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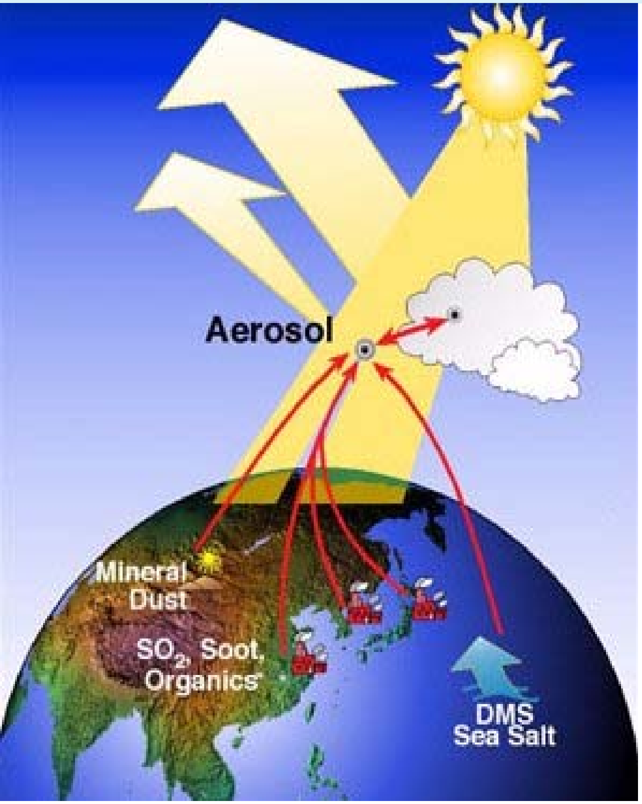
Solar Radiation Measurement

Bruce W Forgan,
WMO RAV Metrology Workshop, Melbourne, Novemberr 2011



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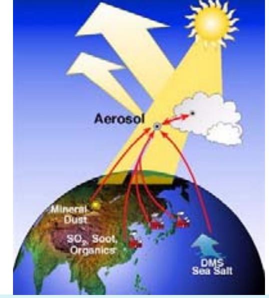
Why Do We Need Data on Solar Energy?



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

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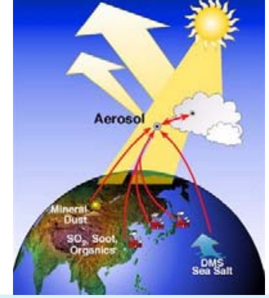
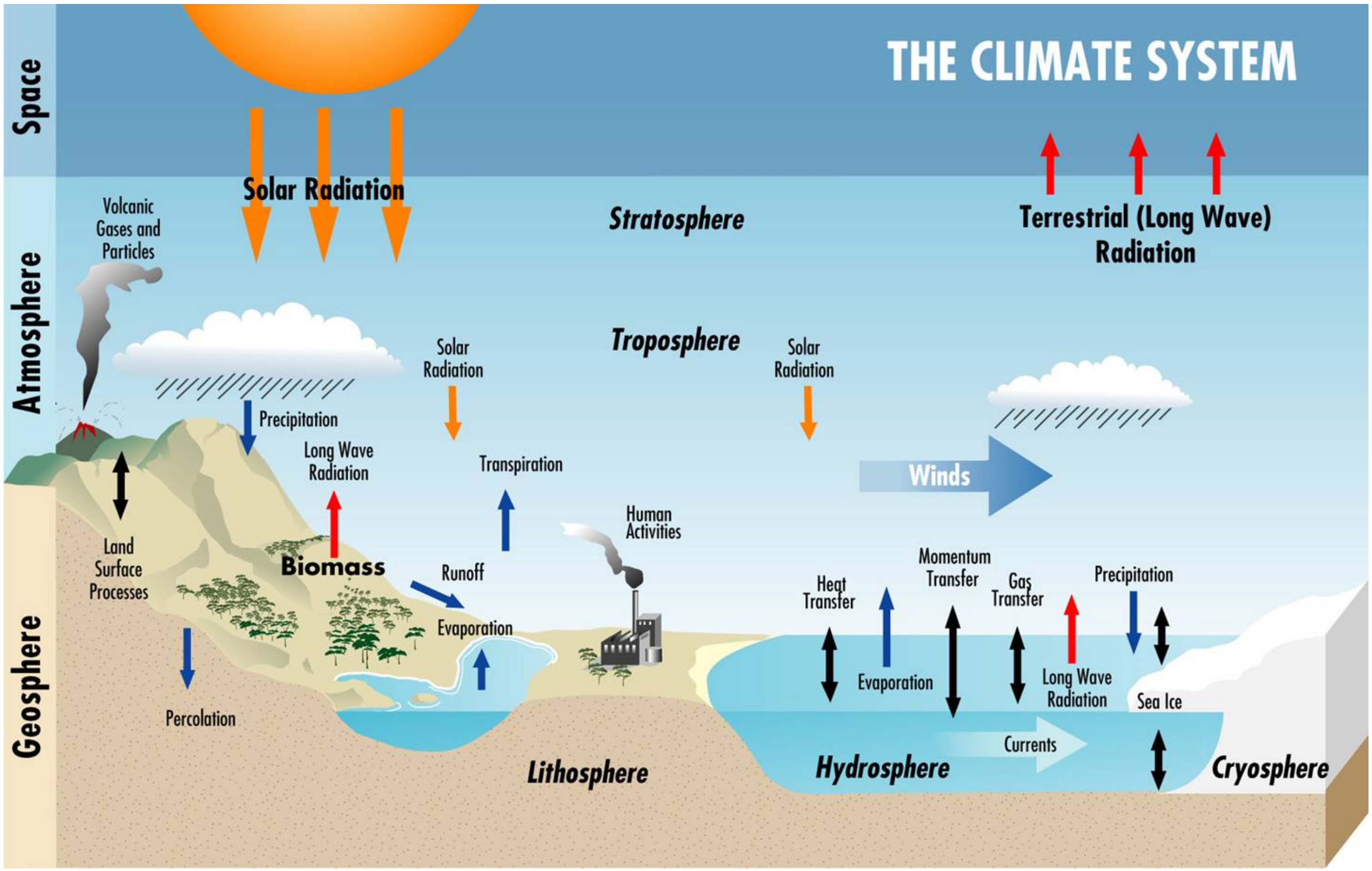
Global Climate System





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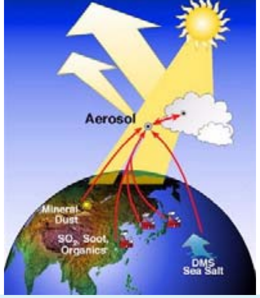
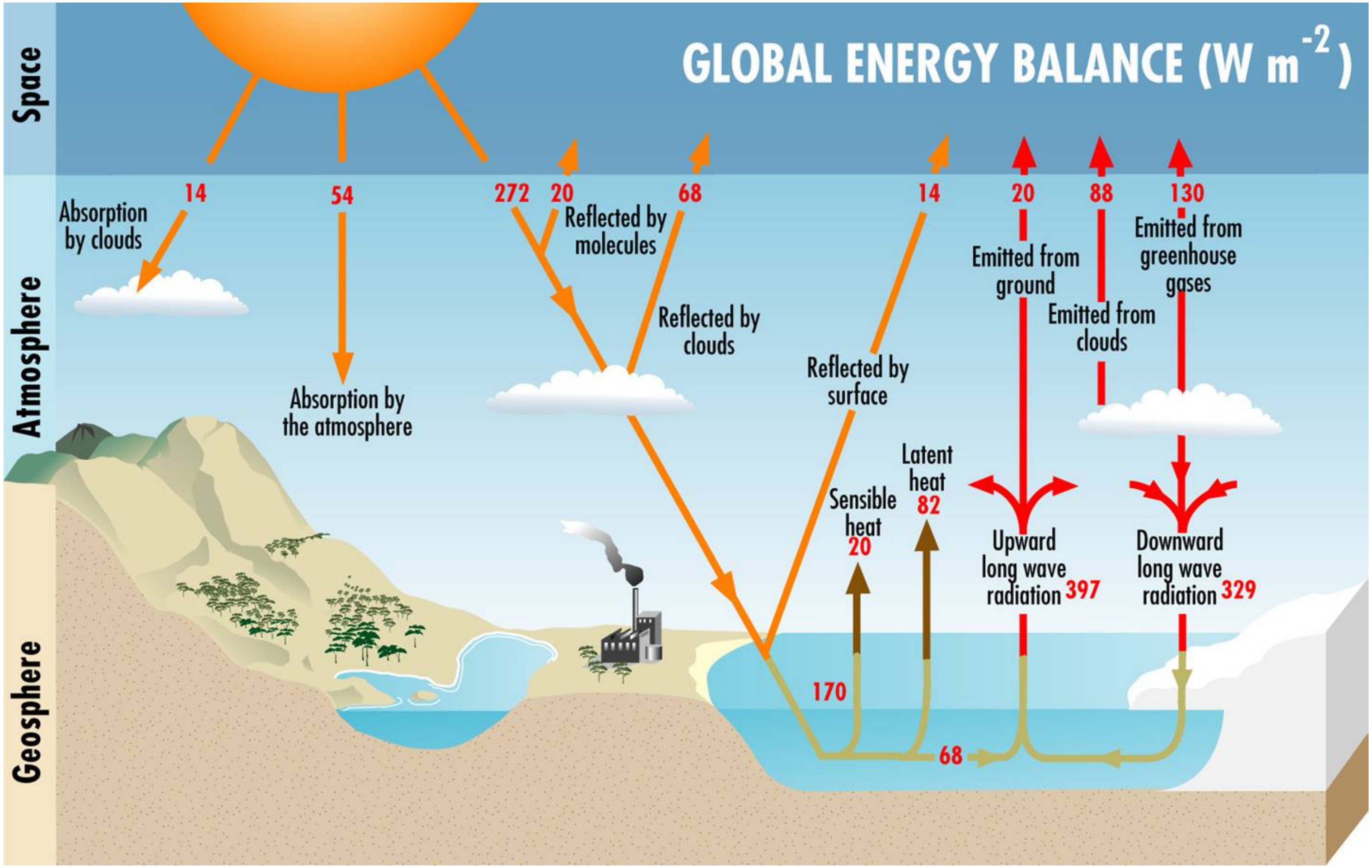
Climate Energy Balance





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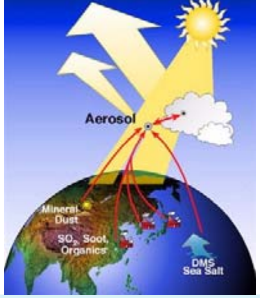
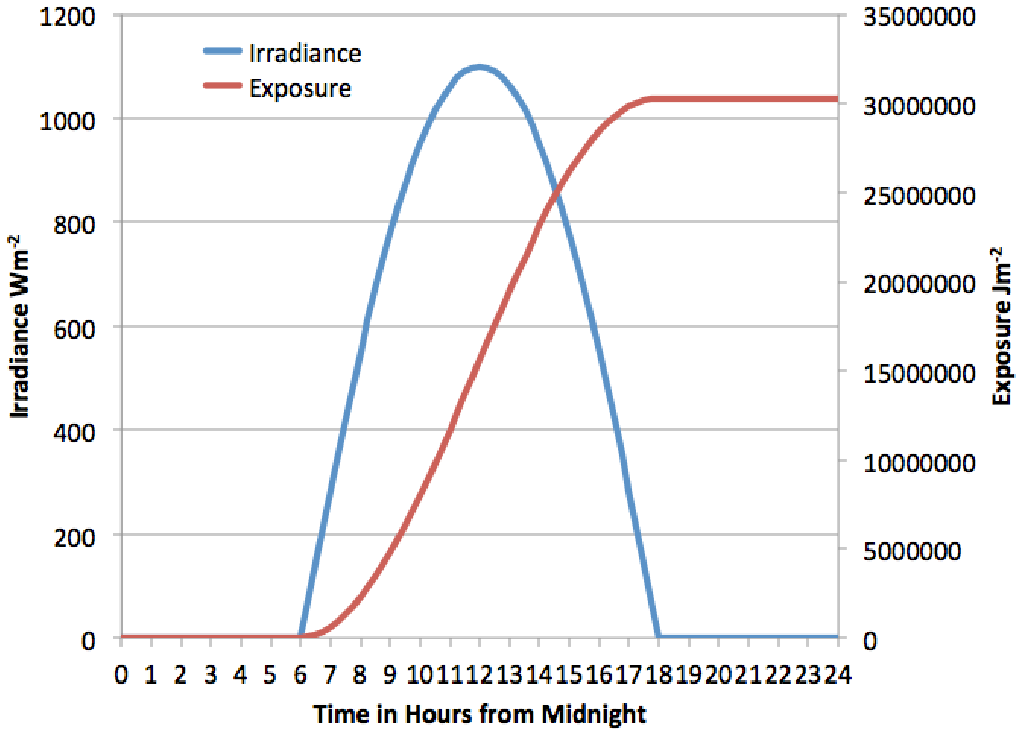
Solar Exposure and Irradiance Definitions




Exposure = H = Radiant energy per square metre (Jm^{-2})
Irradiance = E = Rate of change in Exposure per second ($Jm^{-2}s^{-1} = Wm^{-2}$)
Radiance = L = Rate of change in radiant energy emitted from a unit surface per steradian $Wm^{-2}sr^{-1}$



$$E = \frac{\partial H}{\partial t}$$

Daily Mean E = H/86400

350 Wm^{-2}

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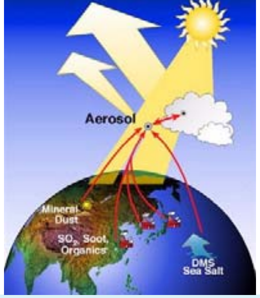
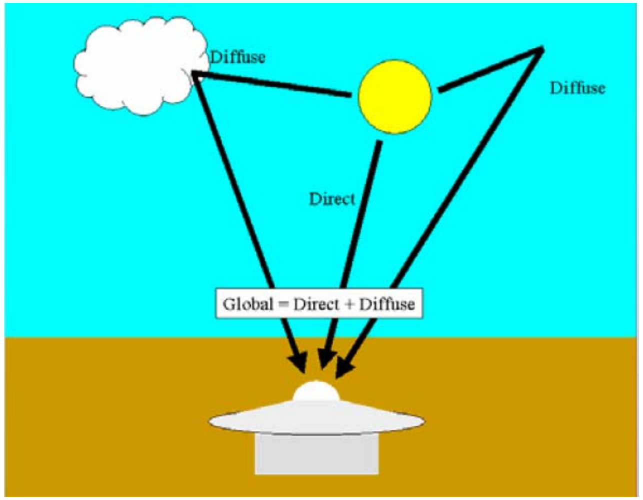
WMO
Solar Radiation Quantities




- Direct Exposure/Irradiance (+Sunshine)
- Diffuse Exposure/Irradiance
- Global Exposure/Irradiance



