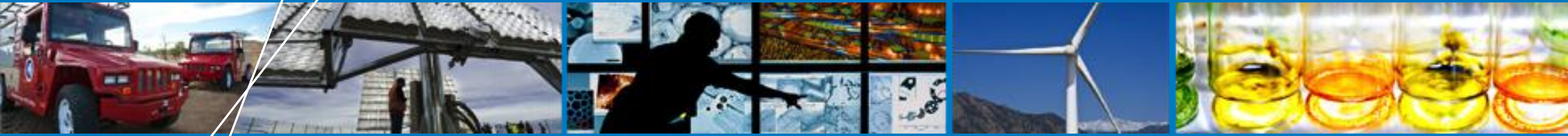
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

A Review of Measured/Modeled Solar Resource Uncertainty

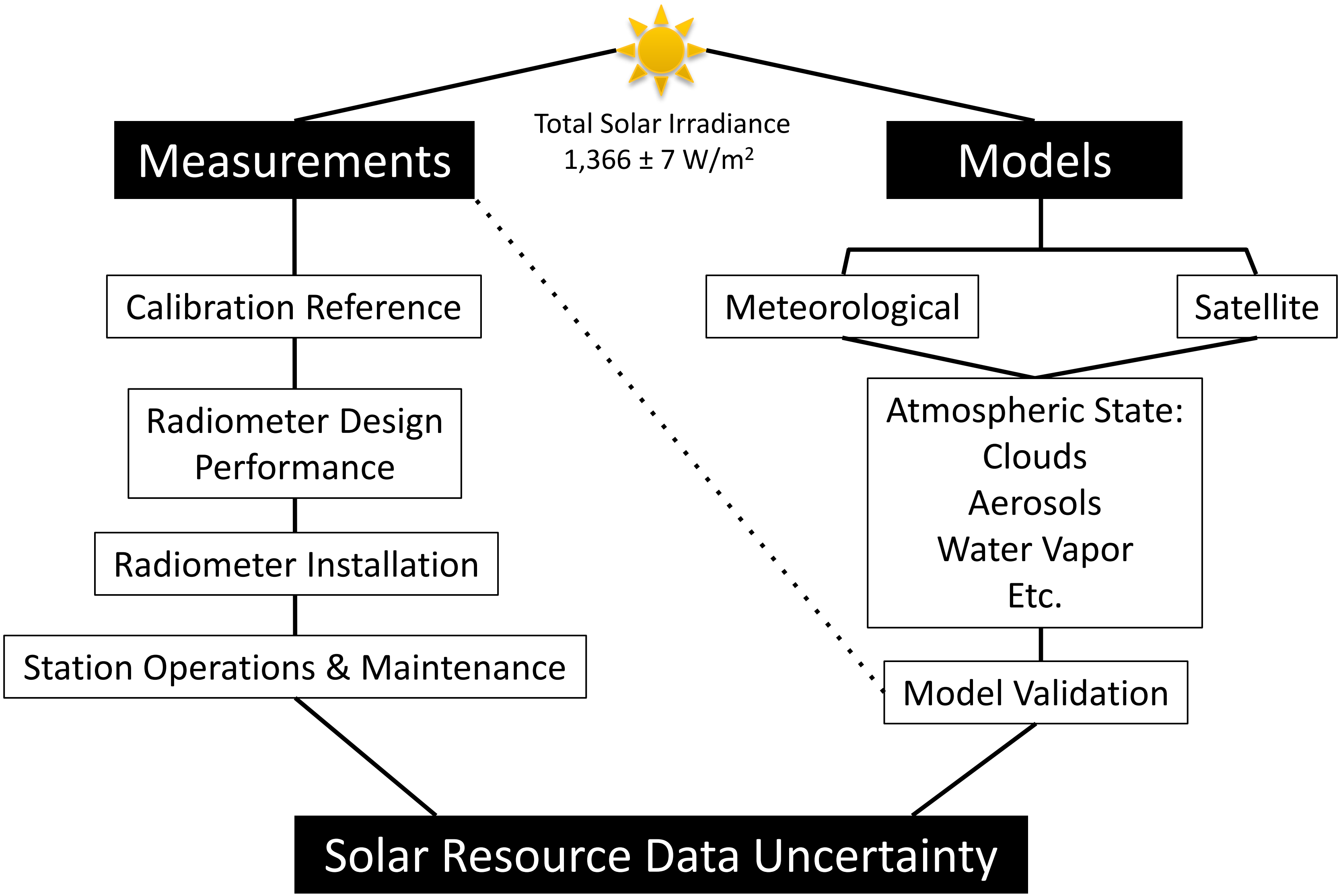


Presented at the 2013 Sandia PV Performance Modeling Workshop

Santa Clara, CA May 1-2, 2013

Tom Stoffel

Getting to PV Performance Model Input Uncertainty



Solar Radiation Components

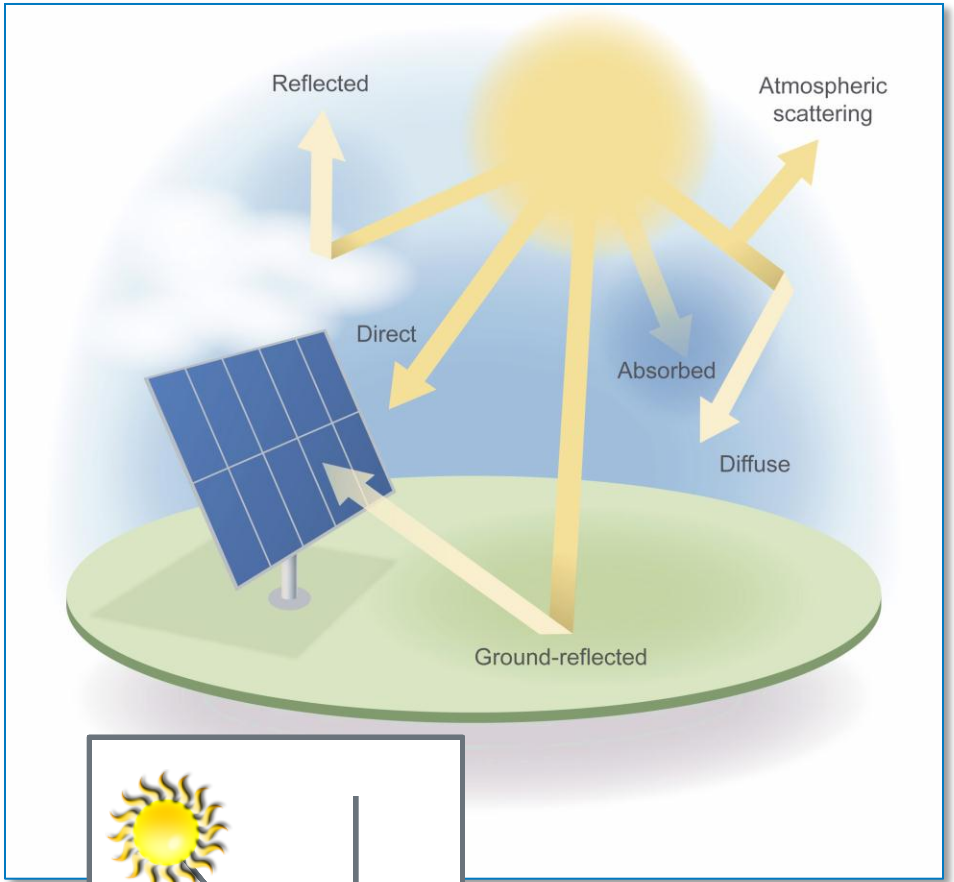
Radiation from the sky dome

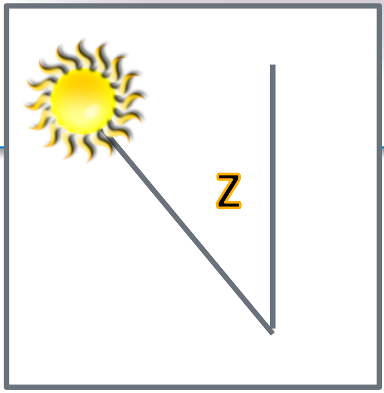
- ***Directly*** from the sun
- Everywhere ***except*** the sun
- ***Entire*** sky
- Available to ***PV Module/Array***

We call it

- Direct Normal Irradiance (DNI)
  Beam
- Diffuse Horizontal Irradiance (DHI)
  Sky
- Global Horizontal Irradiance (GHI)
  Total Hemispheric
- Plane-of-Array (POA)

GHI = DNI * Cos (Z) + DHI





Z = 90° at sunrise & sunset

To Measure is to Know

Lord Kelvin (1824-1907)

Key Concepts:

Uncertainty estimates require a reference

Model performance is limited by the *uncertainty* of the measurements used for development and validation

Uncertainty varies with location and time-scale

Uncertainty with Respect to a Reference

Standard for the *Watt per square meter*

World Radiometric Reference (WRR)

Uncertainty: ±0.3% for DNI ≥ 700 W/m^2

World Standard Group

NREL Standards

NREL Broadband Outdoor Radiometer Calibrations

Instrumentation

Present Day

Direct Normal

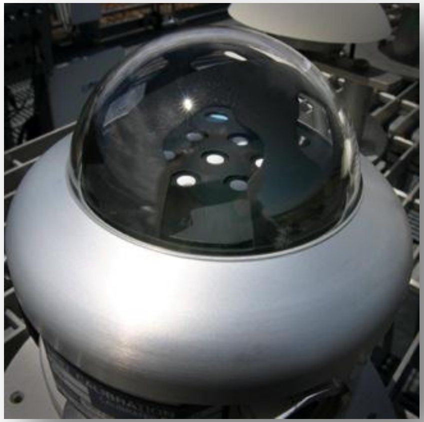
Measured by a *Pyrheliometer* on a sun-following tracker

Global Horizontal

Measured by a *Pyranometer* with a horizontal sensor

Diffuse

Measured by a shaded *Pyranometer* under a tracking ball



DNI = (GHI + DHI)/Cos(Z)

