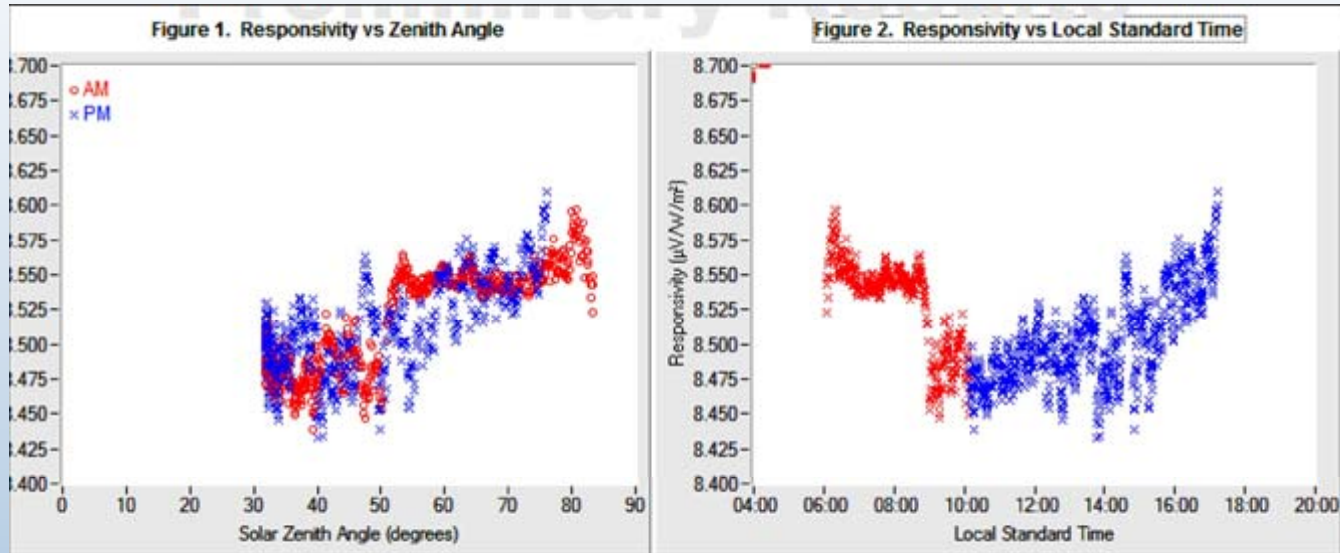


NREL Transfer Standards

NPC  
At SRRL



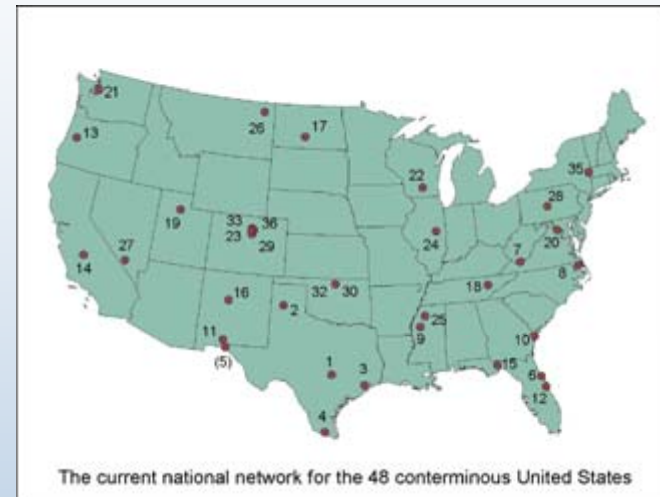
# Radiometer Calibrations



# National Solar Radiation Data Base



NSRDB Stations  
(1961-1990)



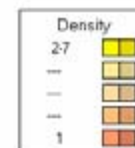
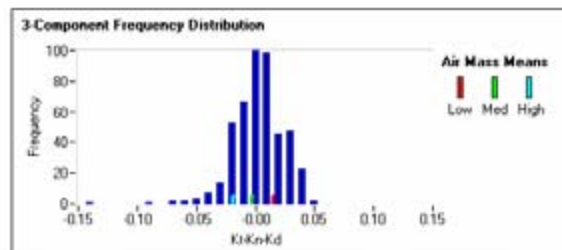
Solar Measurement Stations  
(1990 - Present)