Radiance of the sky hemisphere

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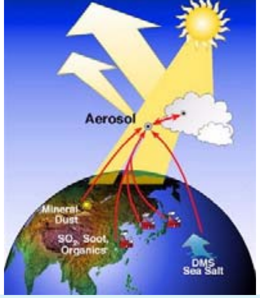
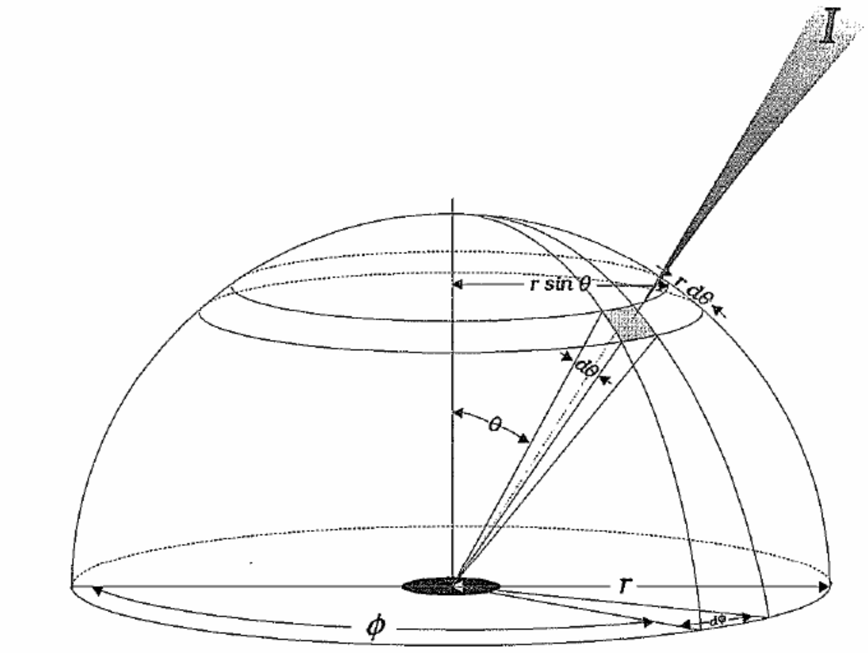
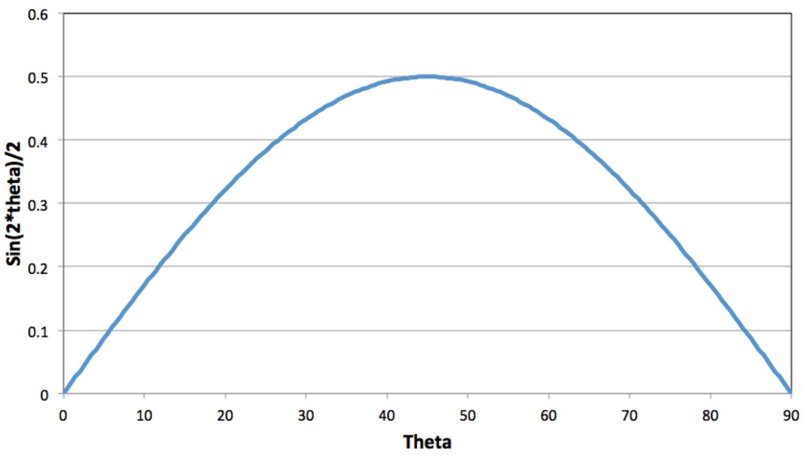
Irradiance on a Flat Unit Surface



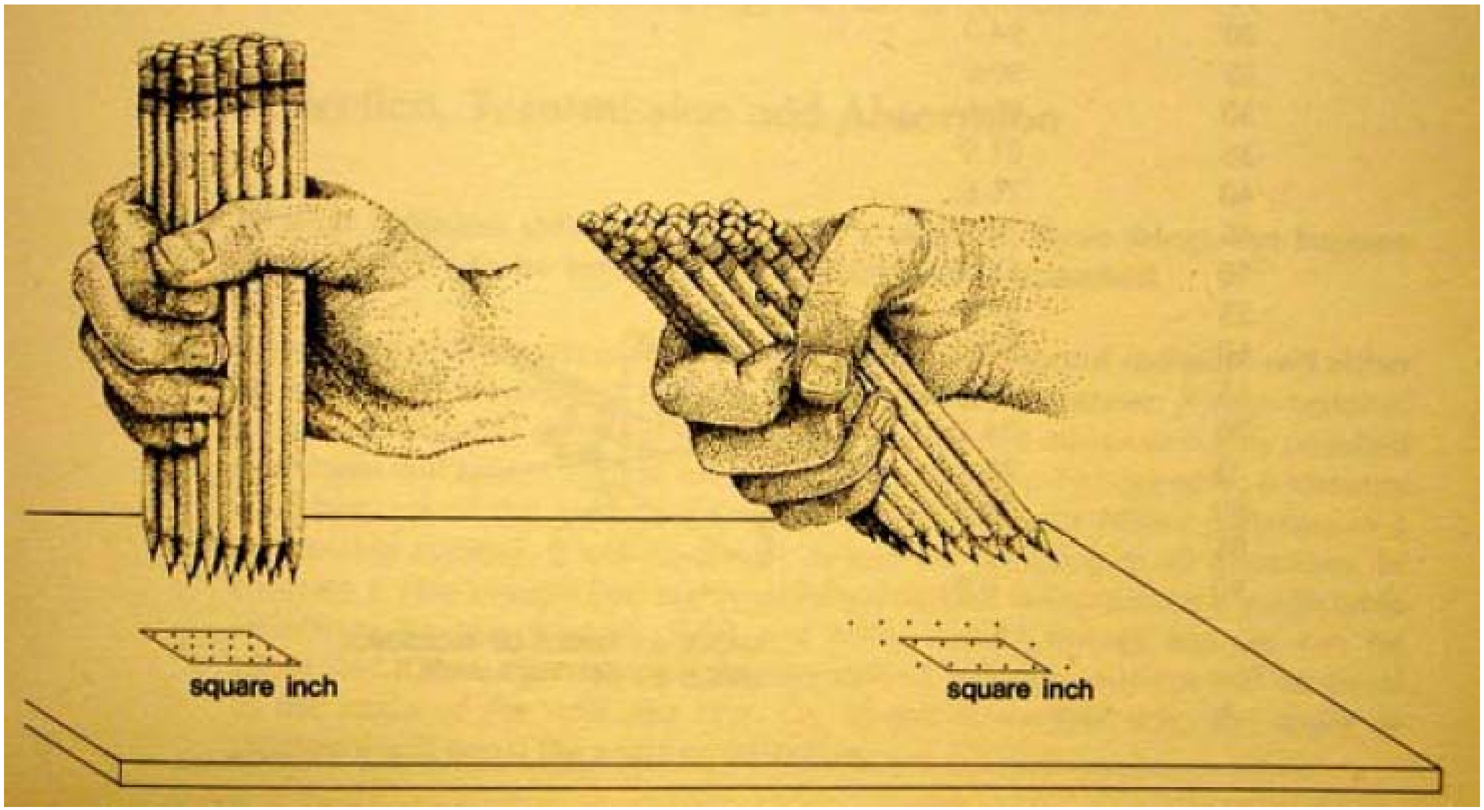


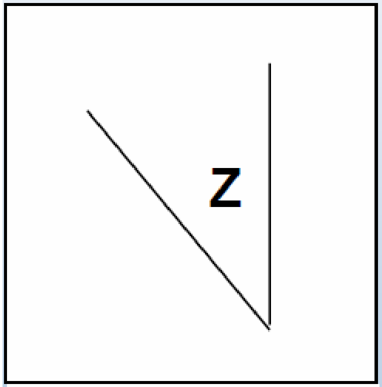
$$E = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} L(\vartheta,\varphi) \cos\vartheta \sin\vartheta \, d\vartheta \, d\varphi$$

$$E = \frac{1}{2} \int_0^{2\pi} \int_0^{\frac{\pi}{2}} L(\vartheta,\varphi) \sin 2\vartheta \, d\vartheta \, d\varphi$$



Angle of Incidence Cosine





$\cos(Z) = 8/18$

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

$Z = 63.6°$

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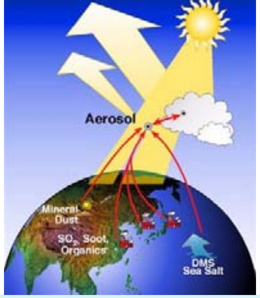
Factors Affecting Solar Radiation




- Location (space and time)
- Clouds (droplet and ice)
- Total precipitable water
- Aerosols and dust
- Surface Albedo
- Total Solar Irradiance (Solar Constant)
- Ozone
- Mixed gases (CO_2, N_2….)

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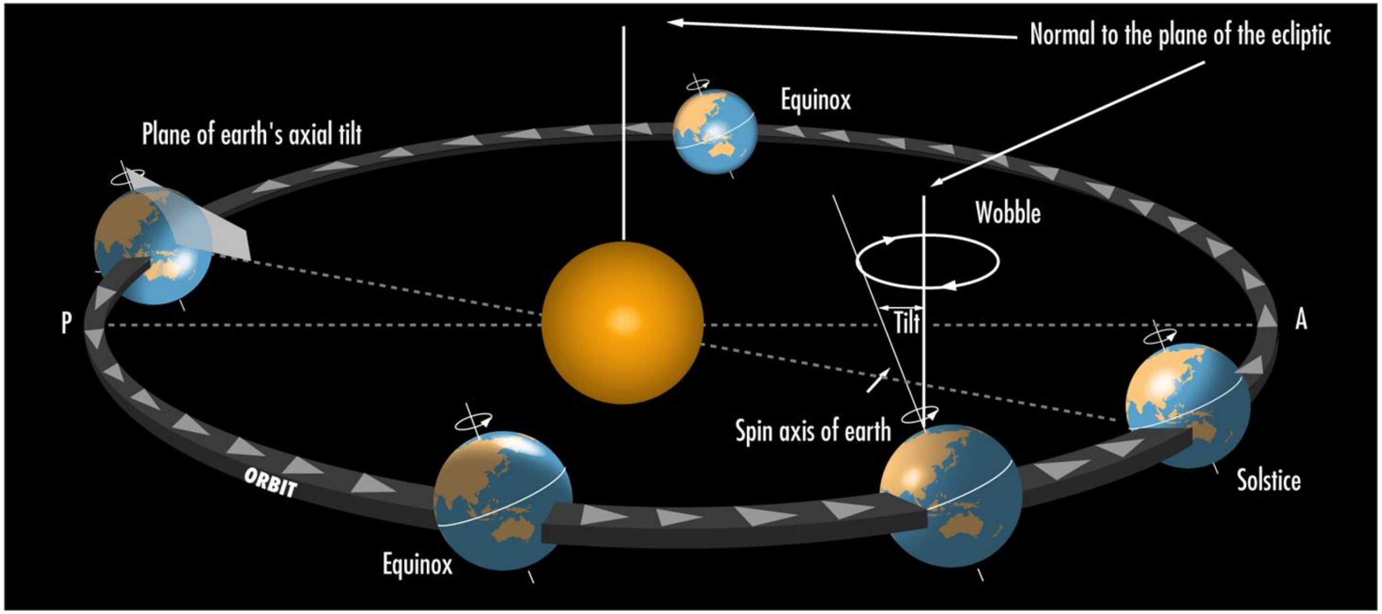
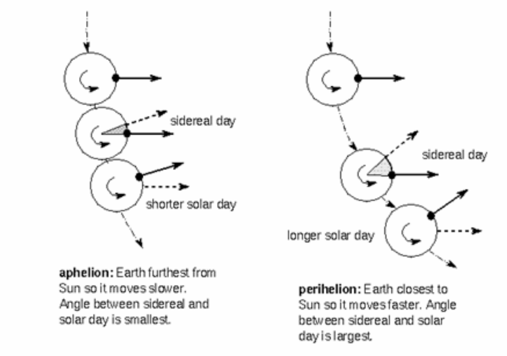
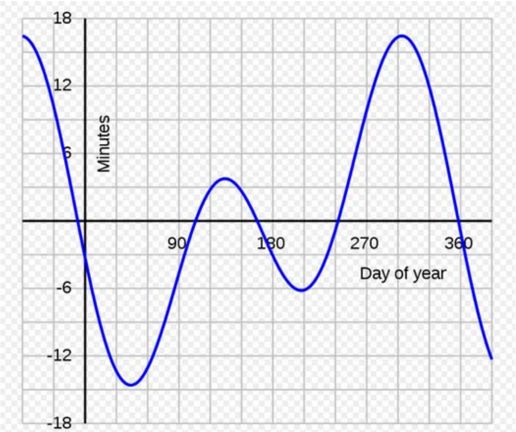
Earth-Sun Location Geometry







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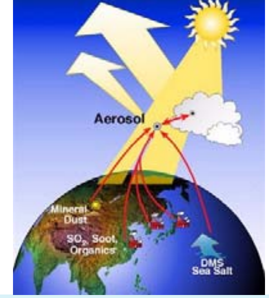
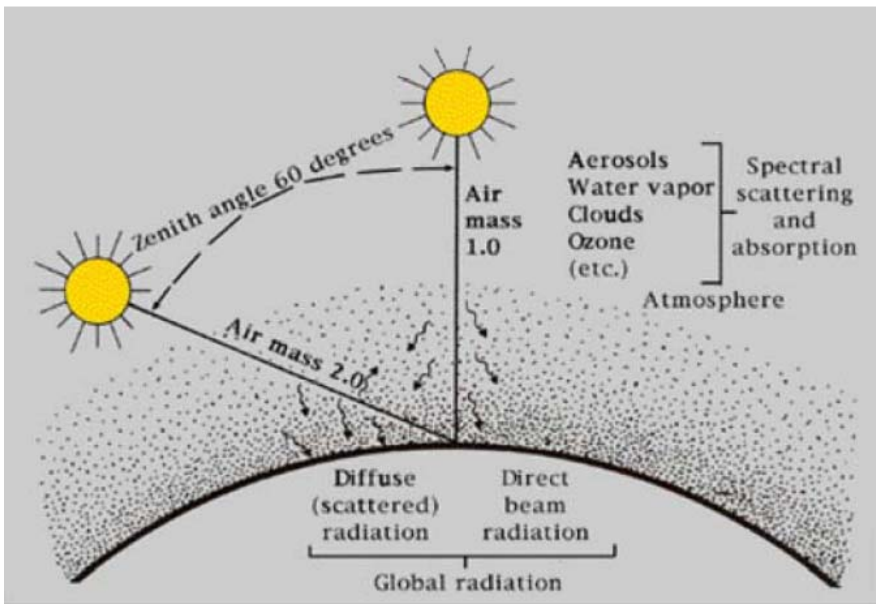
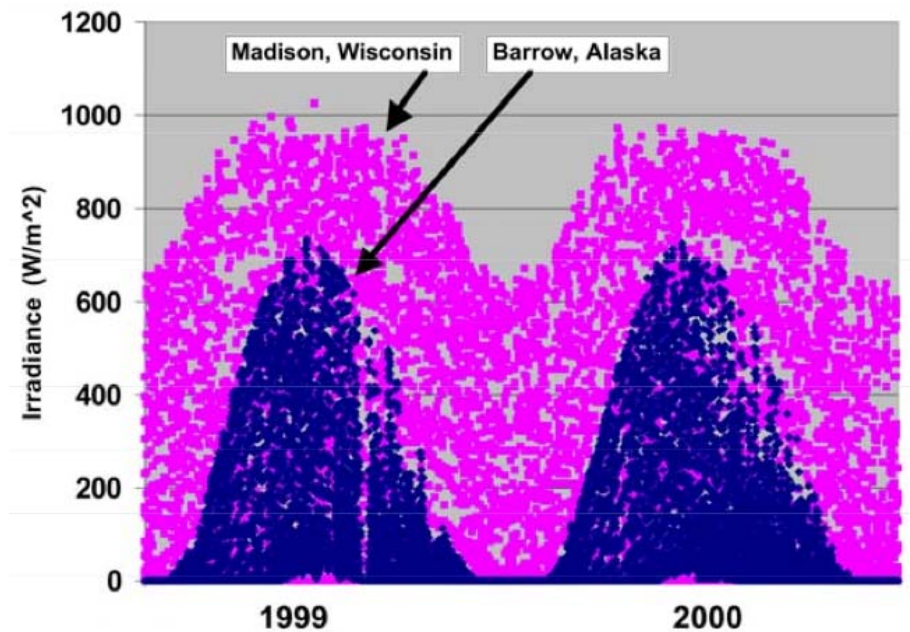
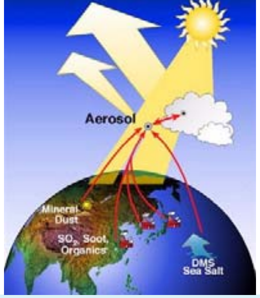
Location, Location, Location