Single Instrument

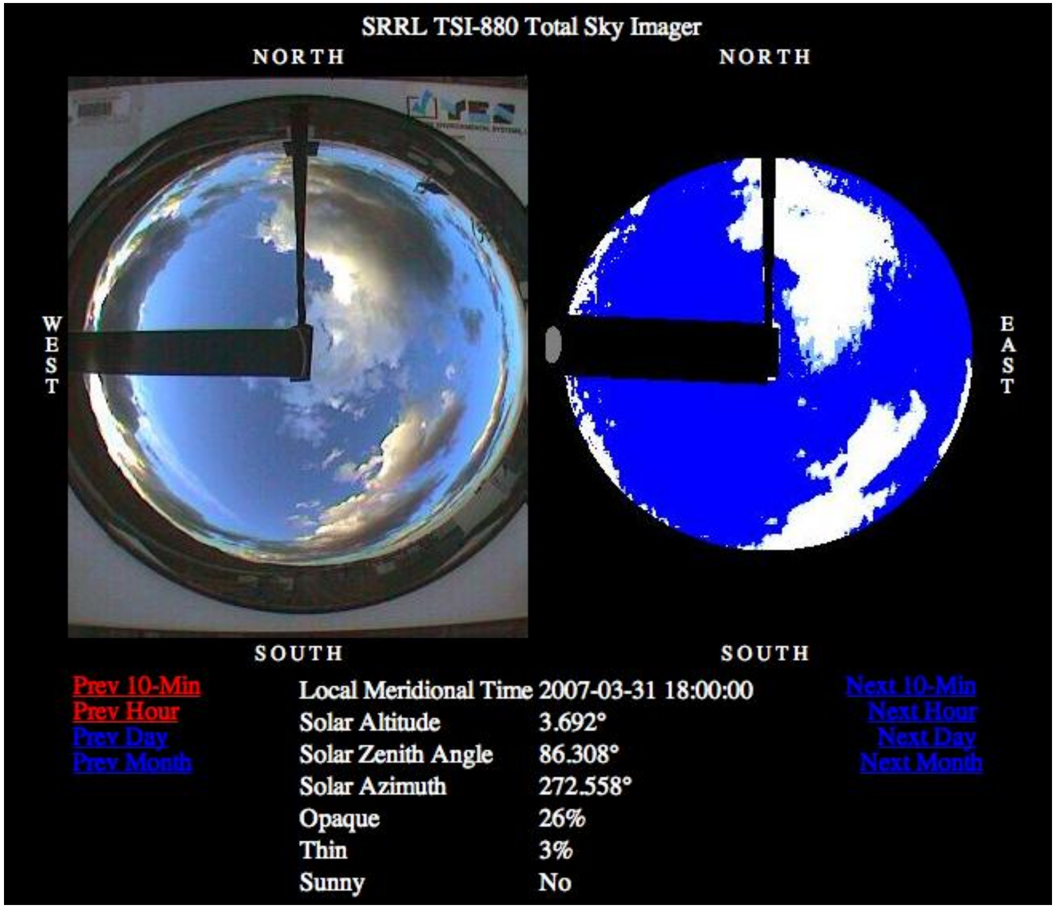
Measure 2 of 3 components by *Internally Shaded Sensors*

or a *Rotating Shadowband Radiometer*

Surface Observations of Clouds

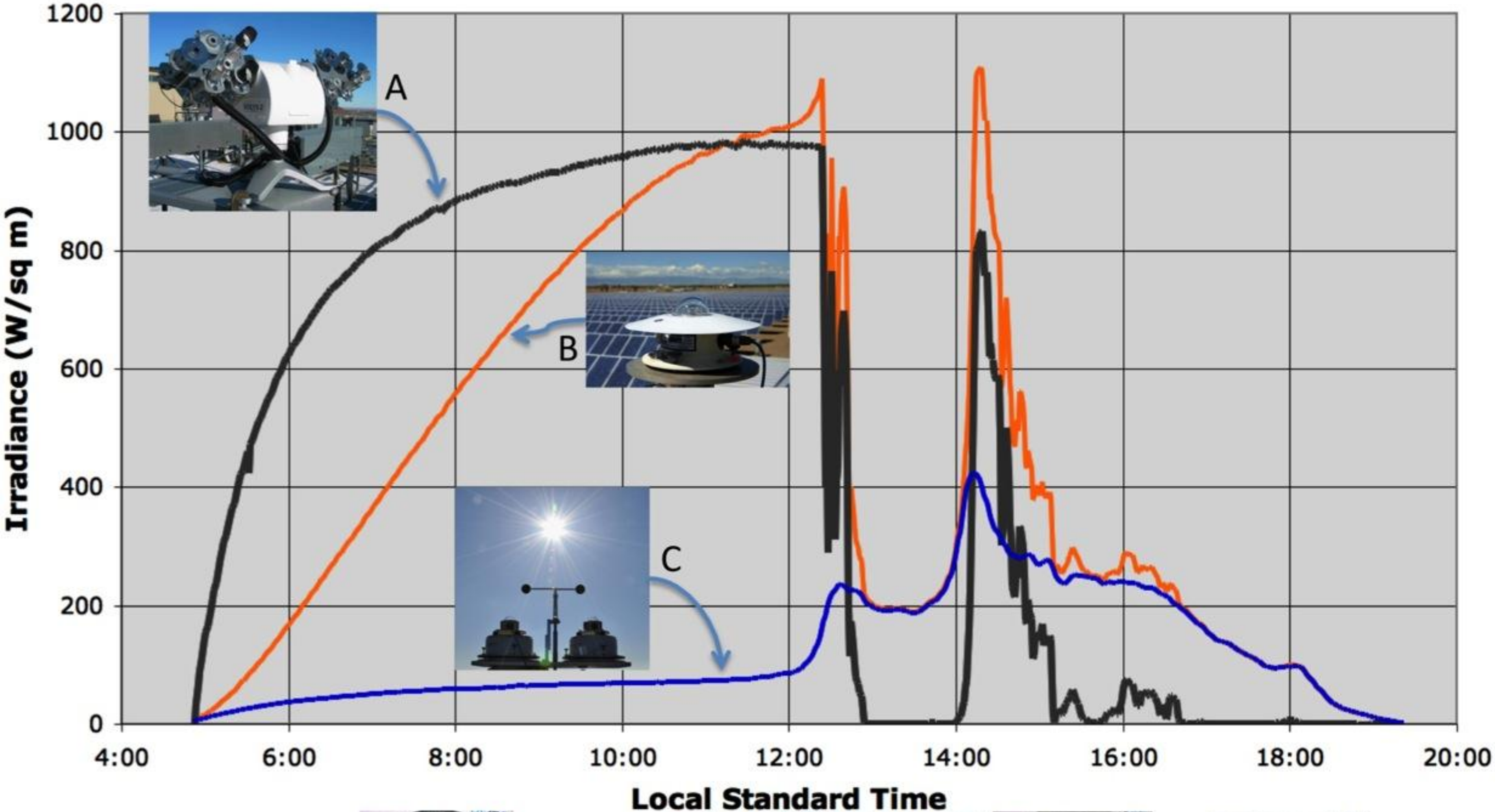
http://www.nrel.gov/midc/srrl_bms

Sky Imaging



National Weather Service used trained observers from 1930's to mid-1990's to report cloud amounts & types by layer before todays automation

Clear – Partly Cloudy – Overcast **1-minute**



Sky Images:

A: DNI – Pyrheliometers B: GHI – Pyranometer C: DHI – Shaded Pyranometers

Radiometers: Searching for *Cheap, Fast, & Accurate*

Pyrheliometers – DNI *

$3,000 to $35,000
0.1 to 1 sec for 1/e
±0.5% to ± 3%

CPV

Absolute Cavity Radiometers

Model AHF (upper)

The Eppley Laboratory, Inc.

Model PMO6 (lower)

World Radiation Center

CHP1
Kipp & Zonen

MS-56
EKO Instruments

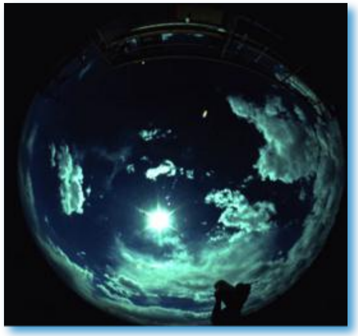
DR01
Hukseflux Thermal Sensors

Normal Incidence Pyrheliometer (NIP)
The Eppley Laboratory, Inc.

* Michalsky, J. et al., An Extensive Comparison of Commercial Pyrheliometers under a Wide Range of Routine Observing Conditions Journal of Atmospheric and Oceanic Technology, Vol 28, pp. 752-766

Radiometers: *Cheap, Fast, & Accurate*

Pyranometer – GHI, DHI, POA*



Fish-Eye Field of View

Pyranometers with Ventilators

$200 to $7,000
10 μs to 5 sec
± 4% to ± 8^{+}%

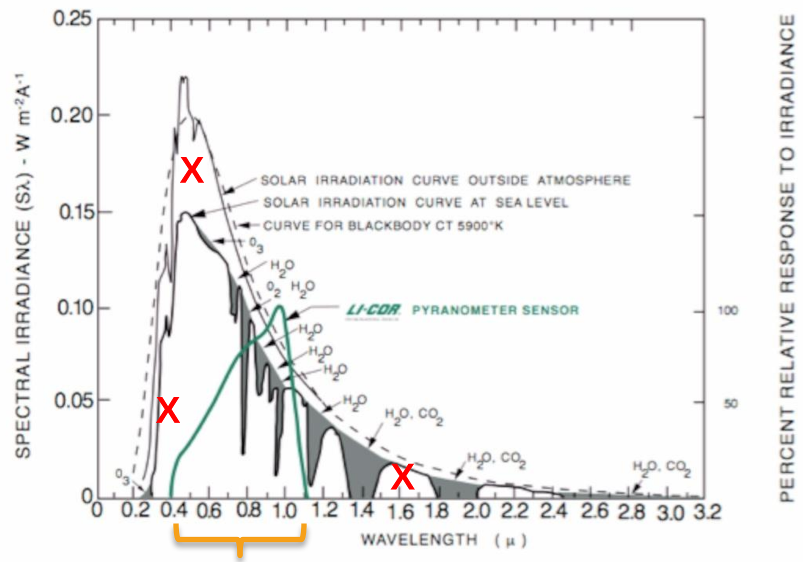
* Wilcox & Myers (2008) *Evaluation of Radiometers in Full-Time Use at the National Renewable Energy Laboratory Solar Radiation Research Laboratory* www.nrel.gov/docs/fy09osti/44627.pdf