# Automatic Data Quality

SRRLH, SRRL Hourly - June

Global / Direct

3 Component Filtering: Off  
K-Space Threshold: —  
Integration Time (min): 60  
Density Plotting: Equal Freq



Curves  
KrMax: 80  
KdMax: 80  
Left: 4.9  
Right: 1.12

In	284
Out	20 (6.6 %)
Active	304
Ignored	0
Total	304
Err (L)	1.6 %
Err (R)	4.3 %

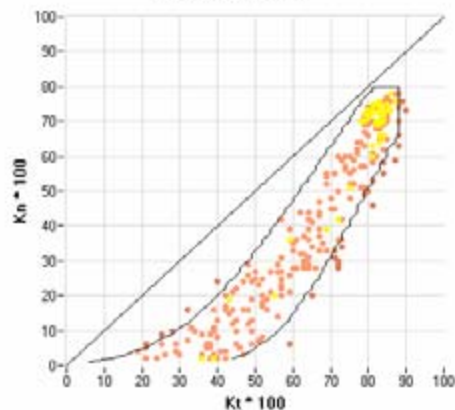
Curves  
KrMax: 75  
KdMax: 85  
Left: 4.9  
Right: 1.11

In	177
Out	10 (5.3 %)
Active	187
Ignored	1
Total	188
Err (L)	1.6 %
Err (R)	3.7 %

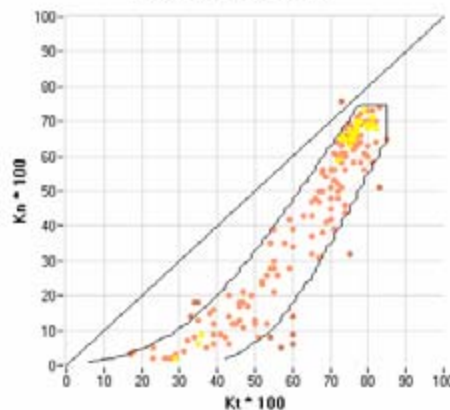
Curves  
KrMax: 65  
KdMax: 70  
Left: 4.8  
Right: 1.9

In	92
Out	9 (8.9 %)
Active	101
Ignored	0
Total	101
Err (L)	3.0 %
Err (R)	5.0 %

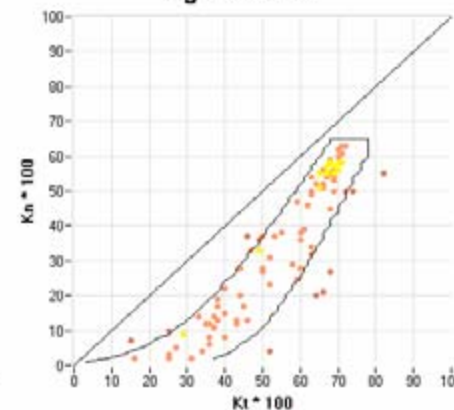
Low Air Mass



Medium Air Mass



High Air Mass





# Where Can You Obtain solar Radiation Data?

- Renewable Resource Data Center
  - <http://rredc.nrel.gov>
- Measurement & Instrumentation Data Center
  - <http://www.nrel.gov/midc>
- NREL Map Server
  - <http://www.nrel.gov/maps>
- World Radiation Data Center
  - <http://wrdc-mgo.nrel.gov>
- National Climatic Data Center
  - <http://www.ncdc.noaa.gov>
- DOE Atmospheric Radiation Measurement Program
  - <http://www.arm.gov>
- NOAA Climate Monitoring & Diagnostic Laboratory
  - <http://www.cmdl.noaa.gov/star>
- NOAA Surface Radiation Research Branch
  - <http://www.srrb.noaa.gov>

# Key Points

- Accurate information is important for policy decisions, technology selection, siting, designing, and monitoring the performance of solar energy conversion systems
- Accurate measurements are important for model development
- The work we do to improve solar measurements
  - Calibration
  - Instrument characterization
  - Measurement techniques (operations and maintenance, radiometer selection, installation considerations, etc.)
  - Data Quality Assessment
  - Training
- Data distribution to meet user needs (MIDC, RReDC, NSRDB)

# Solar Radiation Measurement

Thank you!