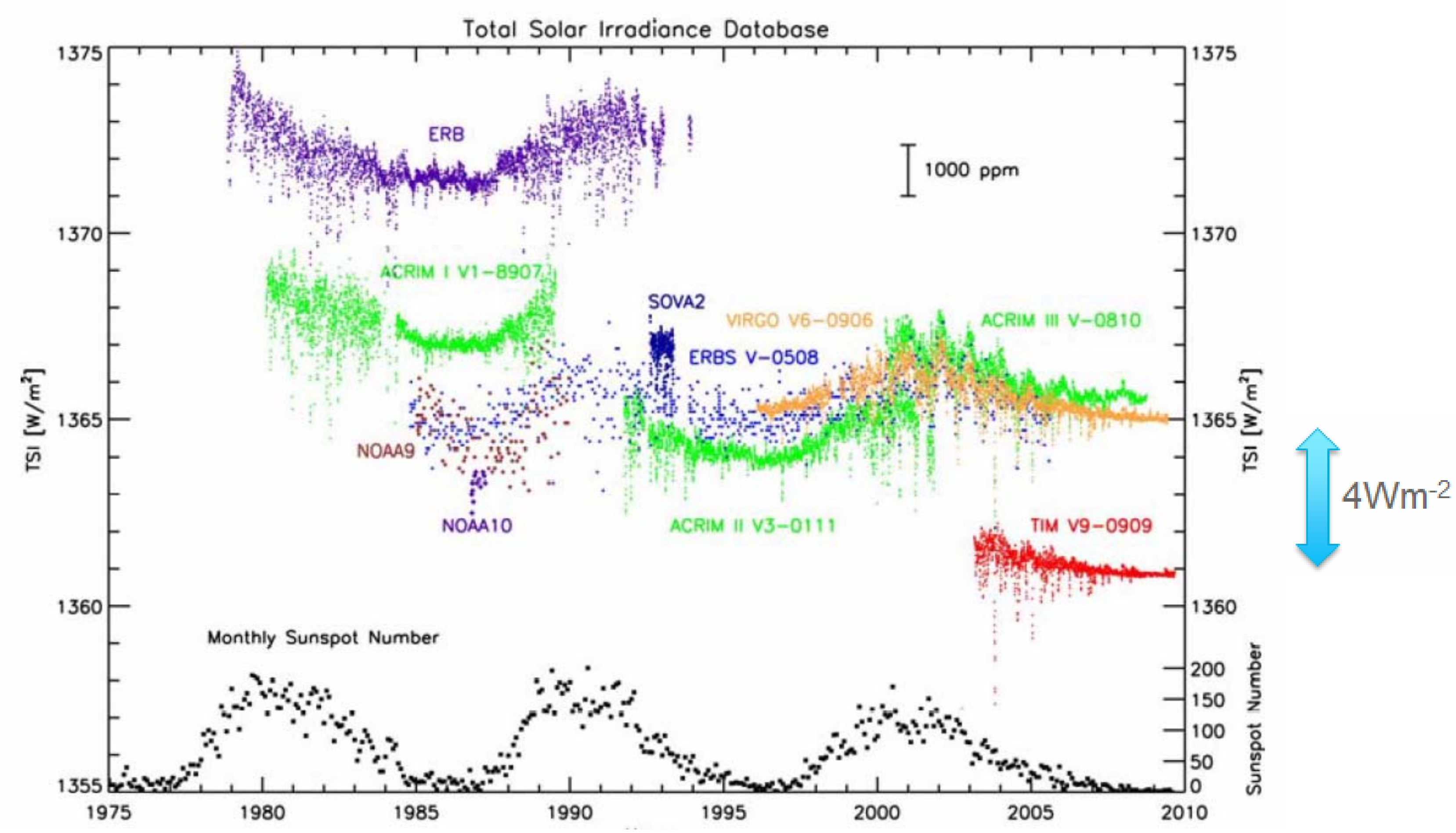




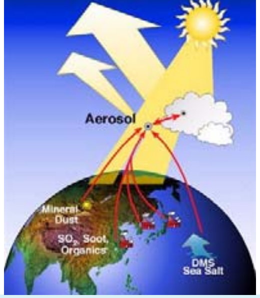
TSI – Total Solar Irradiance (at 1 AU)

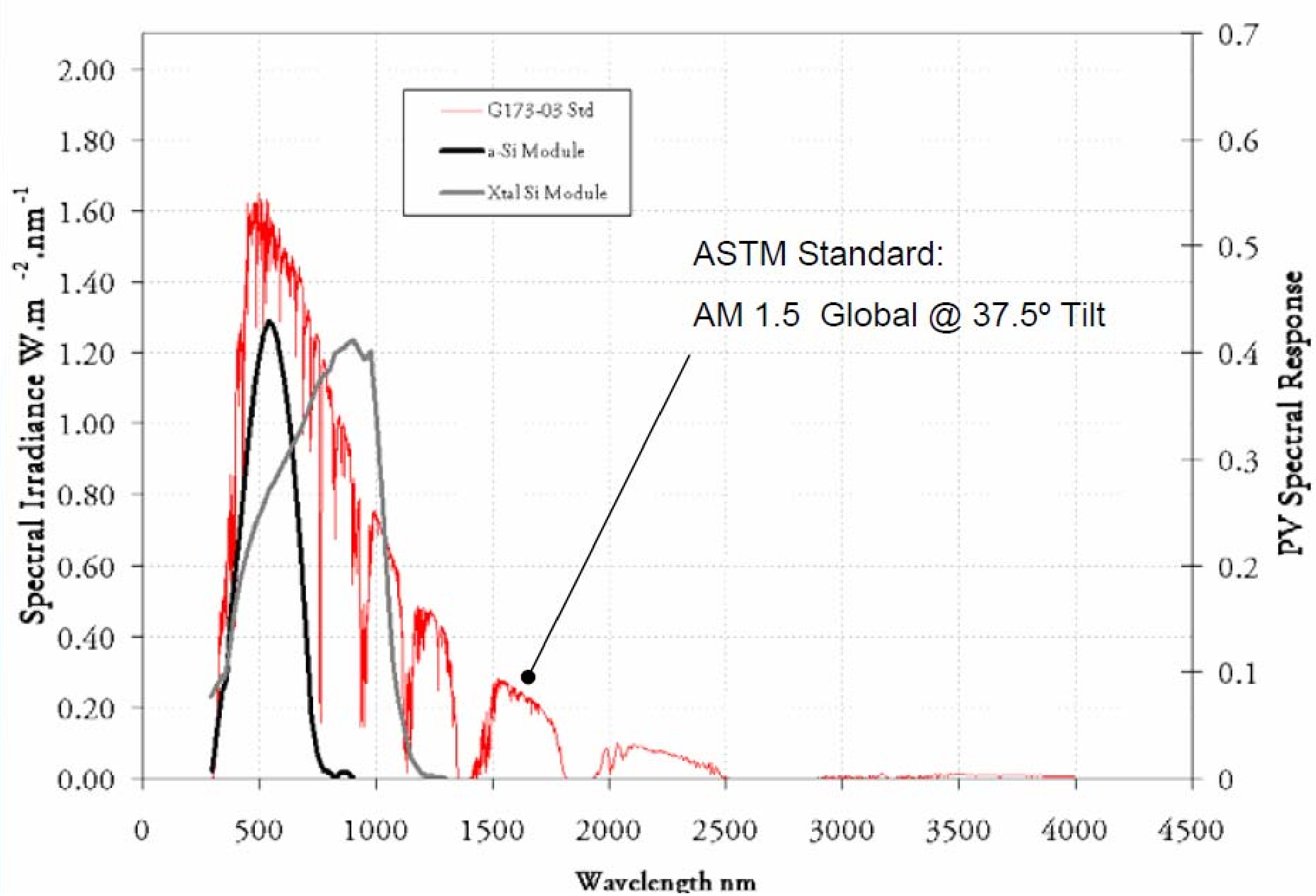


WRR to SI – within 0.1% ~ 1.4 Wm^{-2}



Other Factors





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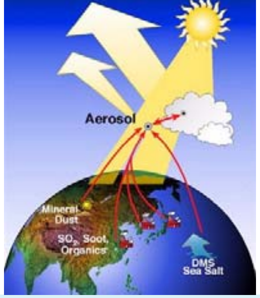
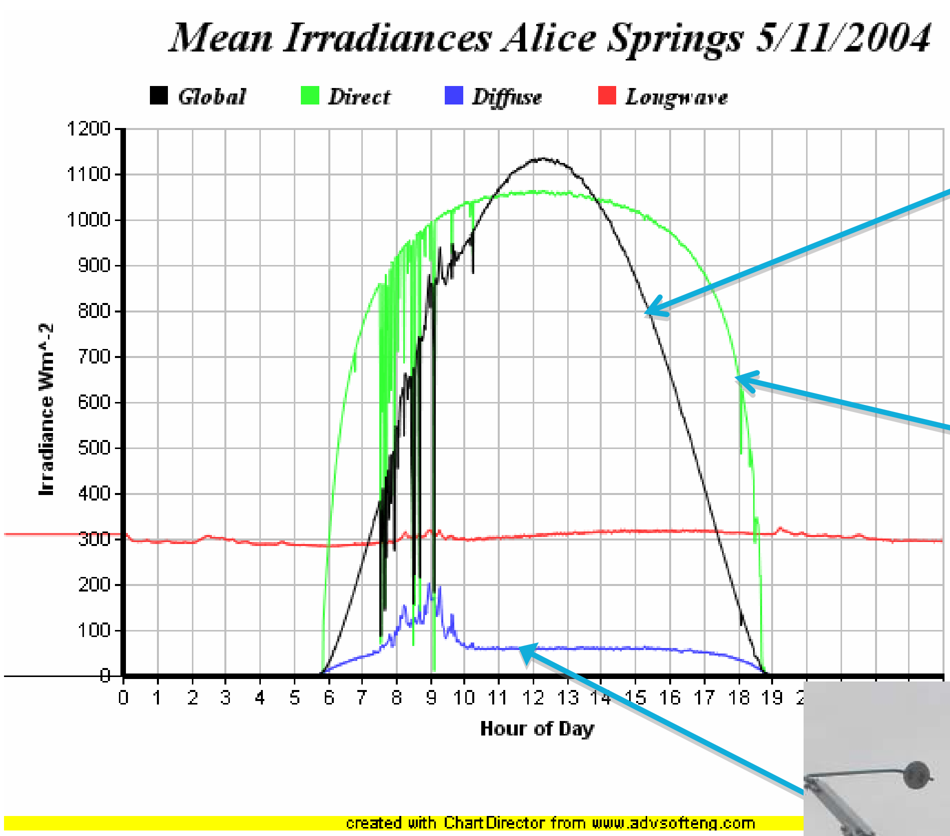
How Solar Components Measured



Global

Direct

Diffuse

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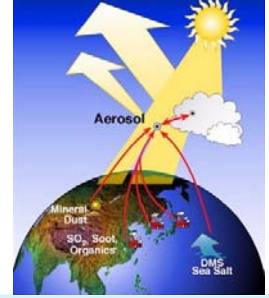
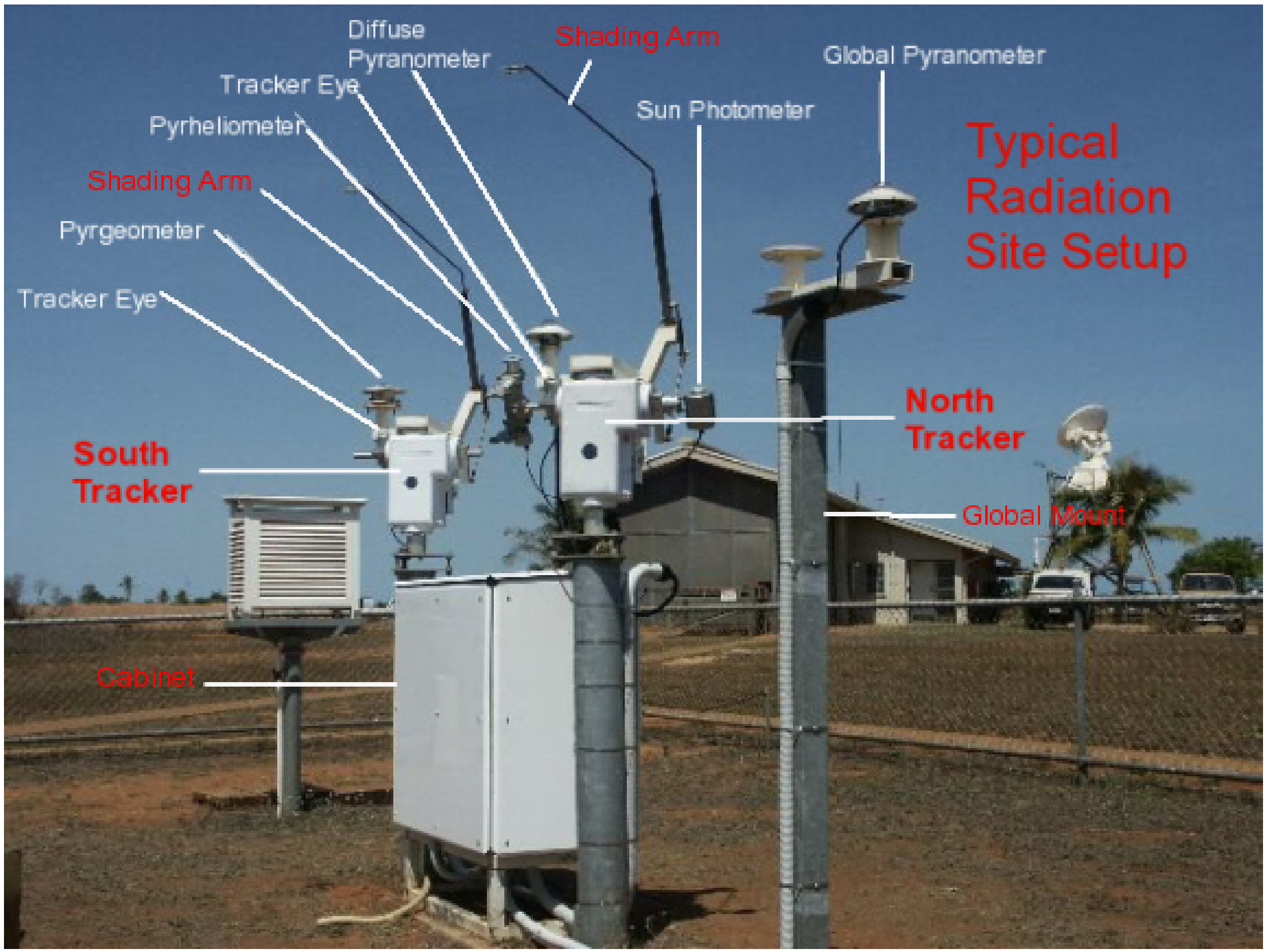
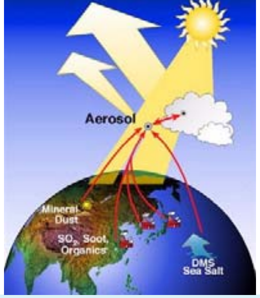
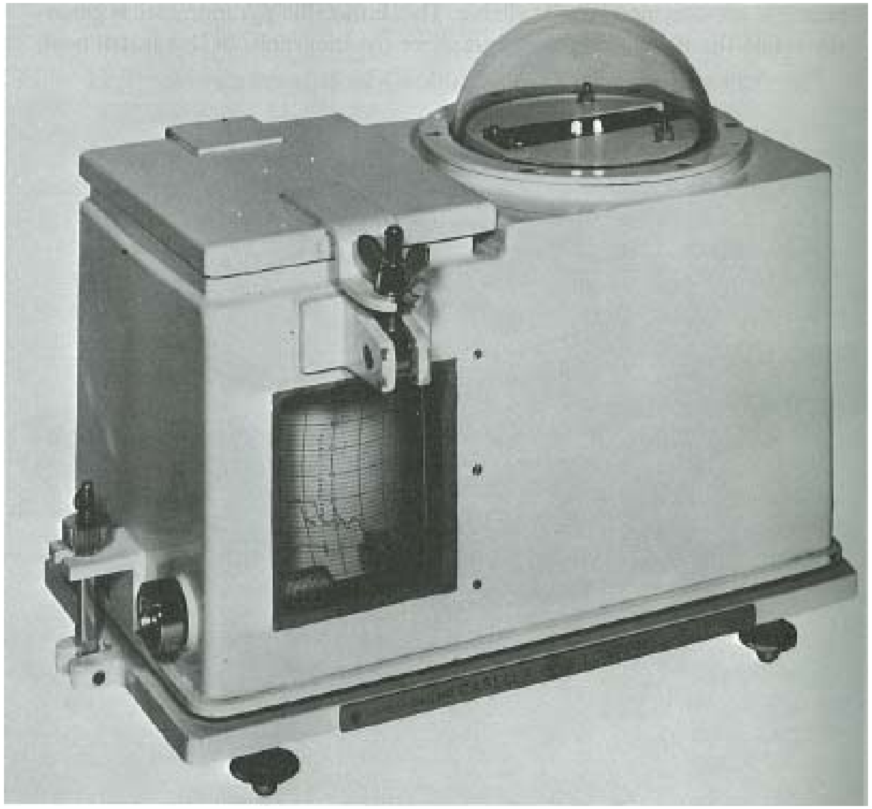
Typical Bureau Radiation Site