Photoelectric Detectors

$200 to $500
10 µsec for 95%
±5% to ±8+%
(Sub-hourly)

Cheap-Fast-Reduced Spectral Response

www.kippzonen.com



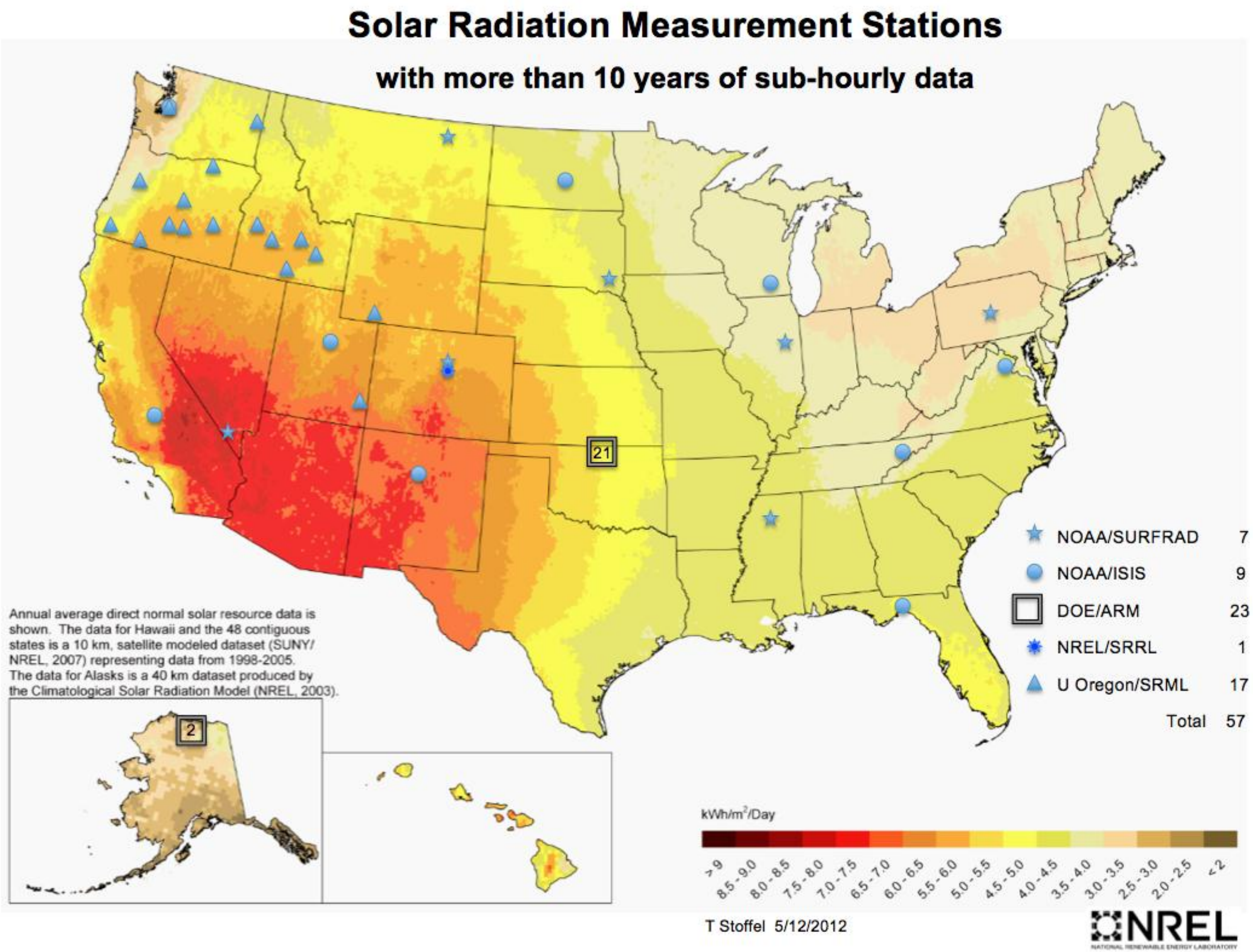
Typical photodiode detector (left) and spectral response of LI-COR pyranometer (right).

www.licor.com

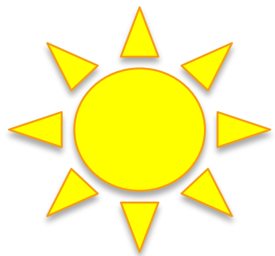
eko-eu.com

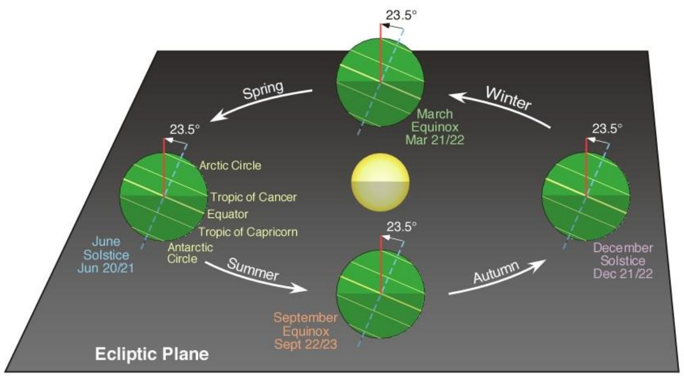
www.apogeeinstruments.com

Solar Measurement Stations



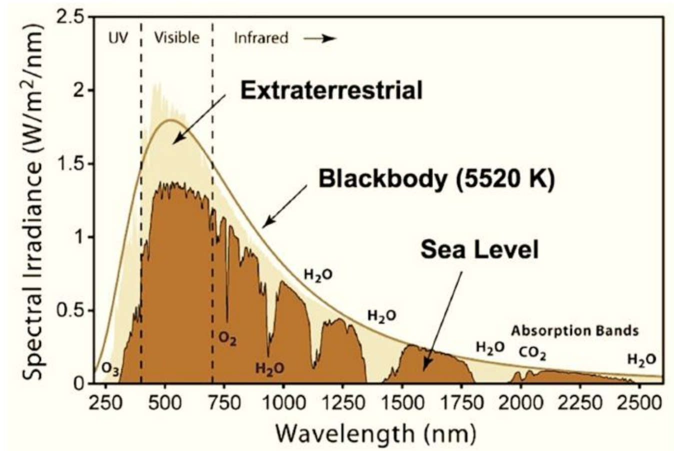
Modeling Solar Radiation



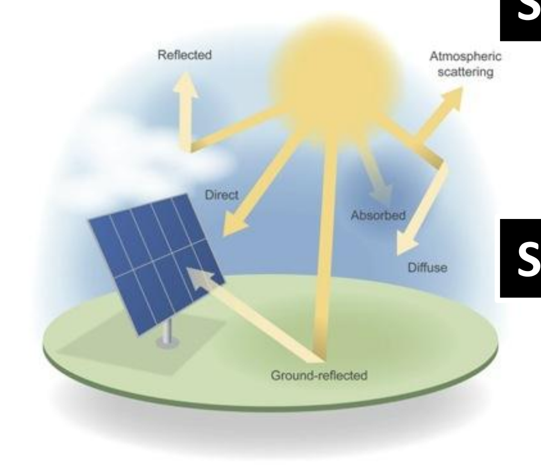


Step 1. Top of Atmosphere

Total Solar Irradiance (TSI): 1366 ± 7 W/m2



Sun-earth distance: ~3% less TSI in summer



Step 2. Through a Clear-Sky Atmosphere

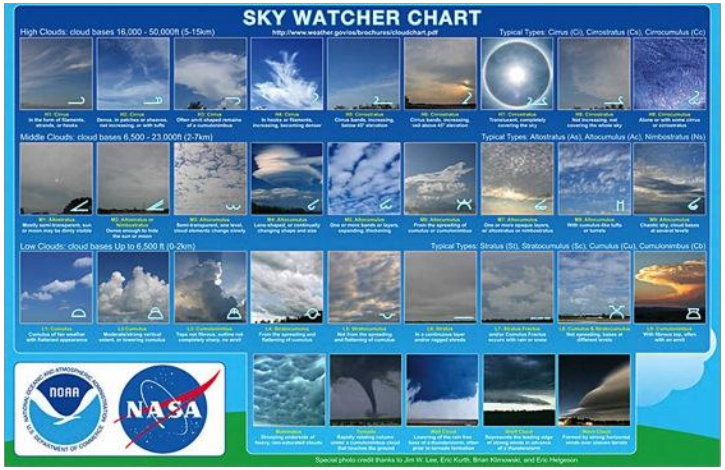
Absorbing & Scattering:

Gases, water vapor, **aerosols**

Step 3. Effects of Clouds

- Empirical Relationships – Cloud Index
- Physical Properties – Radiative Transfer

Ground-Based Models for Point Data



1930's to 1990's Human Observers

- Amount (tenths)
  - Total
  - Opaque
- Types
- Layers

National Solar Radiation Database (NSRDB)

METSTAT Model Evaluation:*

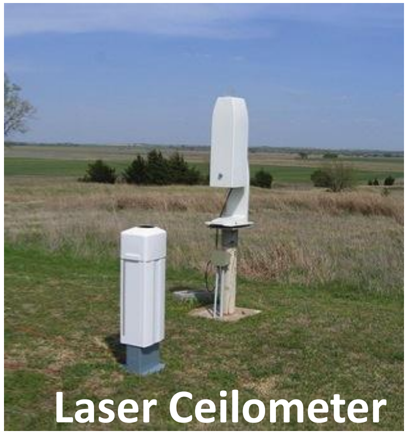
31 stations

1999-2000

	GHI		DNI	
	MBE	RMSE	MBE	RMSE
Hourly (W/m^2)	±50	100	-100 to +150	200
Monthly Mean Daily Total	-13% to +15%	2 to 22%	-32% to +16%	7% to 36%