Questions?

# POP Quiz

Write the relationship between Global, Direct, & Diffuse irradiance.

$$\text{Global} = \text{Direct Normal} * \cos(Z) + \text{Diffuse}$$

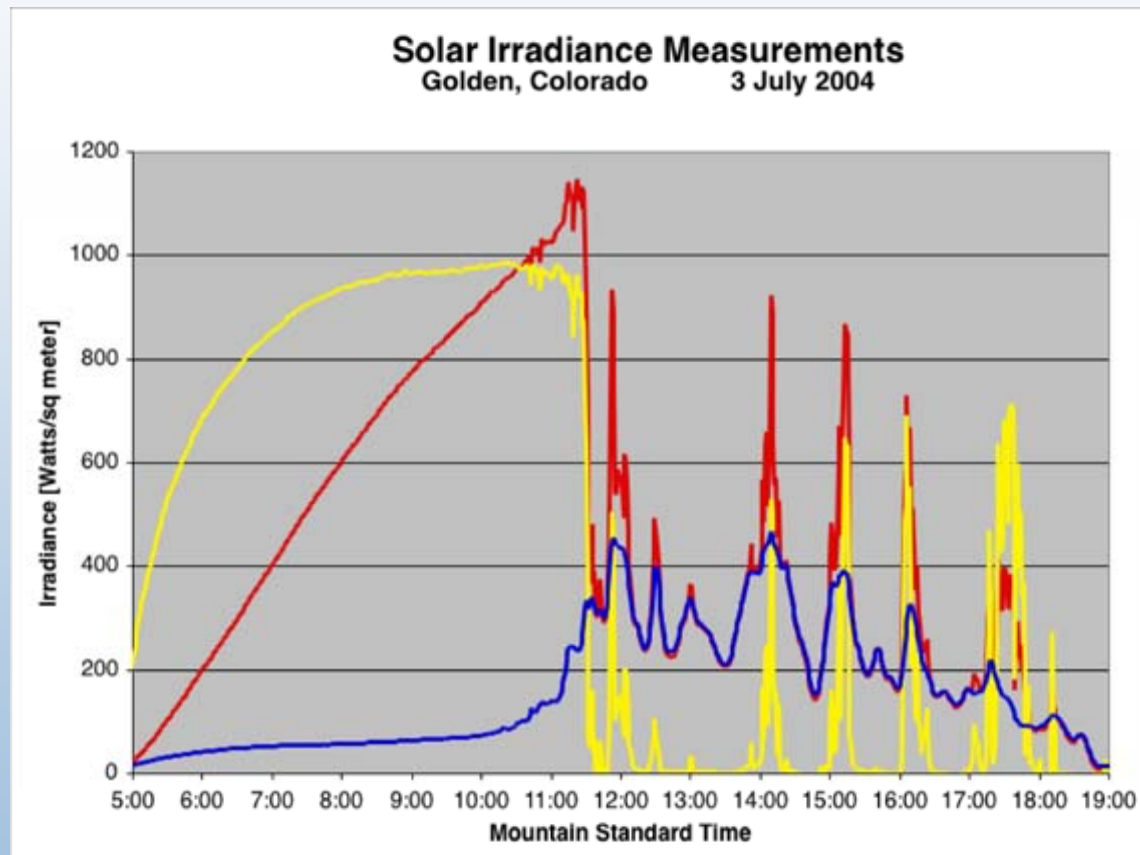
# POP Quiz

Indicate which properties (quick, accurate, or cheap) apply to these pyranometer detector types:

- ✓ Photodiode Fast, Cheap, Spectrally selective
- ✓ Thermopile Accurate, \$\$, Slow

# POP Quiz

T/F: The Global irradiance can never exceed the solar constant.





# POP Quiz

The presently accepted value of the Solar Constant:

- a) 1.96 Langleys per minute
- b) 1366 Watts per square meter
- c) 432.7 BTUs per hour-square foot
- d) All of the above