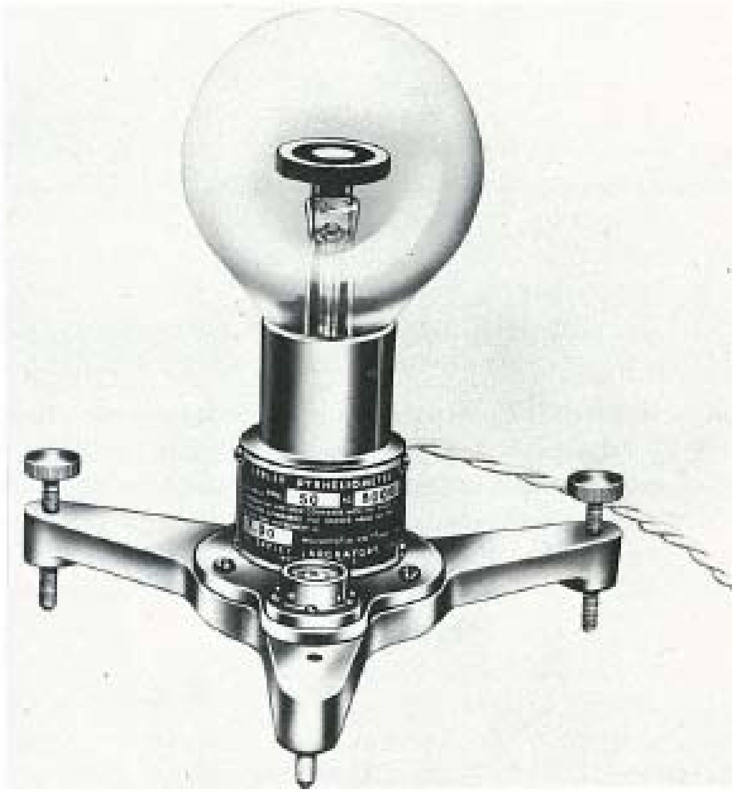




Older Less Accurate Pyranometers





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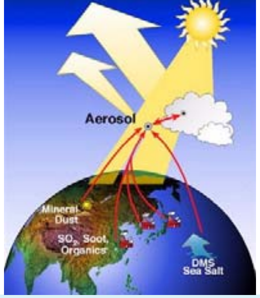
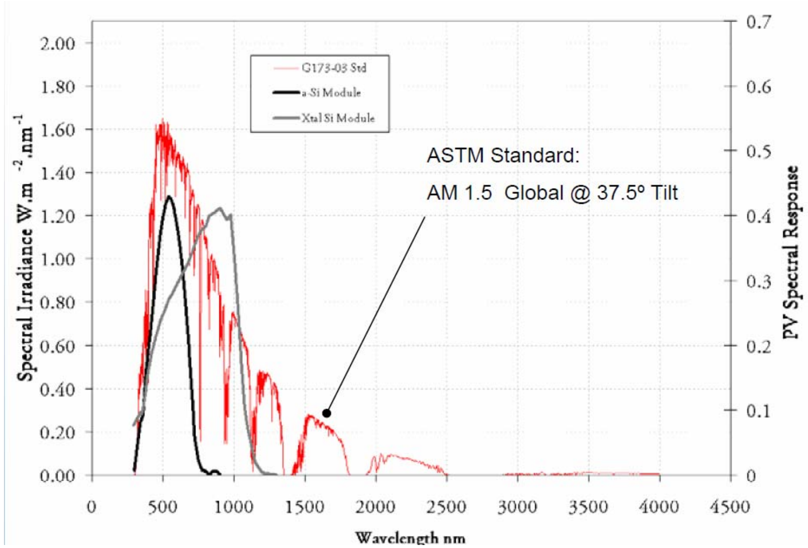
Silicon Diode Pyranometers





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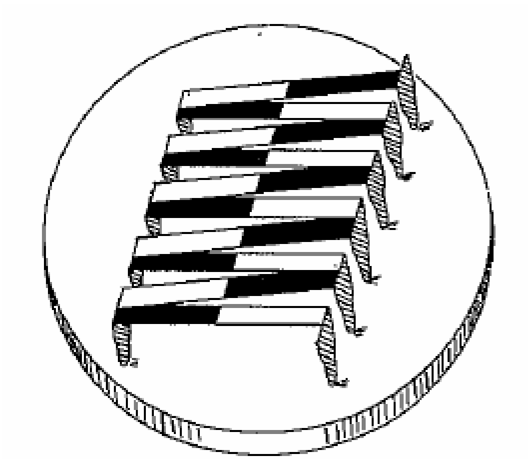
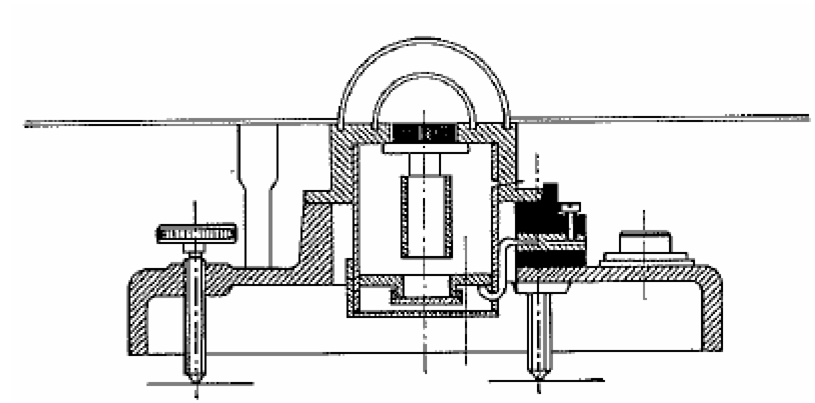
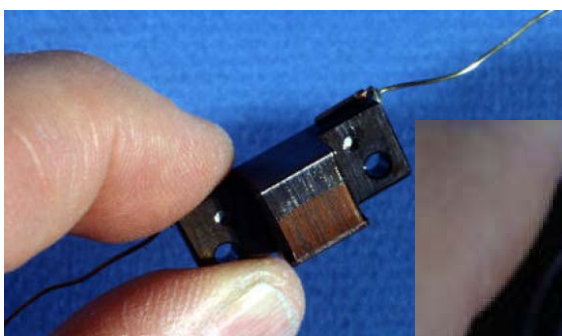
More Accurate Thermopile Pyranometers







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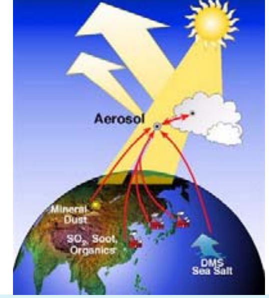
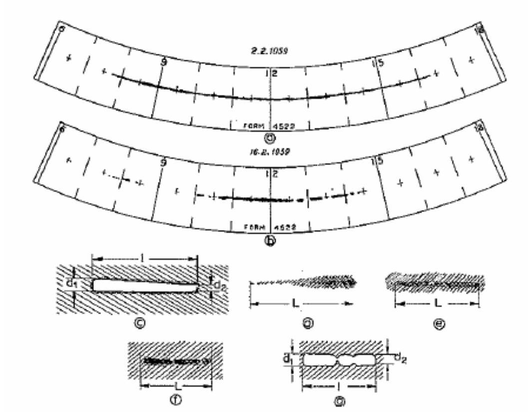
Sunshine Recorders





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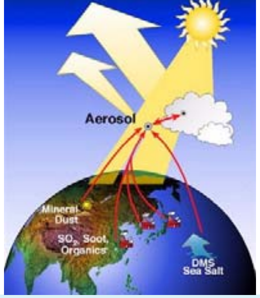
Bureau Solar & Terrestrial Station



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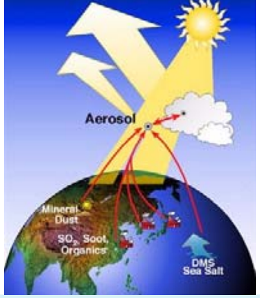
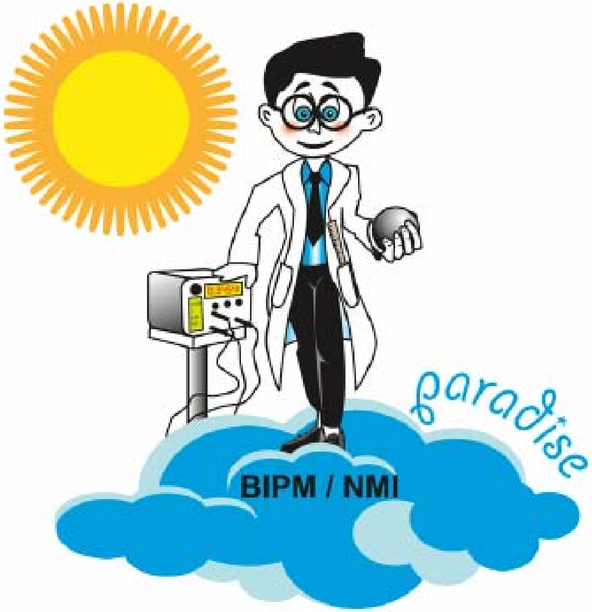
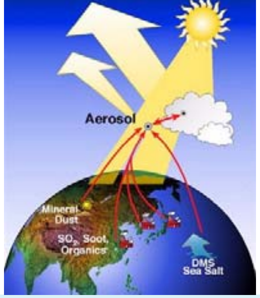
Metrology Laboratory versus Environment



WMO Traceability



- Technical guidance ratified by Commission IMO meetings
- Guide for Instruments and Methods for Observation (CIMO Guide)
  - Radiation: Chapter 7
  - Sunshine: Chapter 8
  - Web address: http://www.wmo.ch/pages/prog/www/IMOP/purpose.html
  - Regularly updated
- Defines traceability chain for member states of the WMO
- Defines the primary standards:
  - Solar: World Radiometric Reference (WRR)
  - Terrestrial/Longwave: World Infra-red Standard Group (WISG)
- Coordinates inputs from the wider community through an CIMO OPAGs and Expert Teams (Standards, Intercomparisons, etc)

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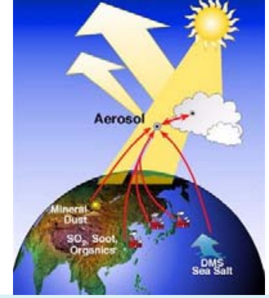
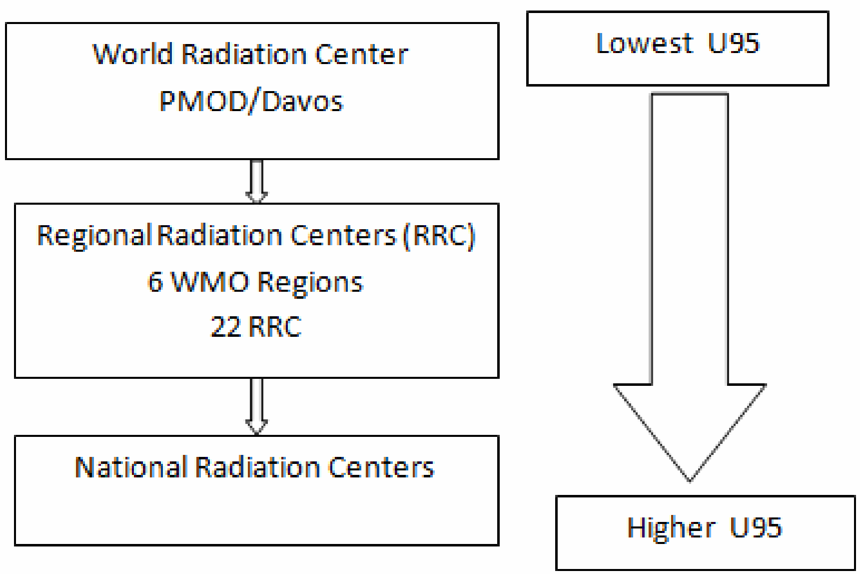
WMO Traceability Methodology





- World Centre
  - World Standard Group (4+)
  - Training
  - Centre of Excellence - BIPM
  - Regular Comparisons
  - Externally audited min. 2 years
- Regional Centres
  - Three radiometers – low U95
  - One radiometer->WSG every 5 yr
  - Assessed by national NMI 5years
- National Centres
  - Two radiometers – mod U95
  - One radiometer->RRC 5 yrs