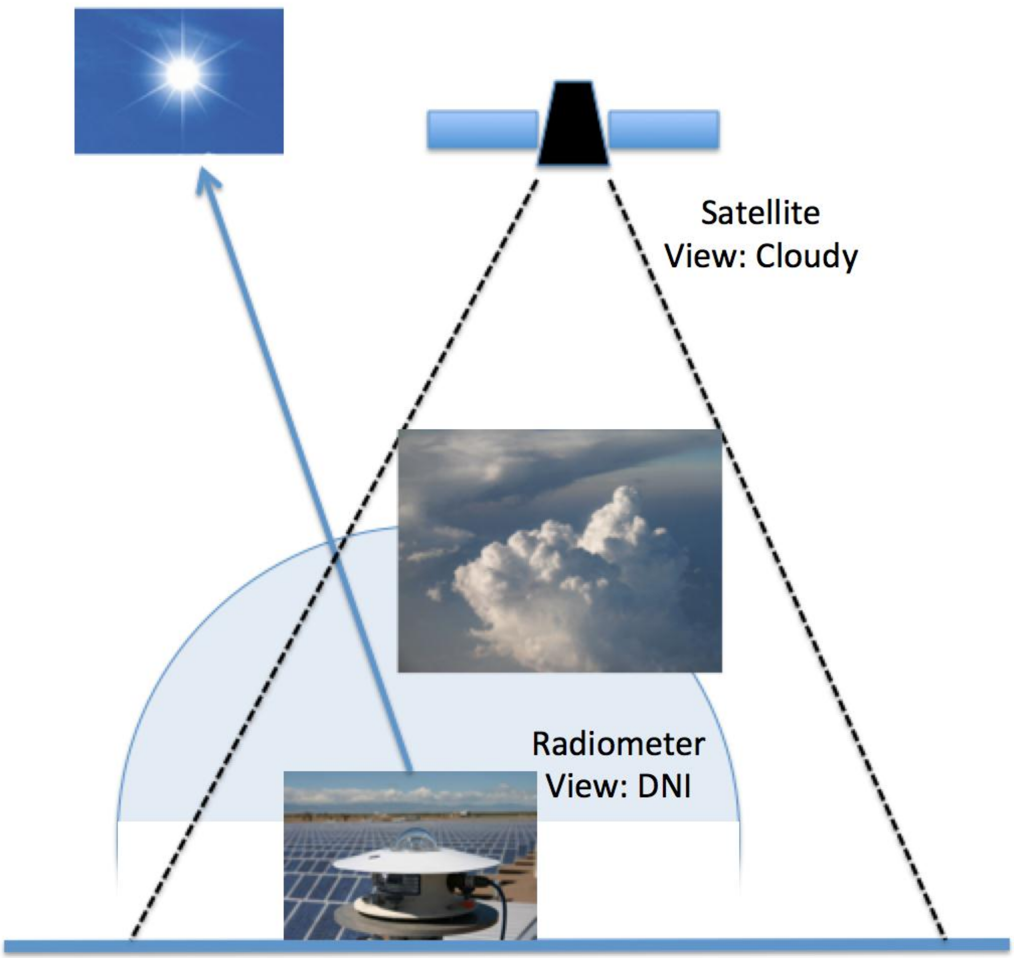
1990's - Present Automated Surface Observing System (ASOS)

- Amount (oktas)
- Total < 12,000 ft

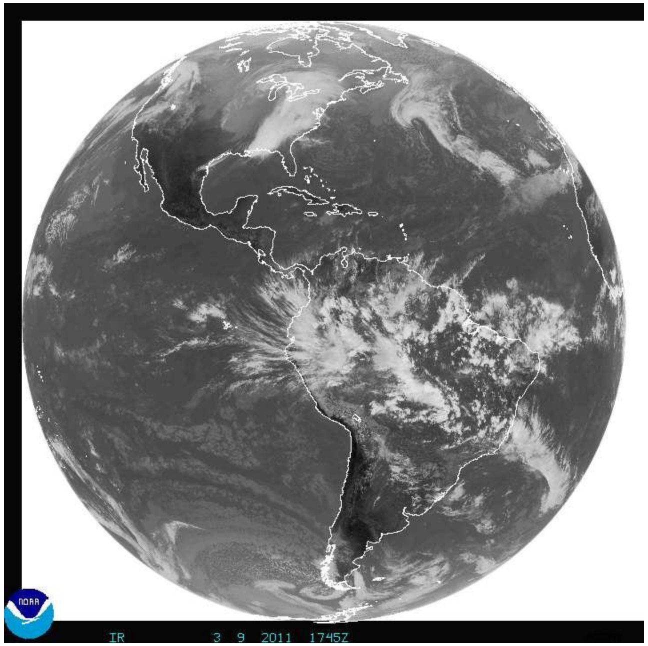


*Myers, D., Wilcox, S.; Marion, W.; George, R.; Anderberg, M. (2005). "Broadband Model Performance for an Updated National Solar Radiation Database in the United States of America." Proc. Solar World Congress, International Solar Energy Society, 2005.

Satellite-Based Models for Gridded Data



GOES E/W pixel = 1 km @ 30-minute snapshots



Geostationary Operational Environmental Satellite (GOES)

Estimates of GHI and DNI are comparable to ground-based Meteorological models (Myers et al. 2005)

National Solar Radiation Database (NSRDB)

Solar Resource Data Evolution

1952-1975 SOLMET [(1)]
ERDA/SERI, NOAA, 1979

TMY

1961-1990 NSRDB [(2)]
DOE/NREL, NOAA, 1994

TMY2

1991-2005 NSRDB [(3)]
DOE/NREL, NOAA, 2007

TMY3

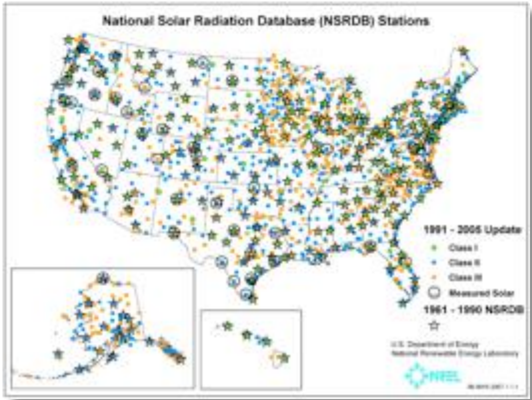
2005-2010 NSRDB [(4)]
DOE/NREL, NOAA, 2012

(1)
38 ***Measurement*** Stations
1977-80

(2)
239 ***Modeled*** Locations
1961-1990

(3,4)
10 km x 10 km
Modeled
1998-2010

(3,4)
1,454 ***Modeled*** Locations
1991-2010



NSRDB Classifications and Uncertainty Levels*

To increase the number of sites for 1961-1990 from 239 to 1,454 for 1991-2010

Based on model *input data* availability:

- **Class I –** All hours 1991-2010 (242 sites)
- **Class II –** Significant periods of interpolated, filled or otherwise lower-quality** input data (618 sites)
- **Class III –** At least 3 years of continuous input data (594 sites)

- Wilcox, S. (2012) ***National Solar Radiation Database Update 1991-2010: User's Manual***, NREL/TP-5500-54824, 479pp. www.nrel.gov/publications

** Generally a result of ASOS – automated – cloud cover data.

NSRDB 1991-2010 Uncertainty Estimates

*Hourly uncertainties for modeled data range from 8% under optimal conditions to more than 25% for less-than-optimal input data.**

Meteorological (METSTAT) and Satellite-based (SUNY) Model Uncertainties - Hourly

Model	**Uncertainty Source**	**GHI or DHI**	**DNI**
METSTAT	Optimum Basis	10	16
	Data Filling	8	8
	Cloud derivation	4	4
	ASOS okta	22	22
	RSS UNC	**25.8**	**28.6**
SUNY	Optimum Basis	8	15
	Time shifting	2	2
	Snow cover	5	5
	RSS UNC	**9.6**	**15.9**

Conservative Estimates

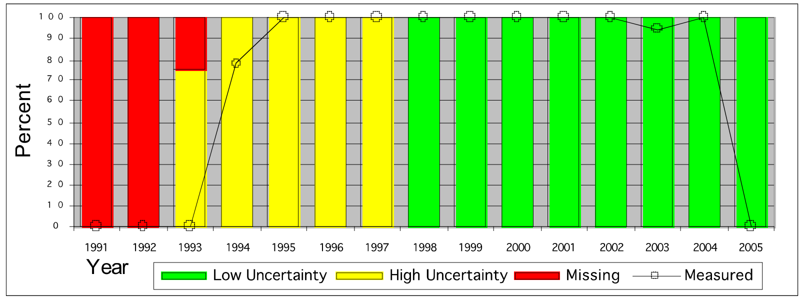
$$\text{RSS UNC} = (U_{opt}{}^2 + U_{add1}{}^2 + U_{add2}{}^2 \ldots)^{1/2}\ (\pm\%)$$

* Wilcox, S. (2012) National Solar Radiation Database Update 1991-2010: User's Manual, NREL/TP-5500-54824, 479pp. www.nrel.gov/publications

NSRDB Uncertainties

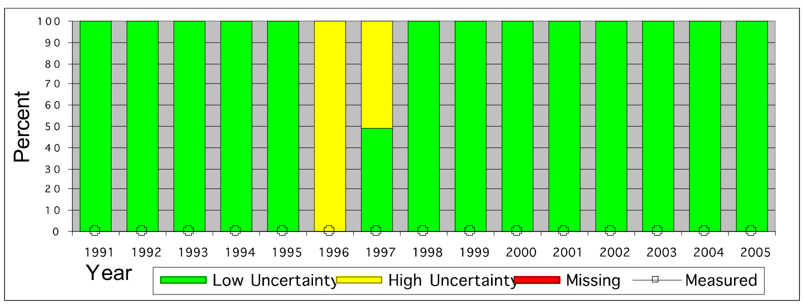
Data Quality Summaries are Available for All Sites