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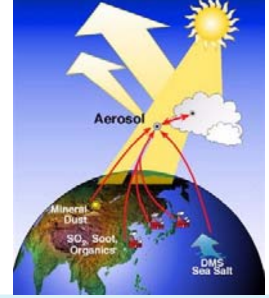
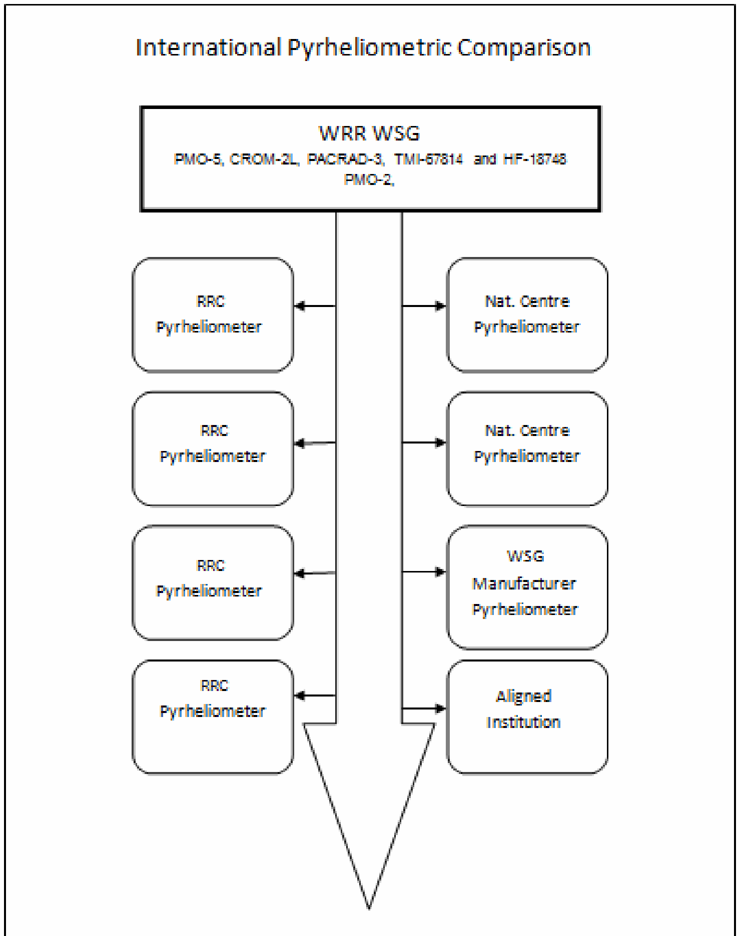
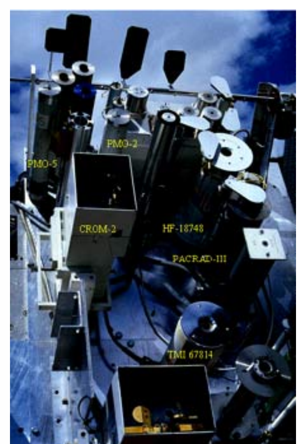
International Pyrheliometric Comparison





- International Pyrheliometric Comps
  - Every 5 years
  - Training Workshops
  - IPC XI 2010
    - 109 Participants
    - 5 WMO Regions
    - 15 RRC, 24 NC
- RPCs – when and if



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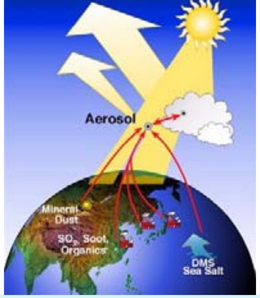
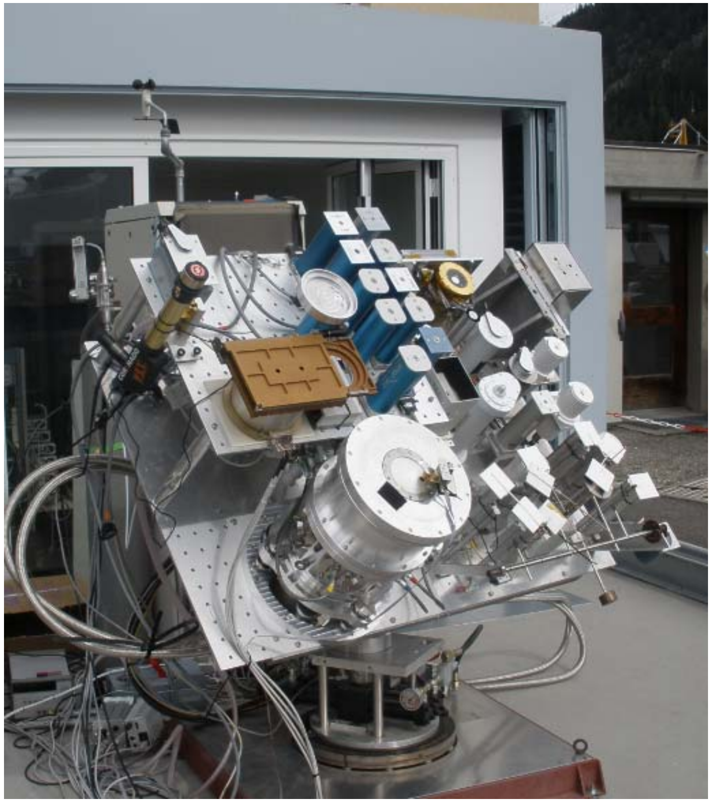
International Pyrheliometric Comparison





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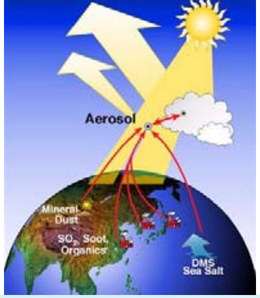
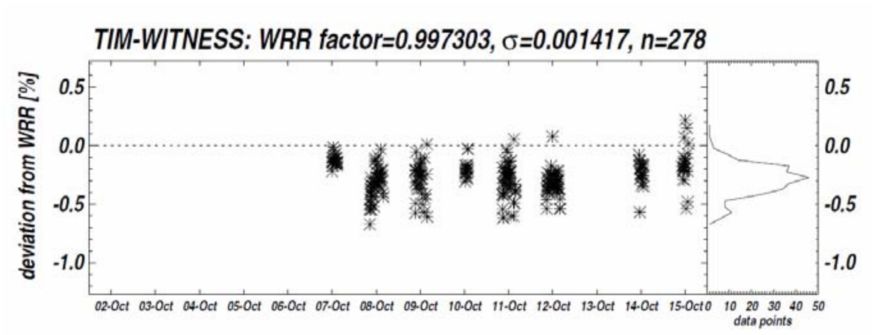
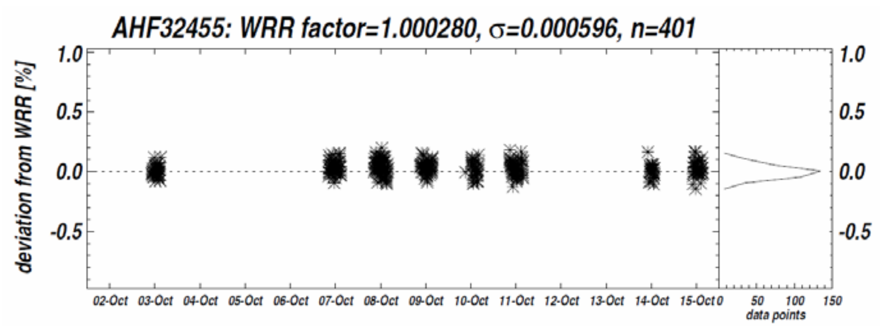
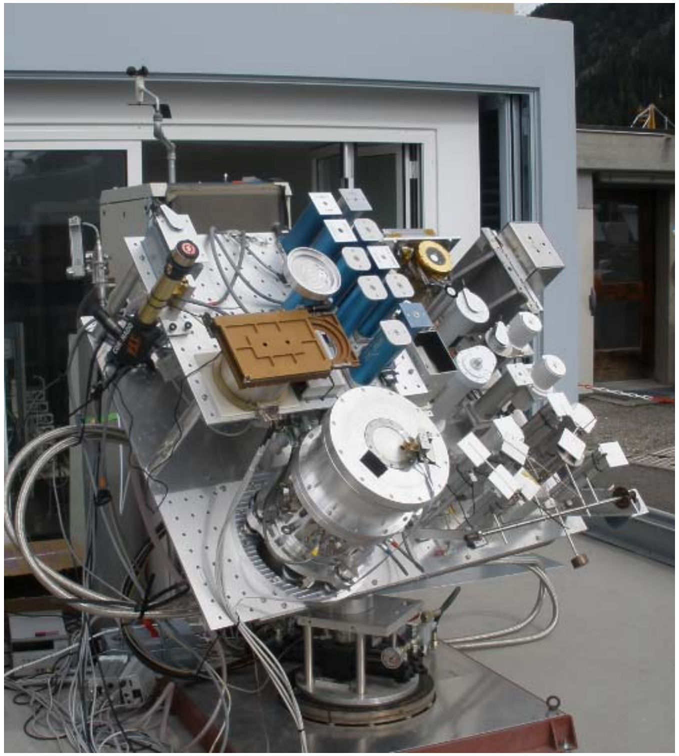
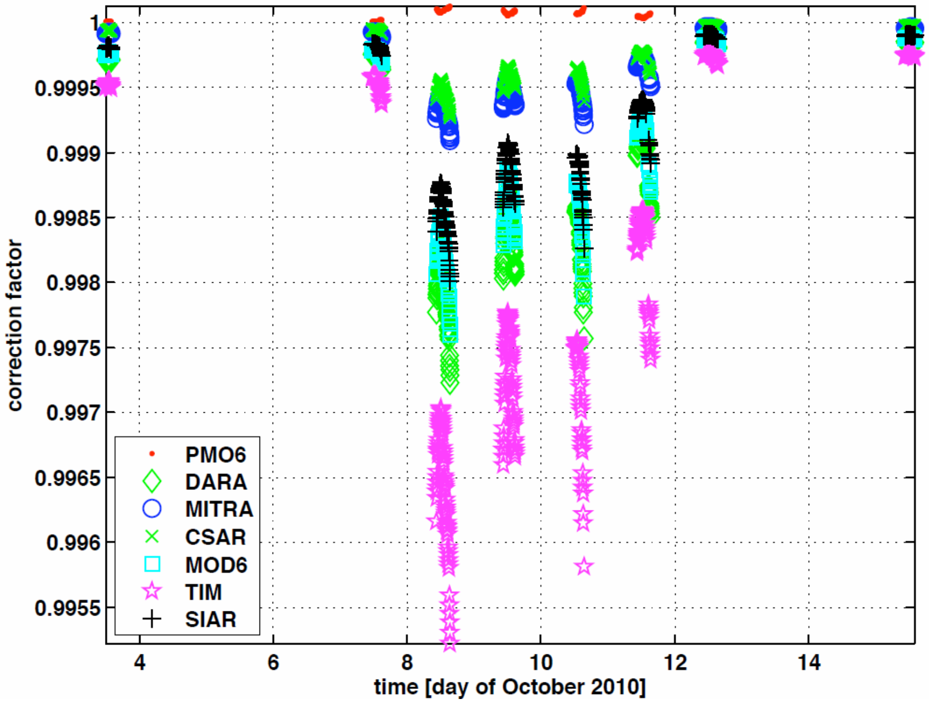
International Pyrheliometric Comparison XI (2010)











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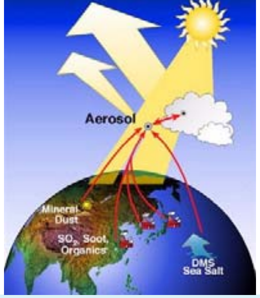
Factors Affecting Measurements




- Sensors
  - Directional response
  - Temperature response
  - Linearity
  - Zero irradiance signal
  - Spectral response
  - Levelling
- Data Acquisition
  - Signal resolution
  - Time resolution
  - Zero monitoring
  - Sampling rate

- Quality assurance
  - Cleaning frequency
  - Moisture
  - Inspection frequency
  - Meta data
  - Traceable Calibration method
  - Calibration frequency
  - Redundancy
- Data processing
  - Assumed sensitivity
  - Zero correction?
  - Cosine correction?
- Quality control
  - Inspection of data
  - Derivation of U_{95}

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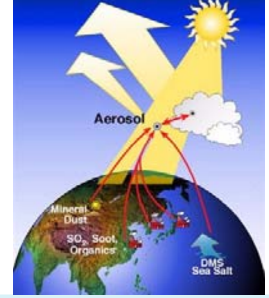
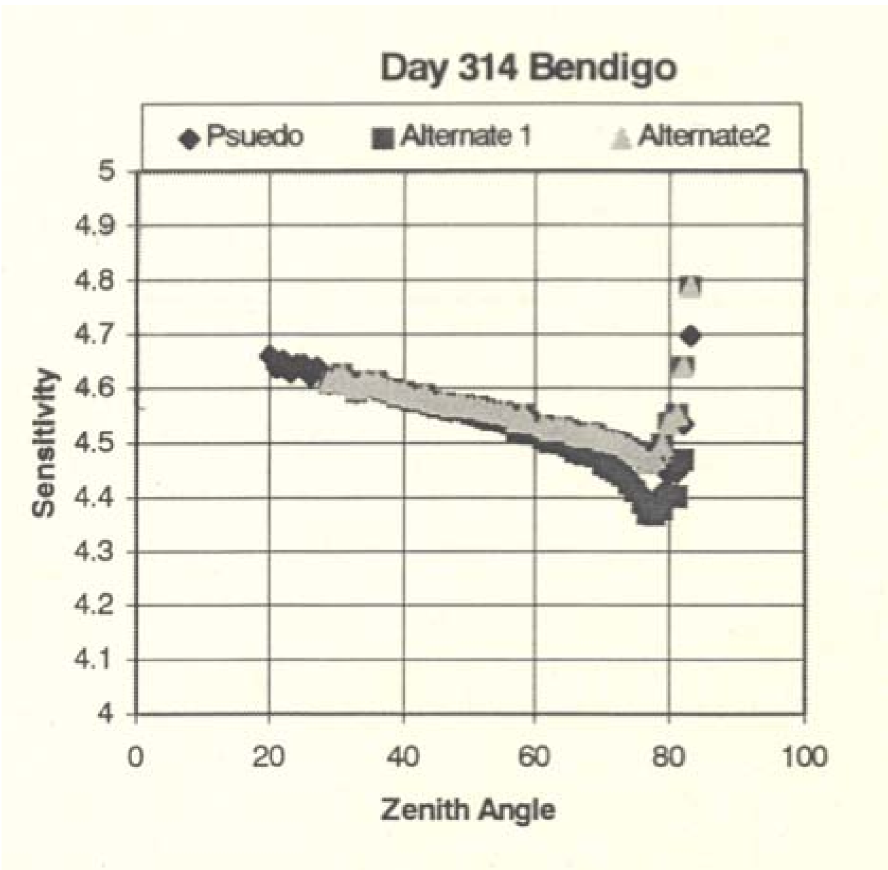
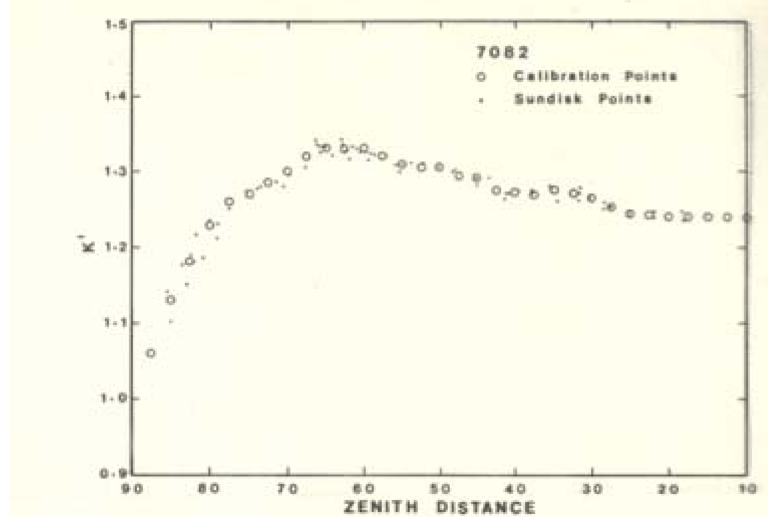
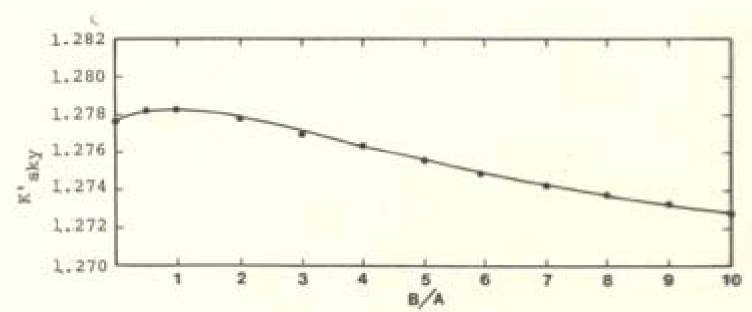
Directional Response Example