724776	MOAB/CANYONLANDS [UO], UT
Class III (with some measured)	
Solar Coordinates	
Latitude: 38.58˚	
Longitude: -109.54˚	
Elevation: 1000 m	
Meteorological Coordinates	
Latitude: 38.75˚	
Longitude: -109.75˚	
Elevation: 1388 m	
Time Zone: -7	

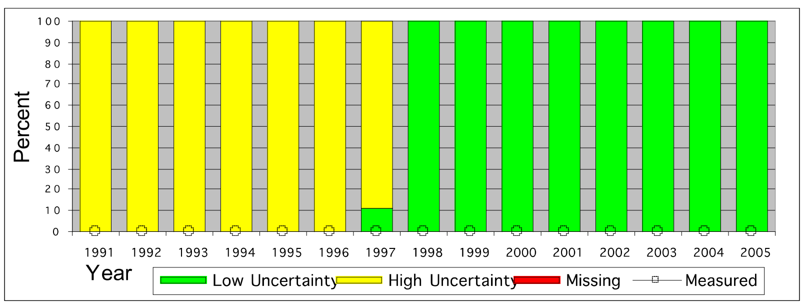


Green: Proportion of "low" uncertainty data
Yellow: Proportion of "high" uncertainty data
Red: Proportion of missing data
Black Line: Percentage of measured data

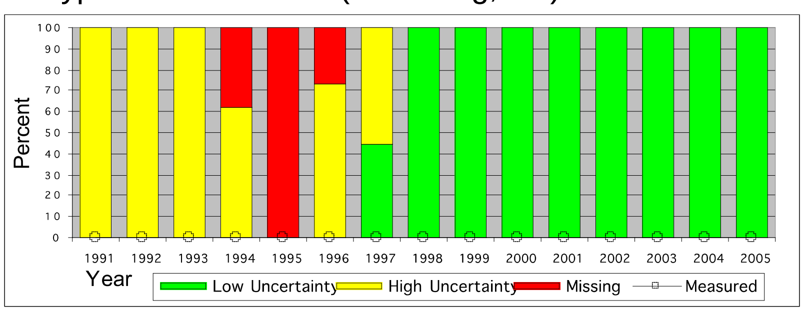
Typical Class I Site (Tucson, AZ)



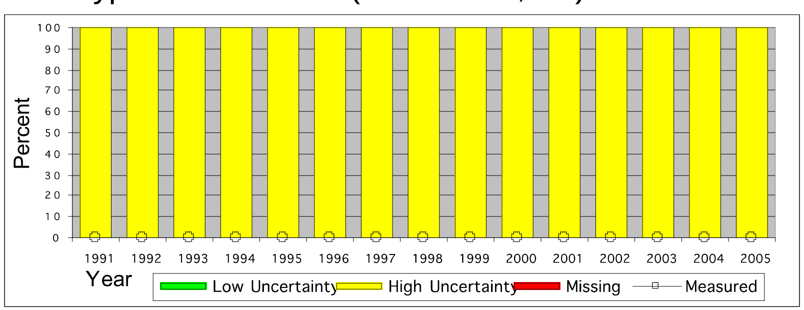
Typical Class II Site (Stillwater, OK)



Typical Class III Site (Sandburg, CA)



Typical Alaska Site (Sand Point, AK)



Typical Meteorological Year (TMY3) Data

2005 Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec

2004 Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec

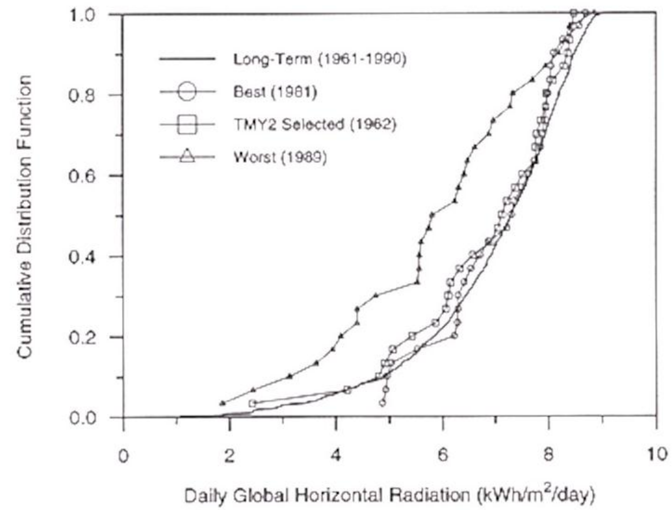
2003 Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec

1991 Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec

TMY3 Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec

TMM Year 97 | 06 | 94 | 01 | 05 | 99 | 91 | 05 | 93 | 93 | 95 | 00

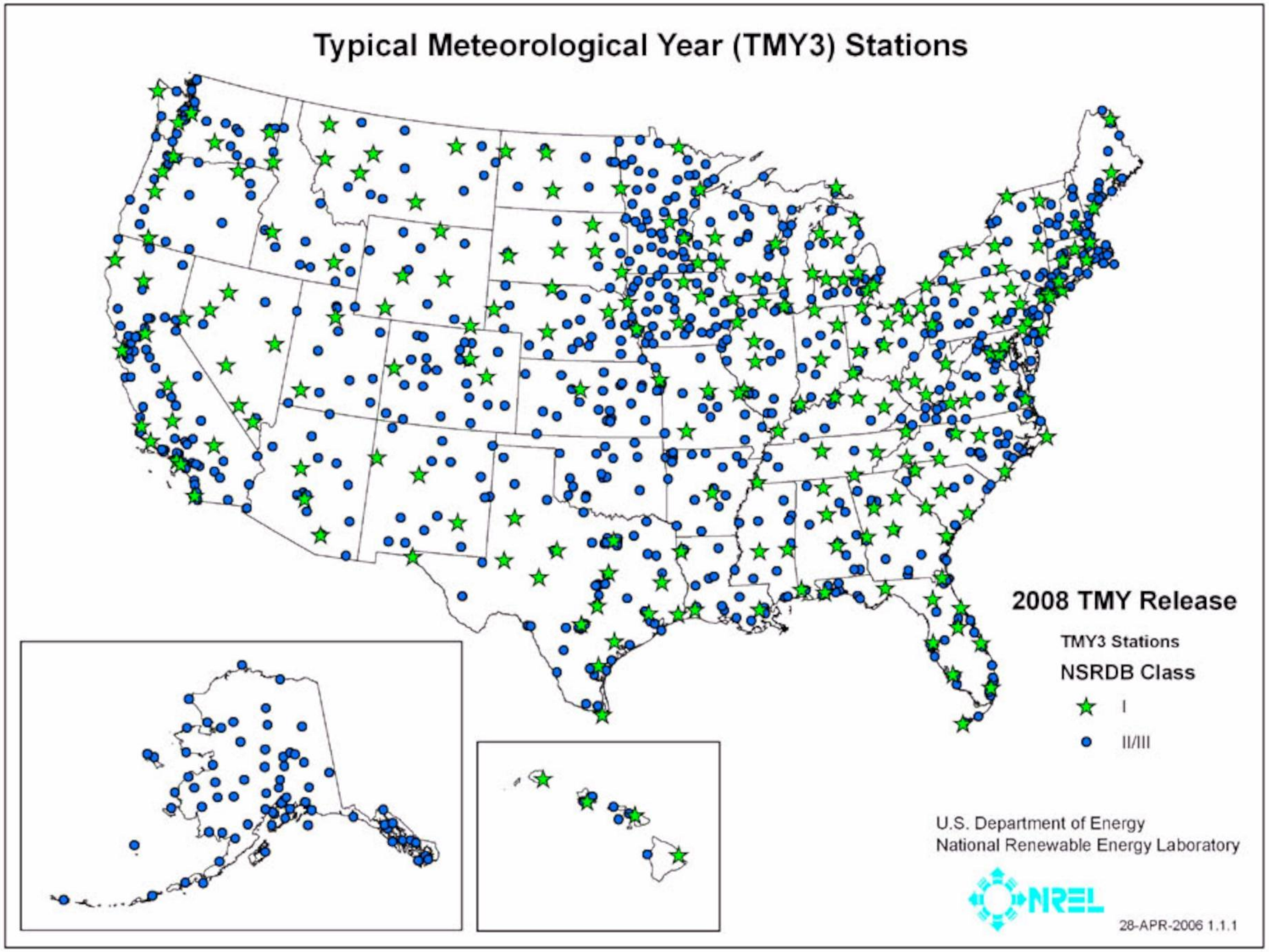
Typical Meteorological Months (TMM) of data are selected from the long term record using comparisons of Cumulative Distribution Functions (CDF) with Finkelstein-Schafer (FS) statistics of Weighted Scores* (see table).



Index	NSRDB TMY
Max Dry Bulb Temp	1/20
Min Dry Bulb Temp	1/20
Mean Dry Bulb Temp	2/20
Max Dew Point Temp	1/20
Min Dew Point Temp	1/20
Mean Dew Point Temp	2/20
Max Wind Velocity	1/20
Mean Wind Velocity	1/20
Global Radiation	5/20
Direct Radiation	5/20

*Hall, et al. (1978) Generation of Typical Meteorological Years for 26 SOLMET Stations, SAND78-1601

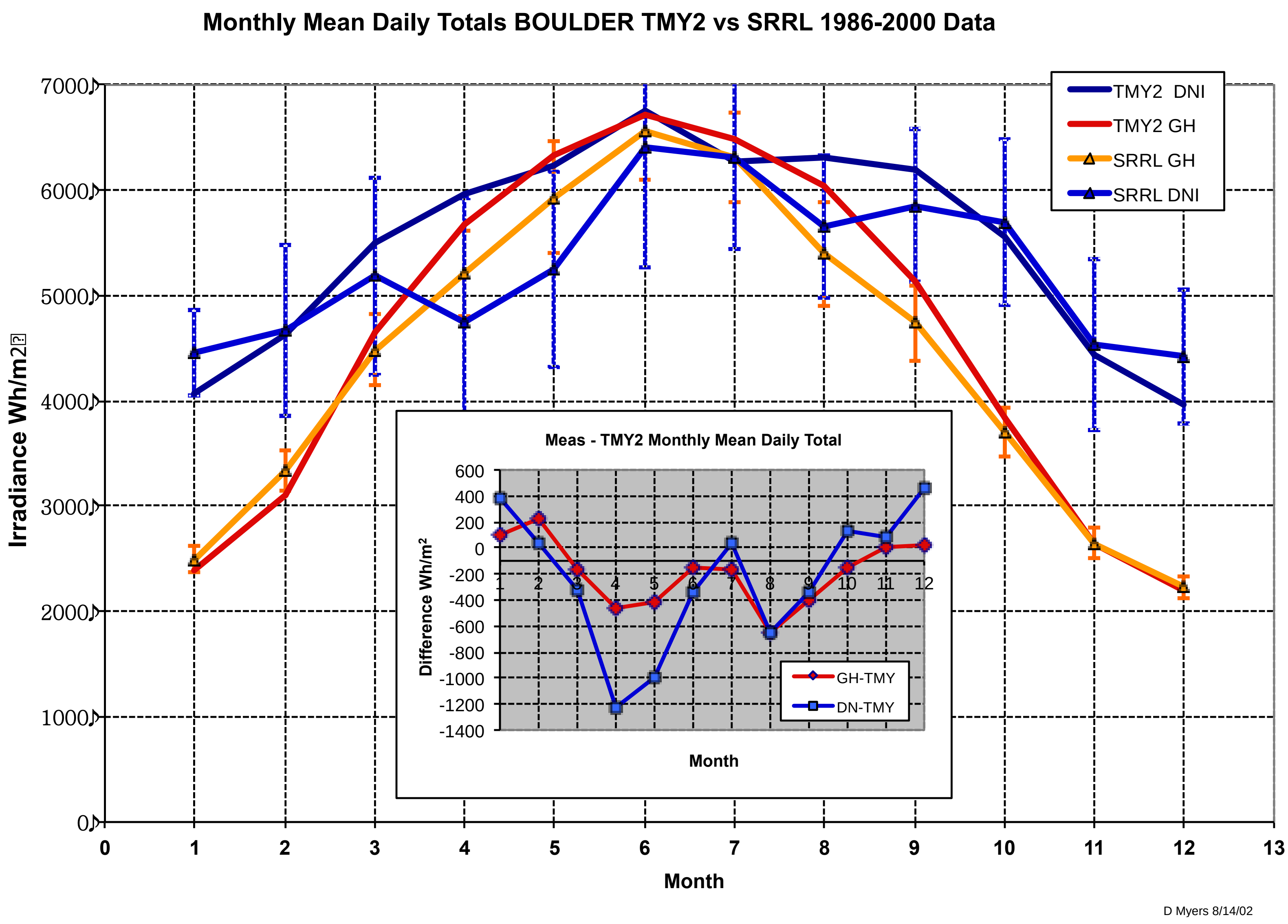
TMY3 (1991-2005)



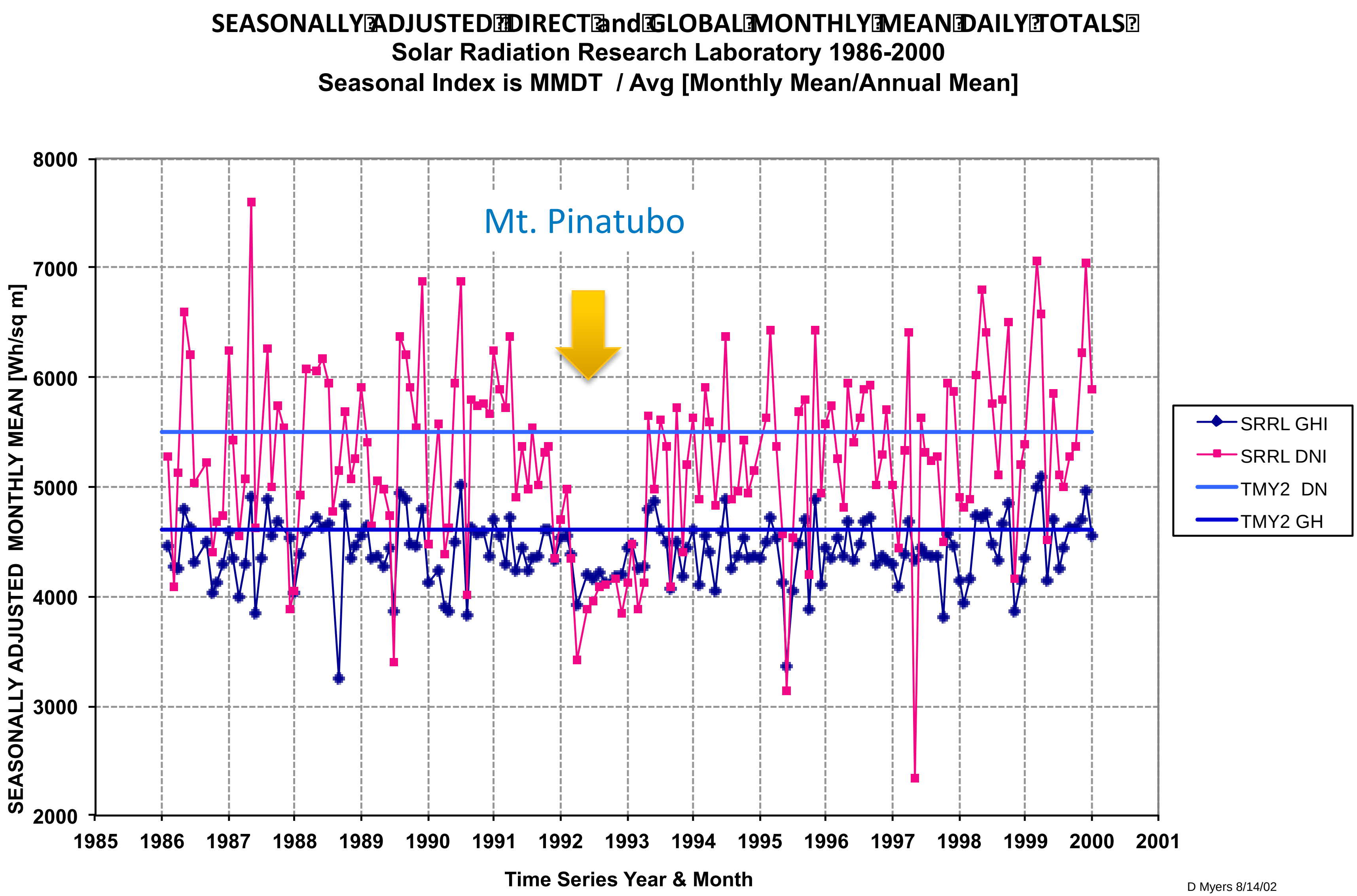
TMY3: 1,020 locations

38 with measurements at times during 1991-2005

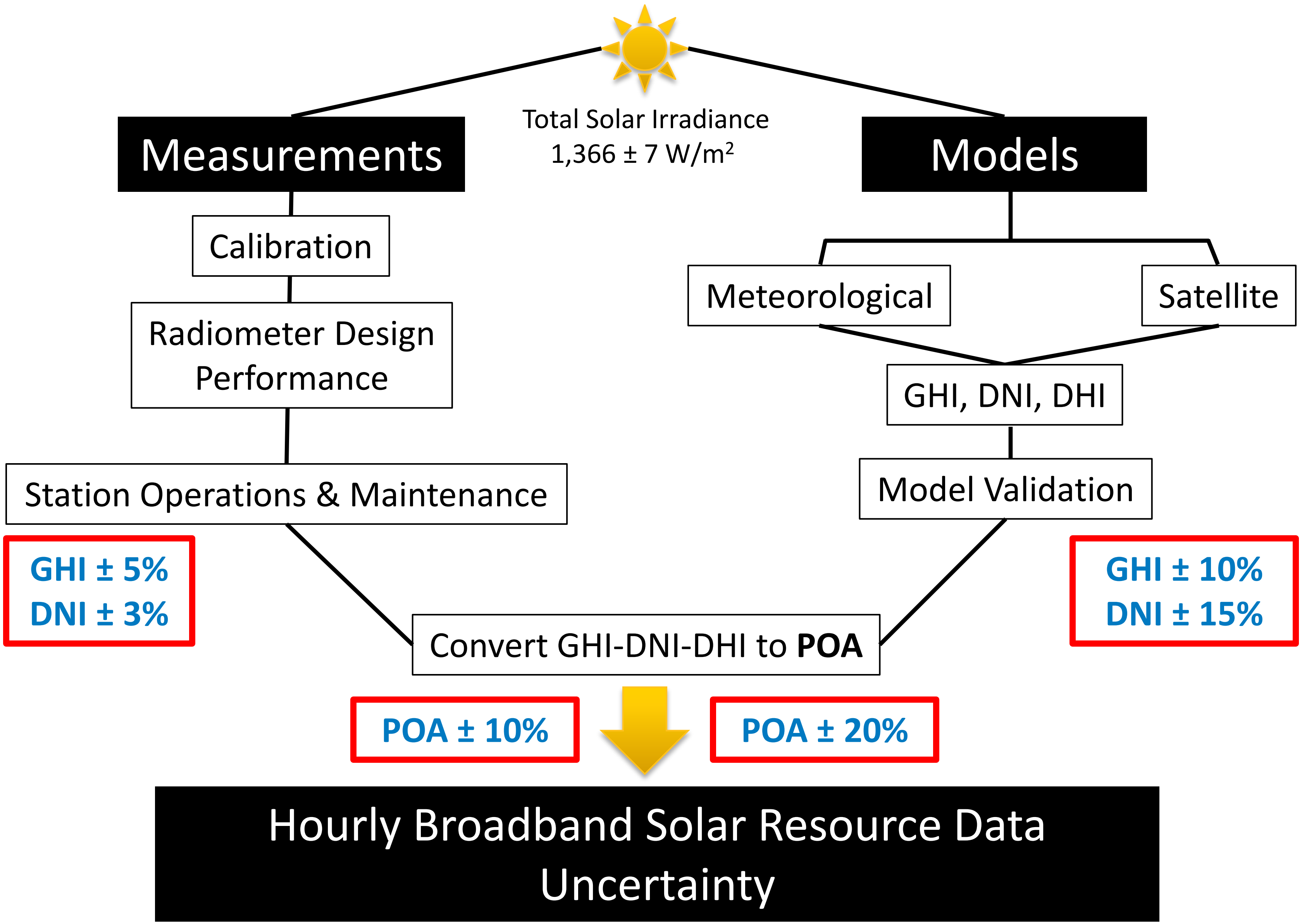
How *Typical* for Golden, CO?