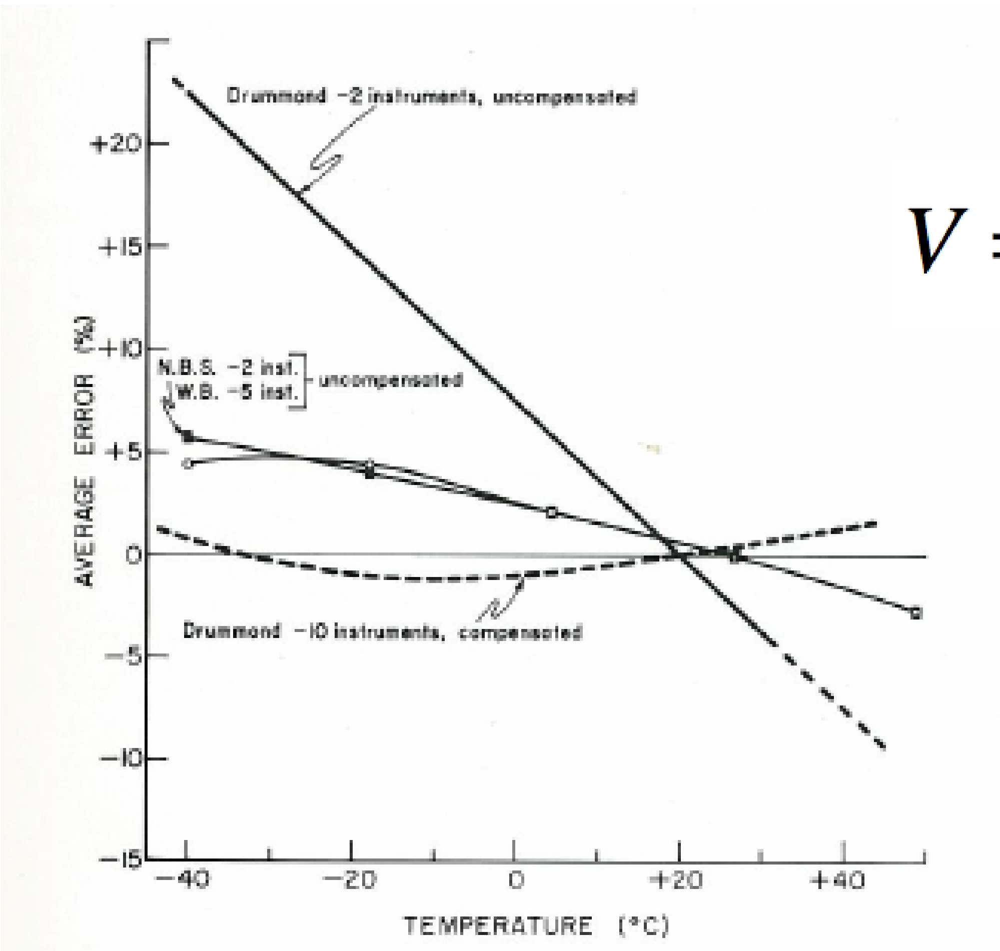








Thermopile Temperature Response



$$V = V_0(1 + \alpha(T - T_0))$$

Typical values for α:

Old Moll thermopiles -0.0014

New thermopiles ~0.001

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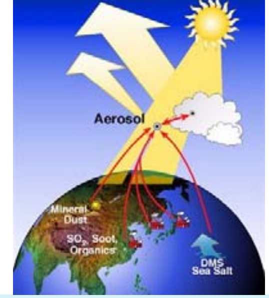
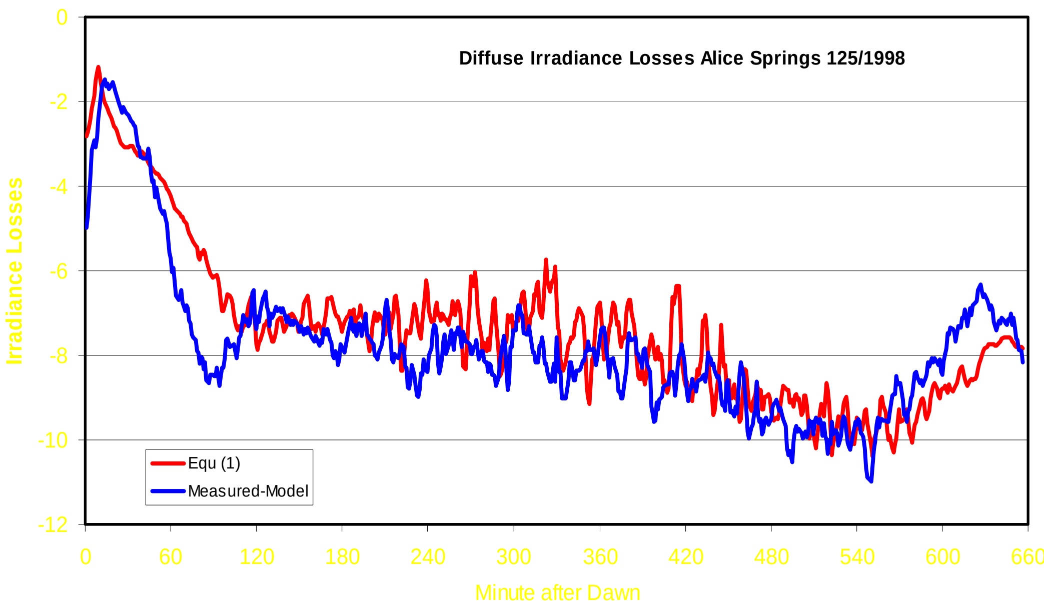
Thermopile Zero Signals



$$V_{solar} = (V_{meas} - V_{zero-ir})$$



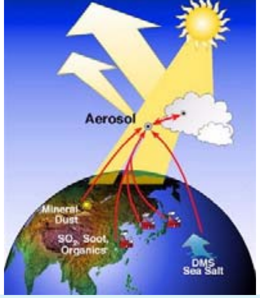
Reason:

- Infrared radiation balance between the ‘hot’ pyranometer and the cold sky

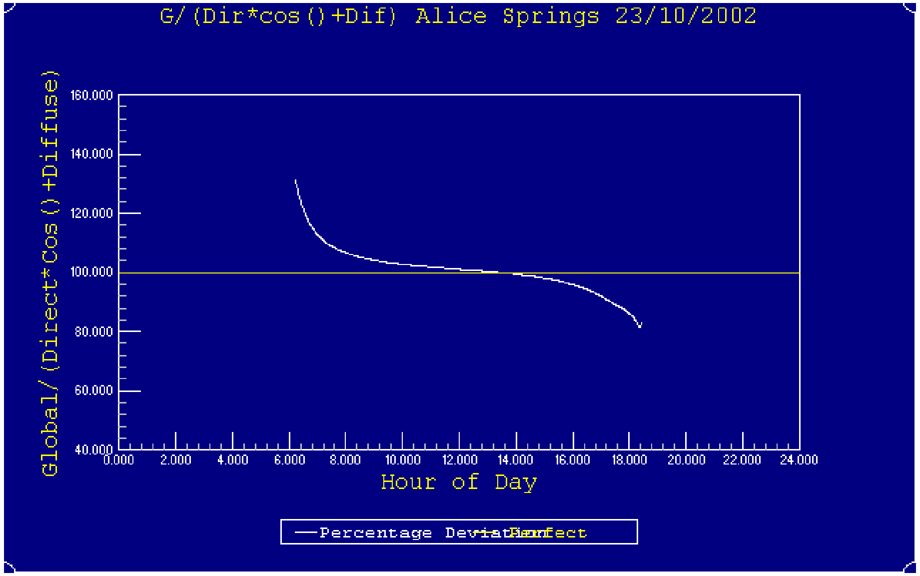
Magnitude:

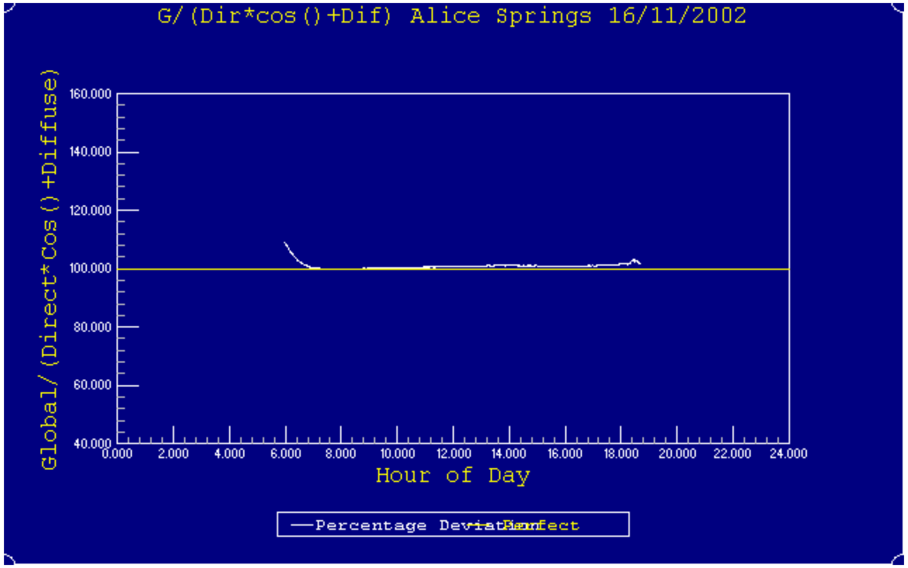
- Between +3 and -20 Wm^{-2}
- Maximum ~ 15:00 TST on clear sky days
- Minimum in fog conditions

Instrument Level or Time Wrong?

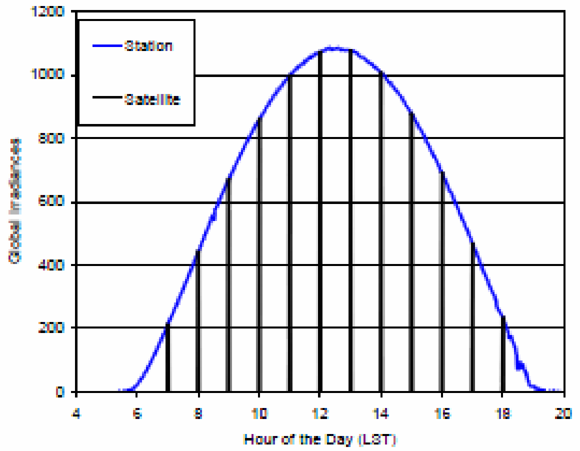


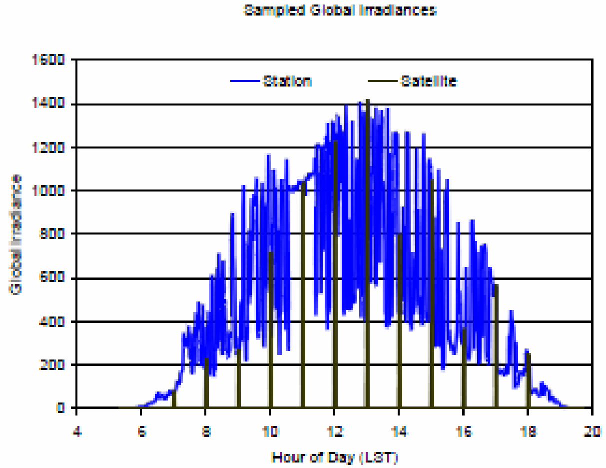
$$R_{global} = \frac{C_{global}(V_{global} - V_{globalzero})}{C_{direct}(V_{directmeas} - V_{directzero})\cos\vartheta_{sun} + C_{skydiffuse}(V_{skymeas} - V_{skyzero})}$$





Under-sampling Example





When the time between samples is longer than the time period of the phenomenon under-sampling occurs.

Under-sampling results in not capturing a representation of the irradiance signals.

Sampling periods must always be shorter than the time constant of the sensor response to change.

This requirement applies to any measurement of a time series and a foundation of sampling theory.

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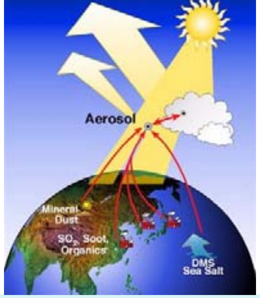
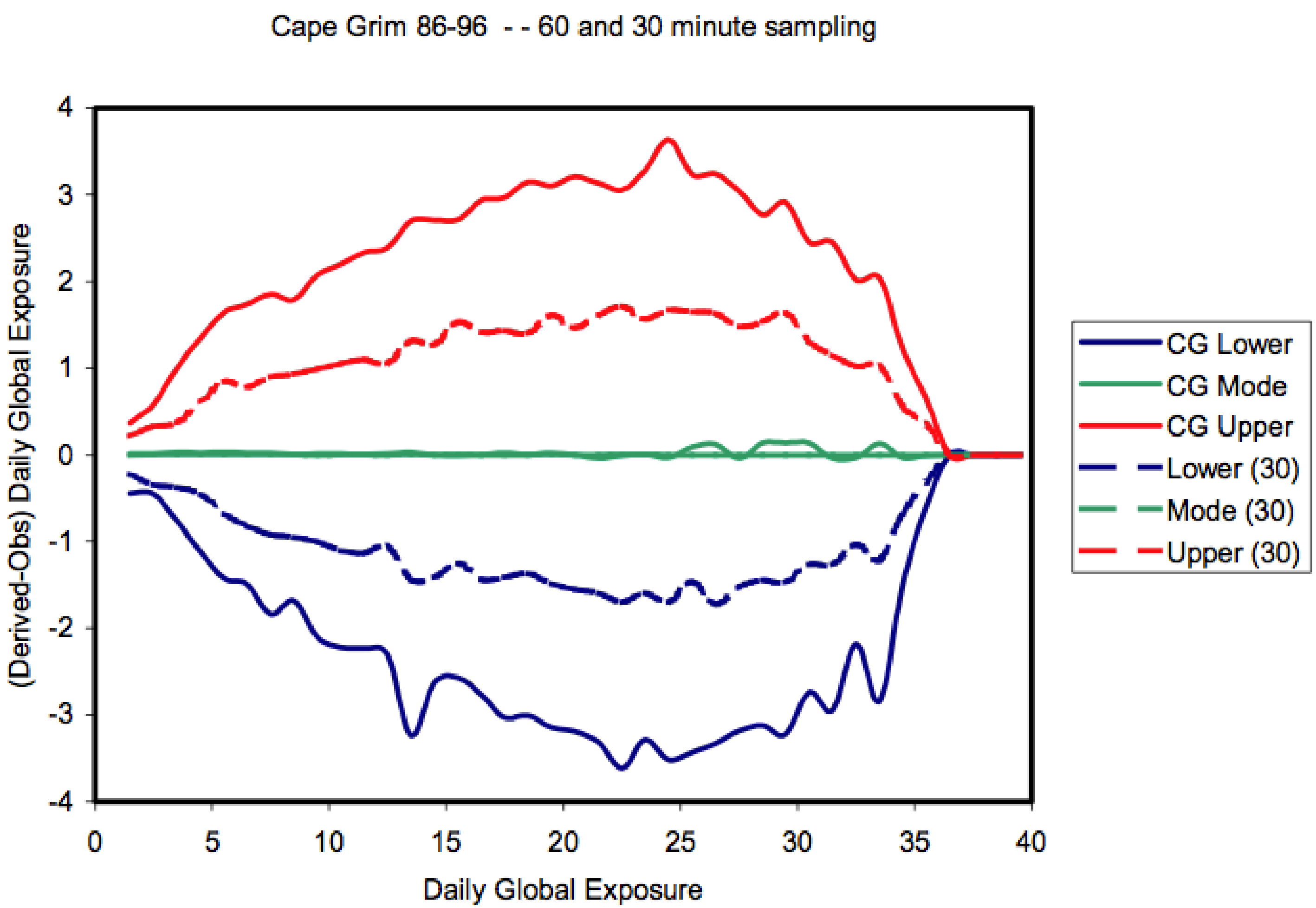
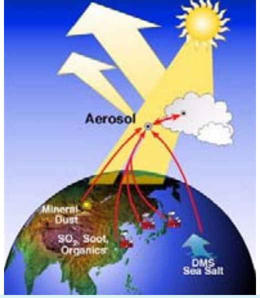
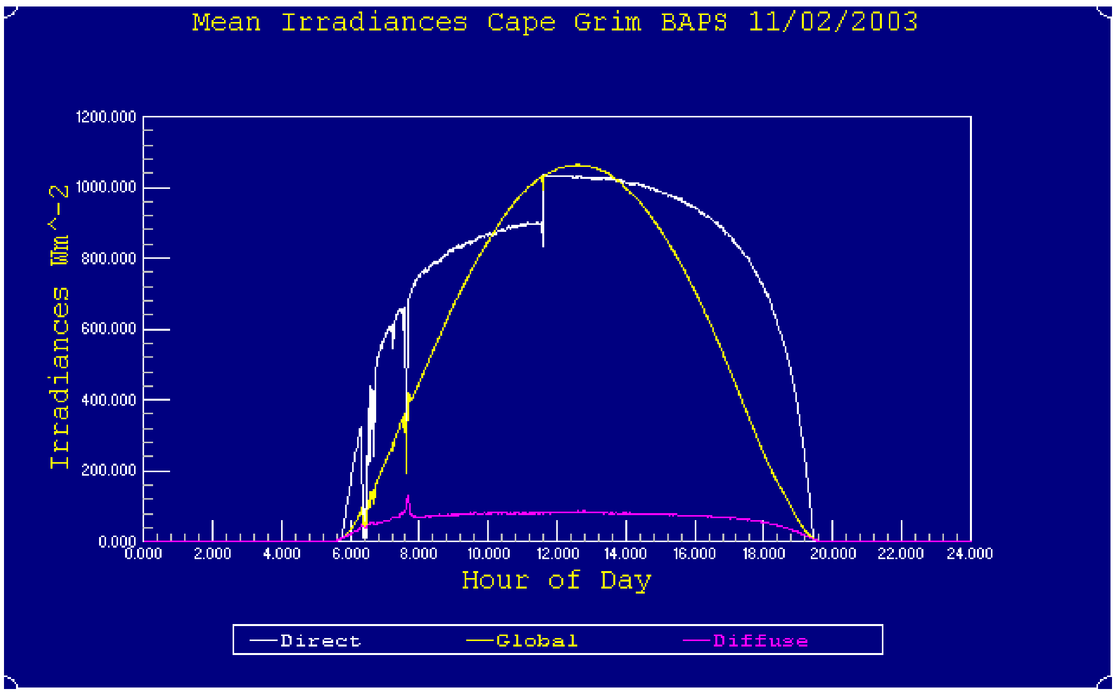
Impact on U_{95} by Undersampling





Daily Cleaning in ‘Dirty’ Environments





This is a problem mainly for glass dome or windowed instruments – especially pyrheliometers.

Silicon pyranometers with diffusers are not affected by salt or dirt build up.

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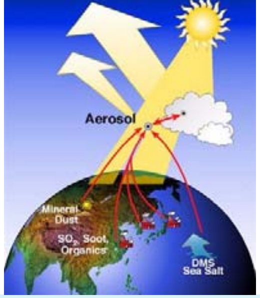
What was said in 1981 about solar data



WMO Technical note 172 “Meteorological aspects of the utilization of solar radiation as an energy source” 1981

Experience has often shown that too little interest is devoted to the calibration of instruments and quality of data. Measurements which are not reliable are useless; they may be misleading and cause wrong investments. Past data have not always been obtained from instruments whose calibration and operation have been checked sufficiently.

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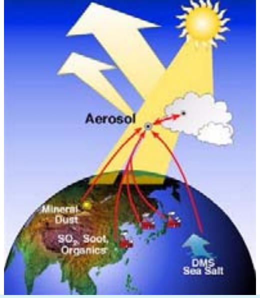
Pyranometer Equations



Global & Diffuse Irradiance - Pyranometer

$$E_{global} = E_{dir} \cos \vartheta + E_{diffuse}$$

$$E_{global} = \frac{S_{dir}}{C_{dir}} \cos \vartheta + \frac{S_{diffuse}}{C_{diffuse}}$$

$$E_{global} = \frac{S_{global}}{C_{global}}$$

$$C_{global\,\&\,diffuse} = c_0 c(T, E, E_{ir}) \frac{\int_0^{2\pi} \int_0^{\pi/2} f(\vartheta, \phi) L_{sun+sky}(\vartheta, \phi) \sin 2\vartheta \, d\vartheta \, d\phi}{\int_0^{2\pi} \int_0^{\pi/2} L_{sun+sky}(\vartheta, \phi) \sin 2\vartheta \, d\vartheta \, d\phi}$$

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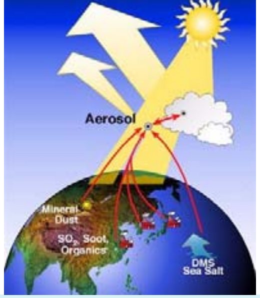
Low Uncertainty ≠ Good Calibration



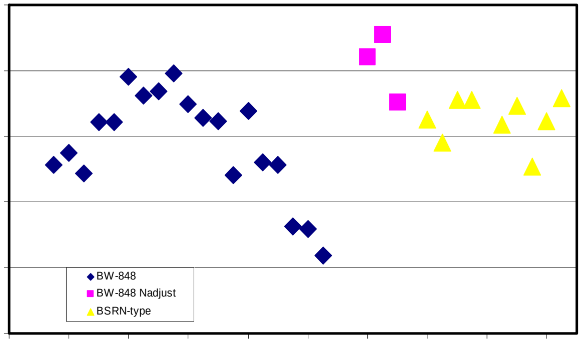
A calibration in winter may produce a very different calibration even if the instrument characteristics have not changed!

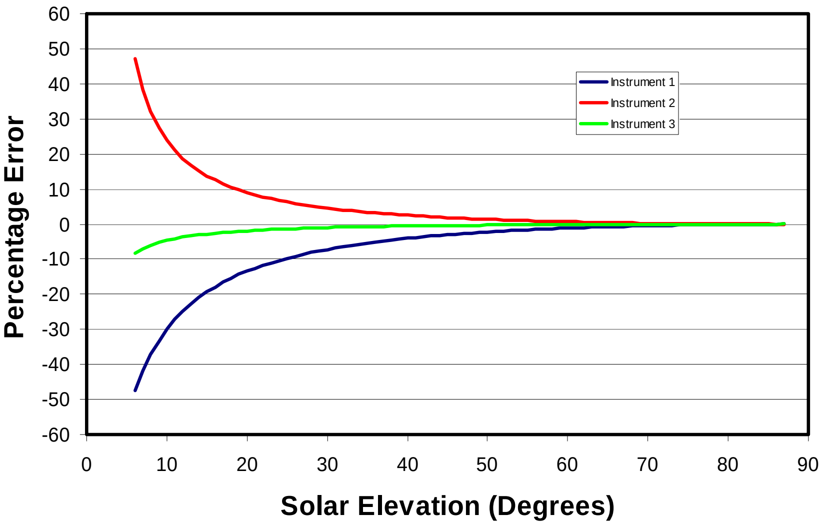
•Different directional response and sun in different position

•Different temperatures in summer and winter

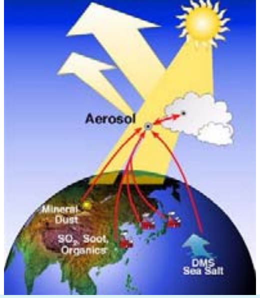
•Best regular calibrations are under similar or identical solar position, sky condition and air temperature conditions.

•Don’t compare and ‘apple’ to and ‘orange’





Pyranometer Calibration Methods



WMO Methods described in CIMO Guide

- Comparison of pyranometers
- Component sum
- Sun disk
- Alternate

ISO described methods

- WMO methods (but not Alternate)
- Iteration

Other Methods

- Pseudo
- Cloudy sky

Use the method that satisfies your U_{95} requirements not the method that provides the most ‘accurate’!

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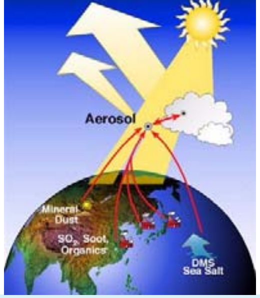
Comparison Method




$$\overline{K} = \sum_{1}^{n} \frac{V_i}{E_{ref_i}}$$

In addition to the pyranometer….

Requires:
•Calibrated pyranometer of same type
i.e. directional, temperature, time constant
Advantages
•Simple and easily automated
•Clear and cloudy skies (best in cloudy)
Calibration in normal state
•Single calibration value?
Disadvantages
•High uncertainty for measured E or H
•Not good for comparing different types
•High uncertainty for reference pyranometer

Most ideal for daily exposure calibrations

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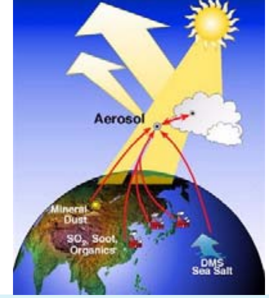
Component Sum Method




$$K_i = \frac{V_i}{E_{dir_i} \cos \vartheta_{sun_i} + E_{diffuse_i}}$$

$$\overline{K} = \sum_{1}^{n} K_i$$

In addition to the pyranometer….

Requires:
- Calibrated diffuse pyranometer
- Calibrated pyrheliometer and solar tracker
- Clear sun periods

Advantages
- Can automated
- Provides best estimate of E (or H)
- Provides biased estimate of cosine response

Disadvantages
- Which value of K?
- Biased by direct/diffuse ratio

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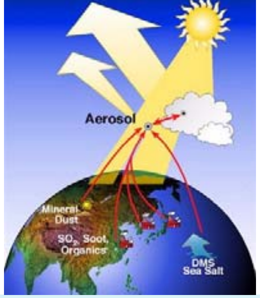
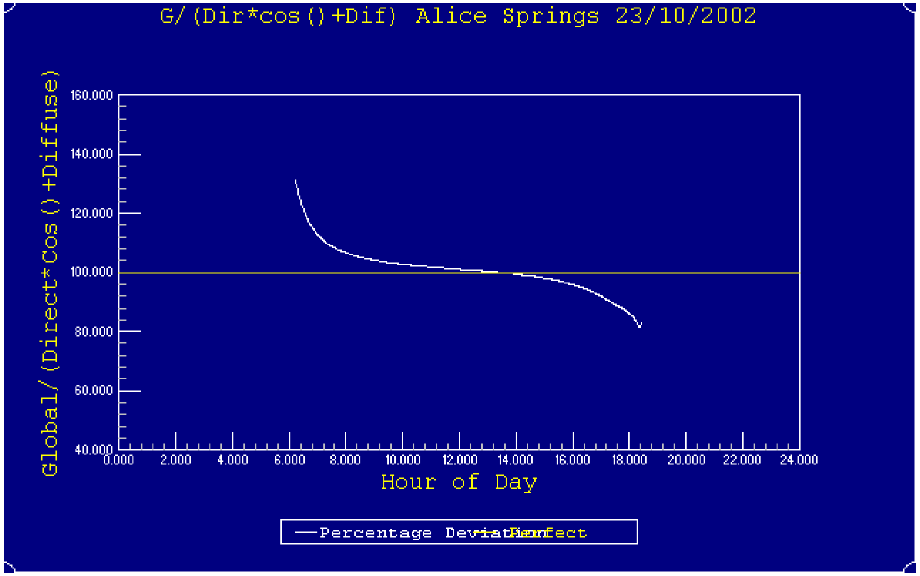
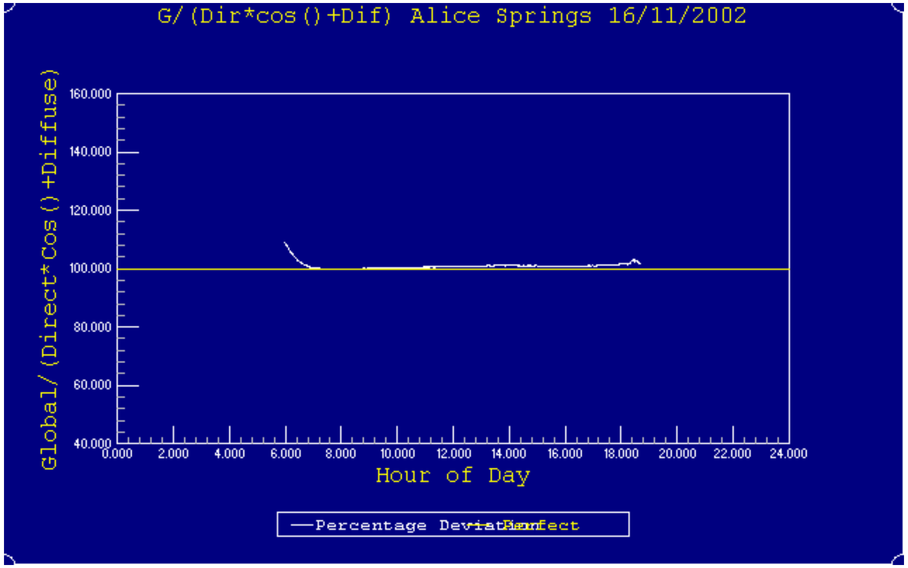
Composite Sum Example & Realtime QC



$$K_i = \frac{V_i}{E_{dir_i} \cos \vartheta_{sun_i} + E_{diffuse_i}}$$





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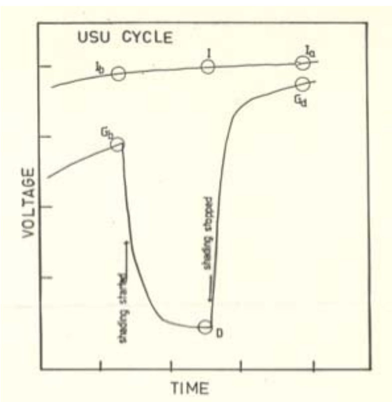
Sun Shade Method

$$K_i = \frac{2(V_{unshaded_i} - V_{shaded_{i+1}})}{(E_{dir_i} \cos \vartheta_{sun_i} + E_{dir_{i+1}} \cos \vartheta_{sun_{i+1}})}$$



In addition to the pyranometer….