How *Typical* for Golden, CO?



Getting to PV Performance Model Input Uncertainty



Summary

- TMY data are intended for **performance comparisons** rather than system design
- TMY data products are based on **NSRDB**
- NSRDB 1991-2010 = Meteorological Model (1,454 sites) + Satellite Model (10 km x 10 km)
- TMY3 data available for 1,020 sites
  38 have partial solar measurements
- Uncertainty (U_{95}) of GHI & DNI is site-dependent
  See NSRDB Data QA Tables
- DNI $U_{95} \cong 2 \times$ GHI U_{95}
- POA $U_{95} >$ U_{95} of DNI, GHI, DHI, and surface albedo
- Visit the Solar Prospector for more information
  maps.nrel.gov/prospector

Solar Resources: References

Concentrating Solar Power: Best Practices Handbook for the Collection and Use of Solar Resource Data
http://www.nrel.gov/docs/fy10osti/47465.pdf (PDF 7.5 MB)

Evaluation of Radiometers in Full-Time Use at the National Renewable Energy Laboratory Solar Radiation Research Laboratory
http://www.nrel.gov/docs/fy09osti/44627.pdf (PDF 1.4 MB)

World Meteorological Organization's Commission for Instruments and Methods of Observation (CIMO) Guide
http://www.wmo.int/pages/prog/www/IMOP/CIMO-Guide.html

U.S. Department of Energy Workshop Report: Solar Resources and Forecasting
http://www.nrel.gov/docs/fy12osti/55432.pdf (PDF 5.0 MB)

Baseline Surface Radiation Network (BSRN). Operations Manual Version 2.1
WCRP-121, WMO/TD-No. 1274 [McArthur L.J.B. 2005]
http://www.bsrn.awi.de/en/other/publications/

Guide to the Expression of Uncertainty in Measurement. Working Group 1 of the Joint Committee for Guides in Metrology. JCGM/WG 1 (2008). *Available on line at* http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

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Hall, I., Prairie, R., Anderson, H., and Boes, E. (1978) Generation of Typical Meteorological Years for 26 SOLMET Stations, SAND78-1601, Sandia National Laboratories, Albuquerque, NM 87185.

Wilcox, S. M. (2012). National Solar Radiation Database 1991-2010 Update: User's Manual. 479 pp.; NREL Report No. TP-5500-54824*.

Wilcox, S.; Marion, W. (2008). Users Manual for TMY3 Data Sets (Revised). 58 pp.; NREL Report No. TP-581-43156*.

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Perez, R. and R. Stewart, 1986. Solar Irradiance Conversion Models. Solar Cells, 18, pp. 213-223.

Perez, R., R. Seals, P. Ineichen, R. Stewart, D. Menicucci, 1987. A New Simplified Version of the Perez Diffuse Irradiance Model for Tilted Surfaces. Description Performance Validation. Solar Energy, 39, pp. 221-232.

* Available from www.nrel.gov/publications

** Available from www.asrc.cestm.albany.edu/perez/directory/ResourceAssessment.html

Solar Resources: References

Solar and Infrared Radiation Measurements
A book by Frank Vignola, Joseph Michalsky, and Thomas Stoffel published by CRC Press as part of the Energy and the Environment Series (Abbas Ghassemi, Editor).
394 pages. ISBN 978-1-4398-5189-0 Catalog Number K12386
www.taylorandfrancisgroup.com

Solar Radiation, Practical Modeling for Renewable Energy Applications
A book by Daryl R. Myers published by CRC Press as part of the Energy and the Environment Series (Abbas Ghassemi, Editor). 182 pages.
ISBN 978-1-4665-0294-9 Catalog Number K14452
www.taylorandfrancisgroup.com

Backup Slides Follow…

How do we measure/model solar radiation?

Ground based instruments (radiometers, pyrheliometers, pyranometers)

Advantages: accurate, high temporal resolution.

Disadvantages: local coverage, regular maintenance and calibration.

Satellite based models (geostationary, polar orbiters)

Advantages: global coverage, reasonably long time series,

Disadvantages: spatial and temporal resolution, complicated retrieval process, accuracy depends on information content of satellite channels.

Numerical models (global, regional, mesoscale)

Advantages: global coverage, long time series (reanalysis data), increasing computing capability results in increasing resolution.

Disadvantages: level of accuracy especially in cloud formation and dissipation (initialization and model physics issues).

NOTE: Methods that combine all 3 will ultimately provide the best solutions.

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Present Assessment of Measurements[1]

Uncertainty Source	Thermopile pyranometer	Semiconductor pyranometer	Thermopile pyrheliometer	Semiconductor pyrheliometer
Calibration[a]	3%	5%	2%	3%
Zenith response[b]	2%	2%	0.5%	1%
Azimuth response	1%	1%	0%	0%
Spectral response	1%	5%	1.5%	8%
Tilt[c]	0.2%	0.2%	0%	0%
Nonlinearity	0.5%	1%	0.5%	1%
Temperature response	1%	1%	1%	1%
Aging per year	0.2%	0.5%	0.1%	0.5%
Total U = Sum	8.9%	15.7%	5.6%	14.5%
Total U = RSS	4.1%	8.0%	2.7%	8.9%

[a] Includes zenith angle response from 30° to 60°
[b] Includes zenith angle response from 0° to 30° and 60° to 90°
[c] This uncertainty is set to zero for un-tilted radiometers

Assumes Perfect Installation, Operations, & Maintenance

Clear Sky
~5 sec Data
Thermopile Radiometers:

DNI ± 2.7%
GHI ± 4.1%

[1] Reda, I., "Method to Calculate Uncertainties in Measuring Shortwave Solar Irradiance Using Thermopile and Semiconductor Solar Radiometers." NREL/TP-3B10-52194, July 2011.

Broadband Outdoor Radiometer Comparisons (BORCAL)

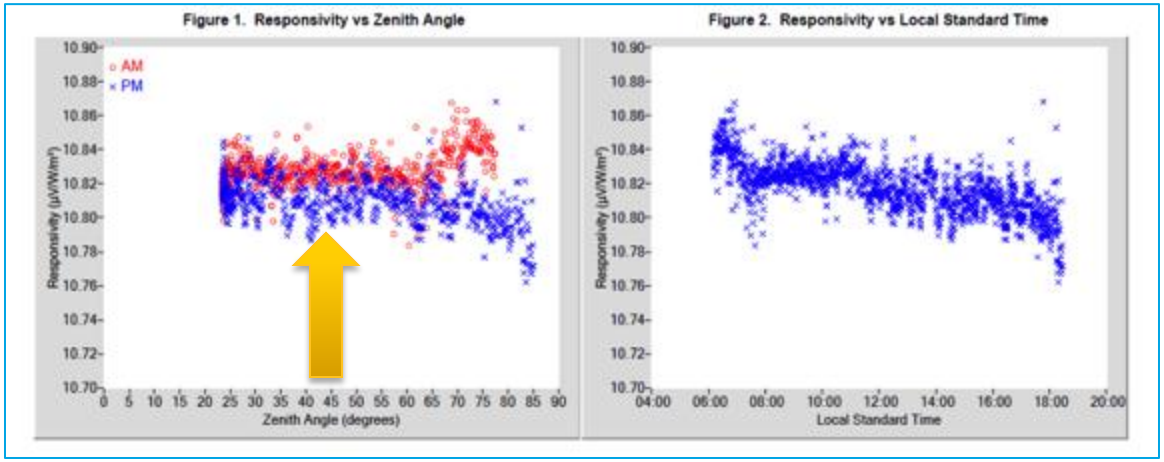
Manufacturer Provides a single Calibration Factor ~45º SZA

Calibration Factors Vary with solar position (time of day)…

No two radiometers are alike…

DNI - Kipp & Zonen CH1 Pyrheliometer

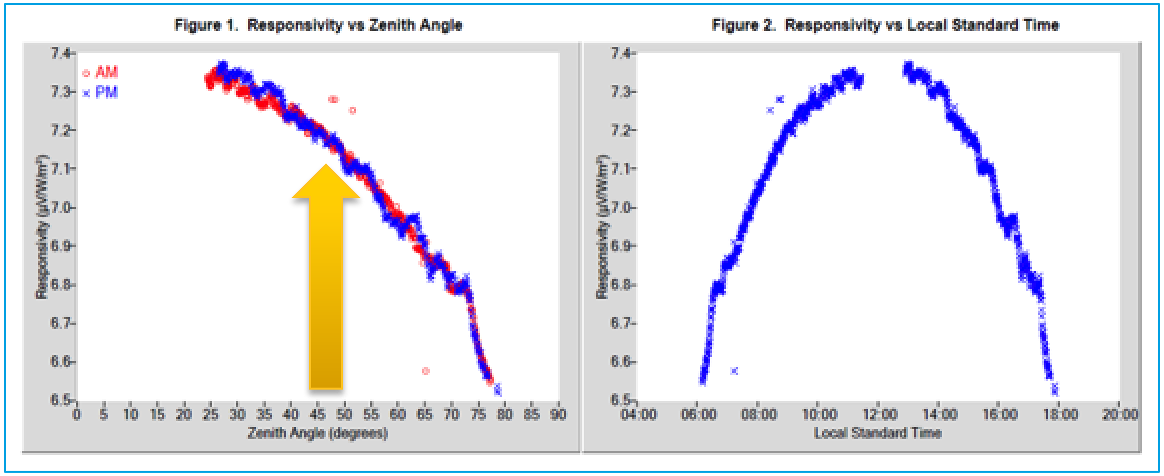
Calibration Factor



Solar Zenith Angle Standard Time

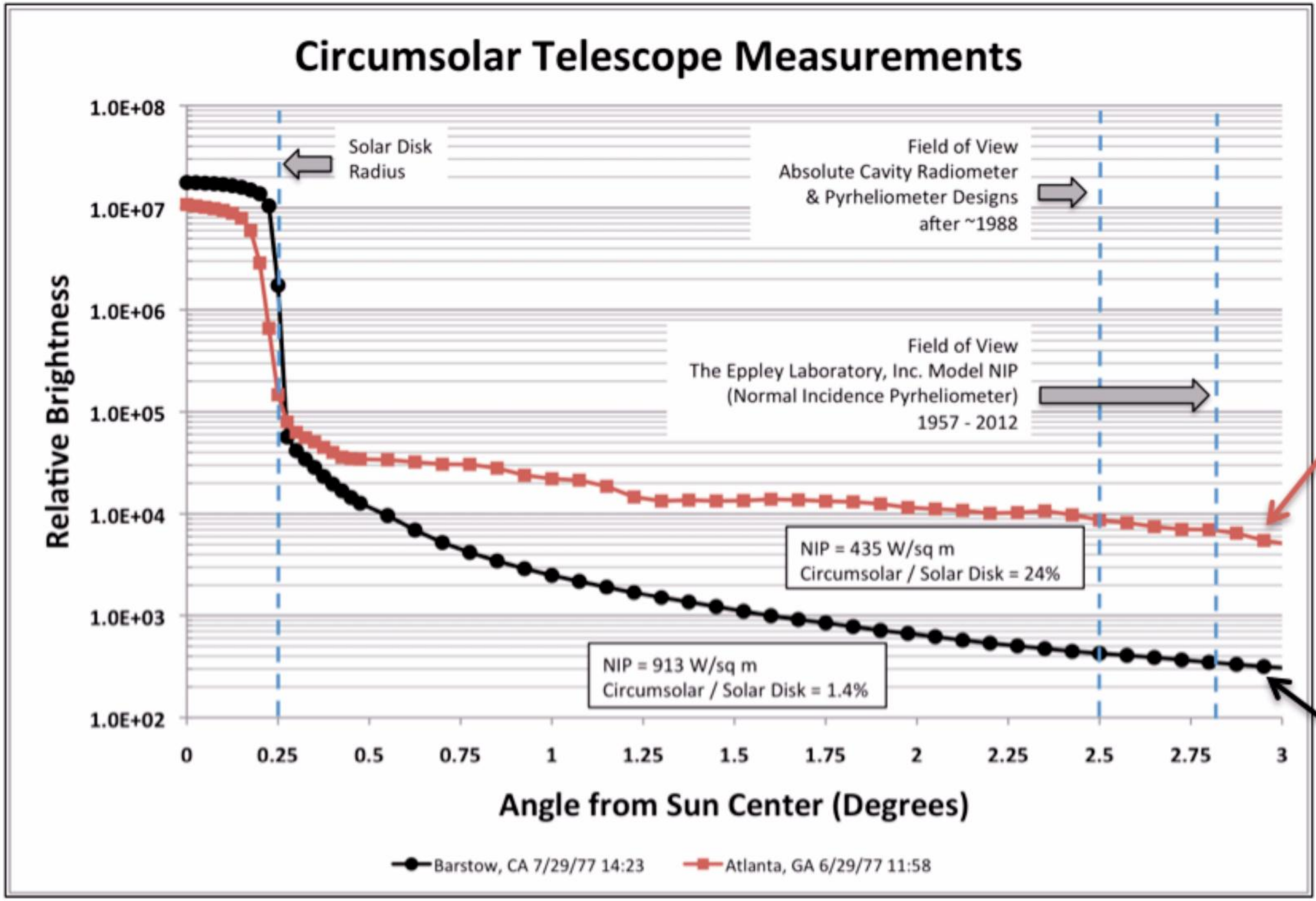
POA, GHI, DHI - Eppley PSP Pyranometer

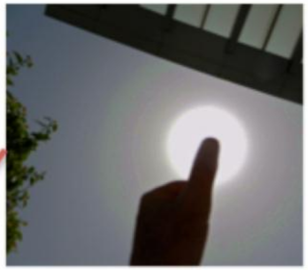
Calibration Factor



Solar Zenith Angle Standard Time

Circumsolar Radiation

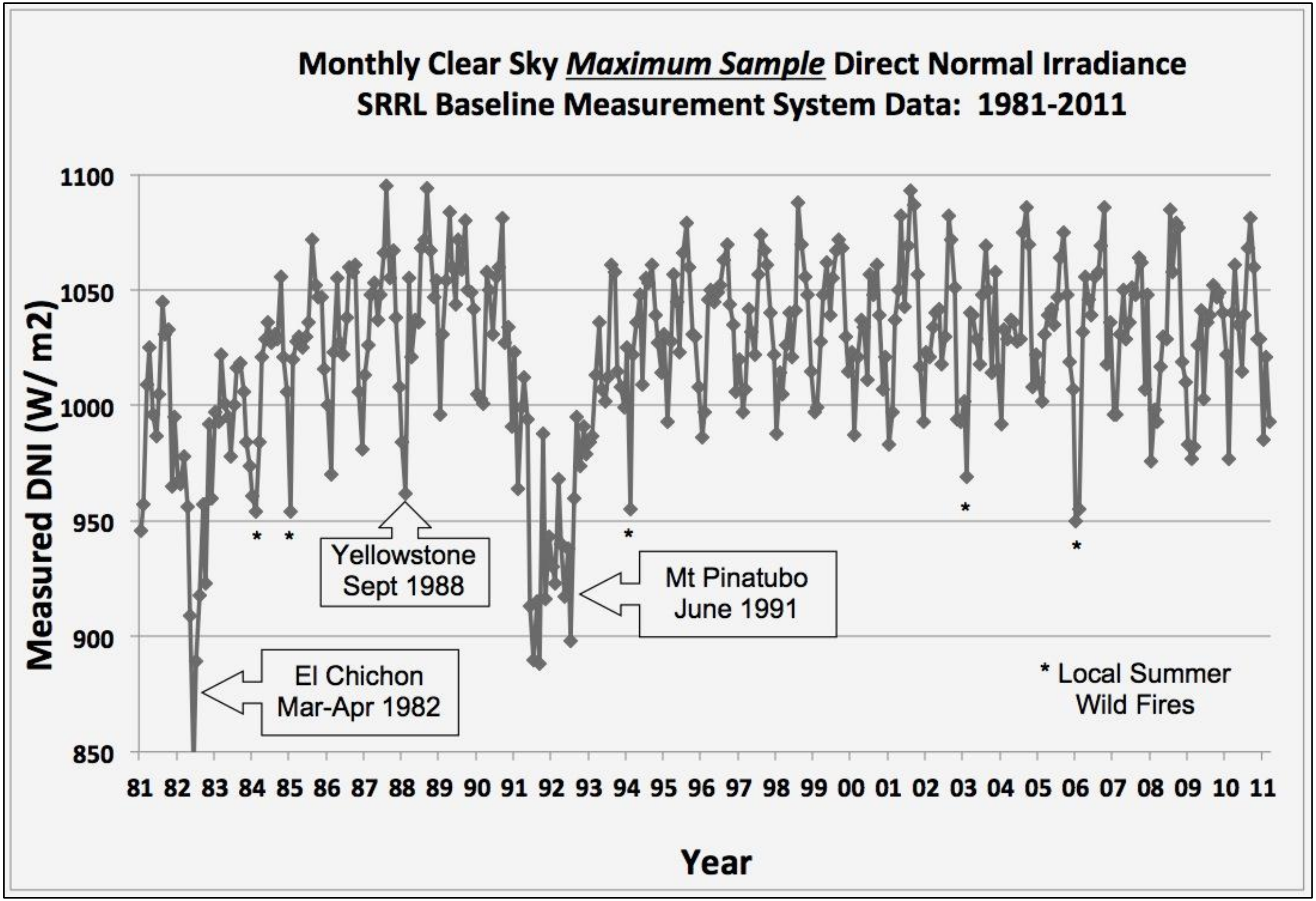




High DHI/GHI

Low DHI/GHI

Accurate and Long-Term Measurements



What impacts surface radiation

- **First order:**
- **(a) Clouds (Ice and water droplets)**
  - –Scatter solar radiation
  - – Ice clouds are more forward scattering that water clouds.
  - –Smaller droplets scatter more.

- **(b) Aerosols (mineral dust, soot etc.)**
  - –Most impact in clear sky situations.
  - –Absorb and scatter solar radiation (depends on aerosol type)

- **Second order:**

(a)water vapor and ozone

Absorb solar radiation.

Elevation associated molecular scattering

(b)3-dimensional clouds effects

- **Cloud edge scattering with enhancement in surface radiation**

How do satellites model surface radiation?

- **Empirical Approach:**
  - Build model relating satellite observations and ground measurements of solar irradiance.
  - Use those models to obtain solar radiation at the surface from satellite observations of scene “brightness”.

- **Semi-Empirical Approach:**
  - Retrieve “cloud index” from visible radiance channel of satellite.
  - Use clear-sky radiative transfer models and scale by cloud index.

- **Physical Approach:**
  - Retrieve cloud properties and aerosol information from multi-channel observations from satellites.
  - Use the information in a radiative transfer model to compute surface irradiances.