Requires:
- Calibrated pyrheliometer and solar tracker
- Clear sky periods
- Alternate shade and unshade of pyranometer

Advantages
- Can automated
- Provides unbiased estimate of cosine response
- No zero irradiance bias

Disadvantages
- Which value of K?
- Transitions of bright sun to sky

Most ideal for daily exposure calibrations

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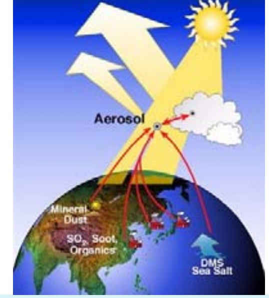
Alternate Method



$$\frac{V_{1A}(\theta)}{K_1(\theta)} = E_{dirA}\cos(\theta) + \frac{V_{2A}(\theta)}{K_2(\theta)}$$

$$\frac{V_{2B}(\theta)}{K_2(\theta)} = E_{dirB}\cos(\theta) + \frac{V_{1B}(\theta)}{K_1(\theta)}$$

In addition to the pyranometer….

Requires:
- Identical set up to composite method
- Except the diffuse pyranometer does not need to be calibrated
- Swapping of pyranometers after a few clear sky days
- Suitable for routine operations

Advantages
- Can automated
- Provides unbiased estimate of cosine response

Disadvantages
- Which value of K?

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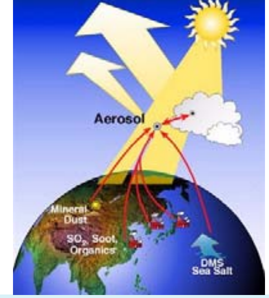
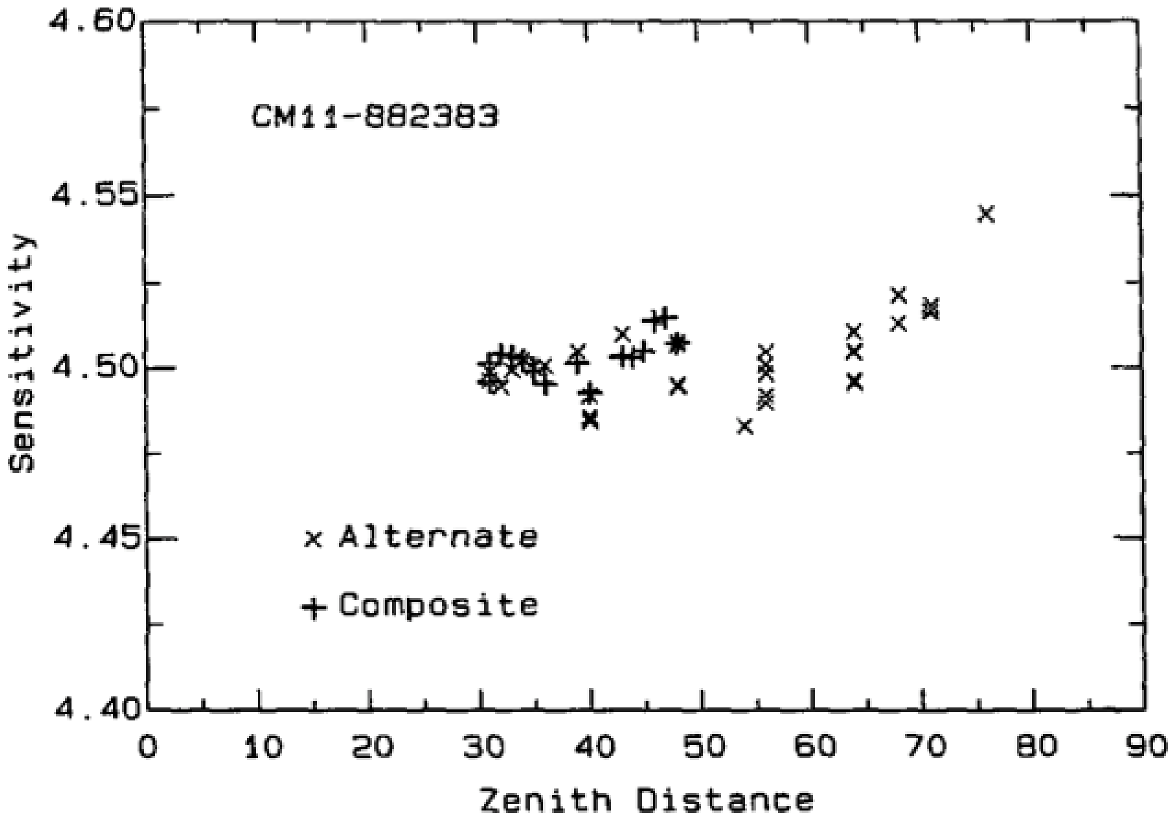
Comparison
Composite vs Alternate





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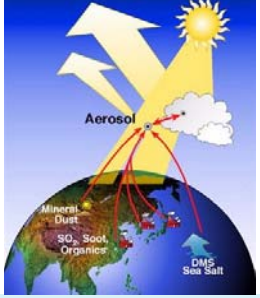
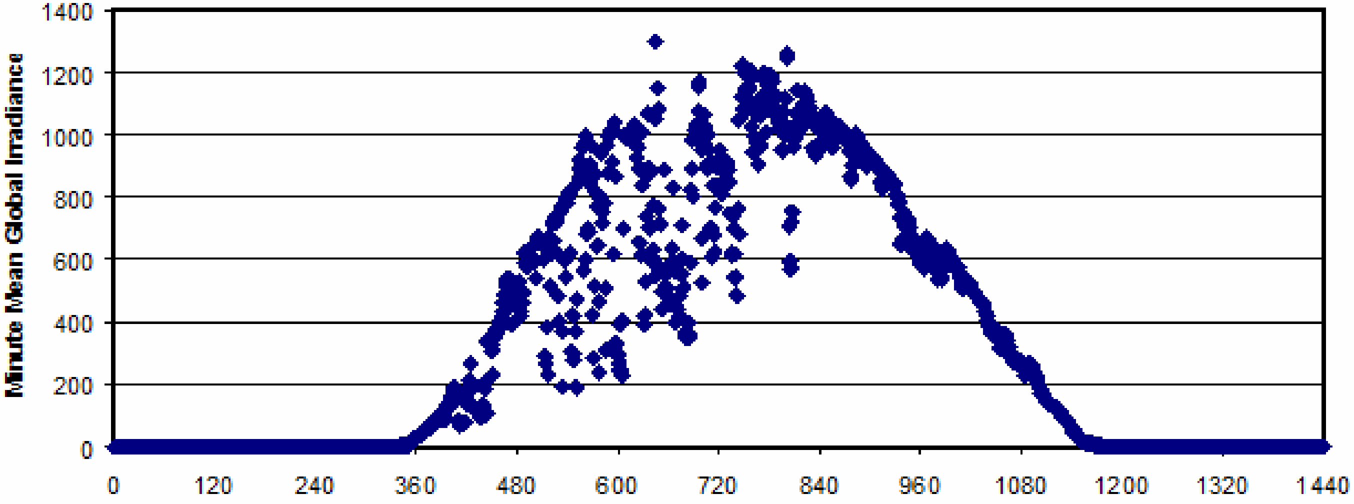
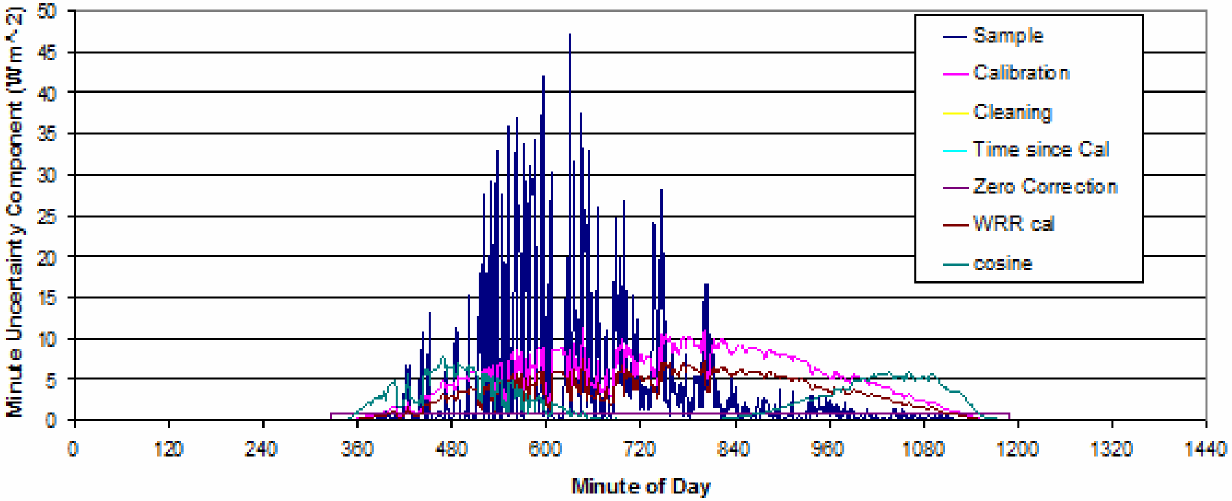
Quantifying Uncertainty U_{95}







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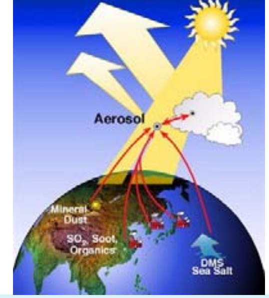
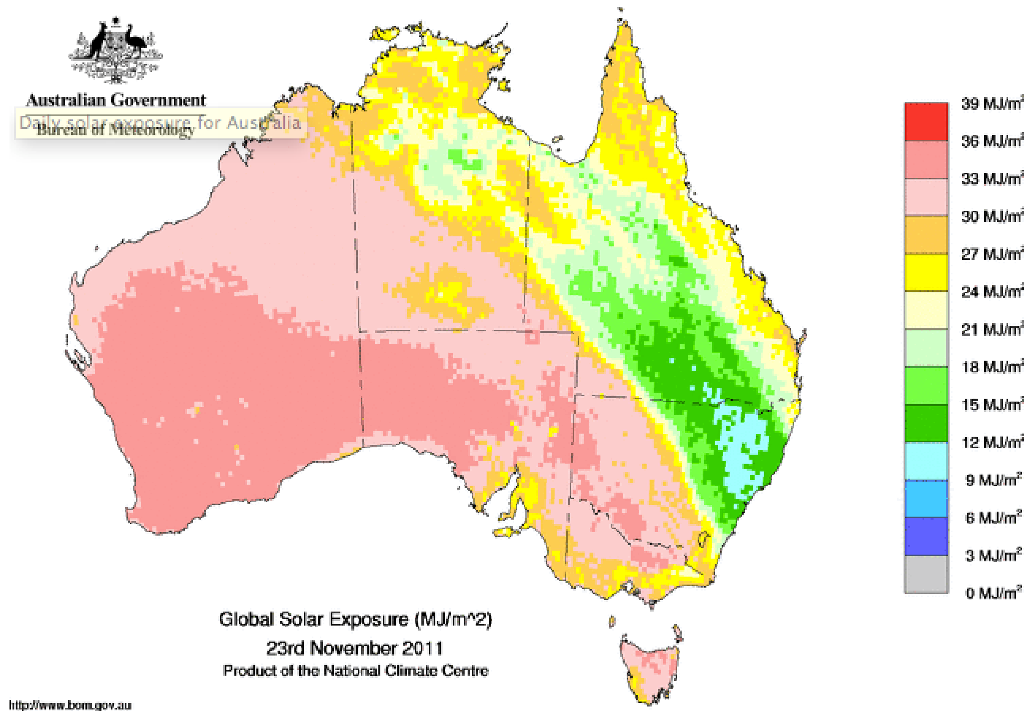
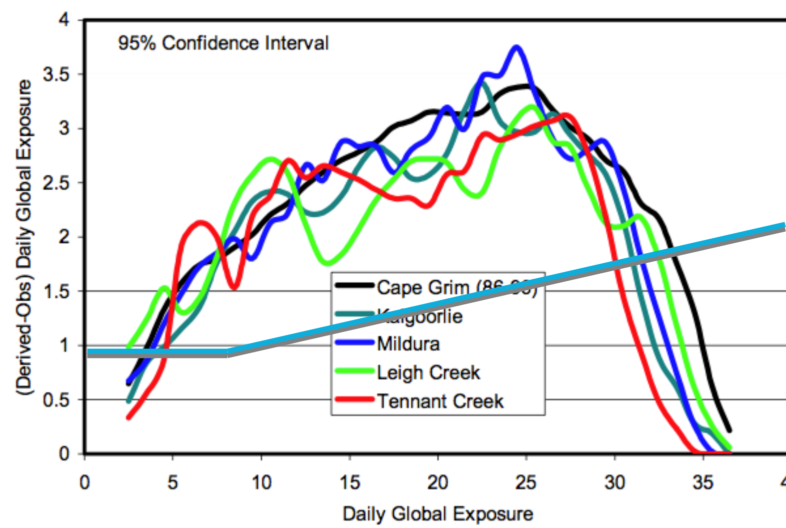
Satellite Estimates of Daily Exposure







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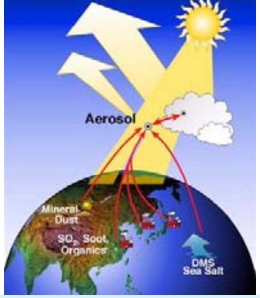
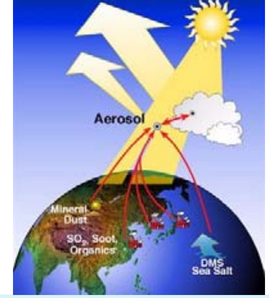
Global Solar Irradiance and Exposure Metrology



What you need to know

- Your location in space and time
- Understanding of basic solar equation:

  $E = E_{sun}\cos(\theta) + E_{sky}$
- Factors that affect the measurement of pyranometer or system signals
- Defining what you want to measure and what U_{95}
- A traceability method to the World Radiometric Reference




What you need to do

- Putting in place quality assurance to ensure the quantities you measure are met meet your uncertainty requirements
- Regular checks that you achieve your quality goals
- Log any activity associated with your measurements or data analysis
- Use simple models to verify your data i.e. compare to satellite or clear sky models
- Generate a representative U_{95}
- Provide hourly or daily exposure data to the World Radiation Data Centre, St Petersburg, Russia

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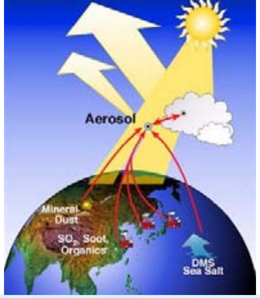
Key References for Solar References



- Commission for Instruments and Methods of Observation Guide (CIMO Guide) – WMO - free
- Baseline Surface Radiation Network Manual (BSRN Guide) – AWI - free
- Guide to the Expression of Uncertainty in Measurement (ISO GUM) – ISO (1995+)
- ISO Standards – TC/180 SC1 ~1993 (moribund)
  - 6 standards based on CIMO Guide (~1982) – solar resource focus
- ***Plus***
  - ***BSRN Workshops and Working Groups (12)***