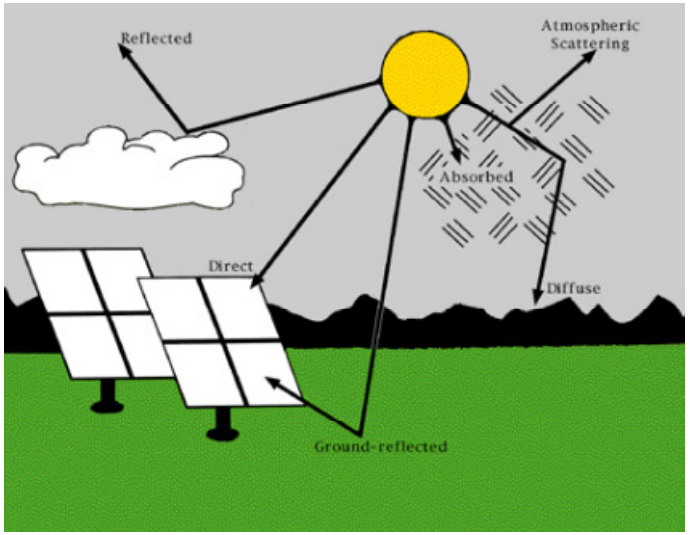
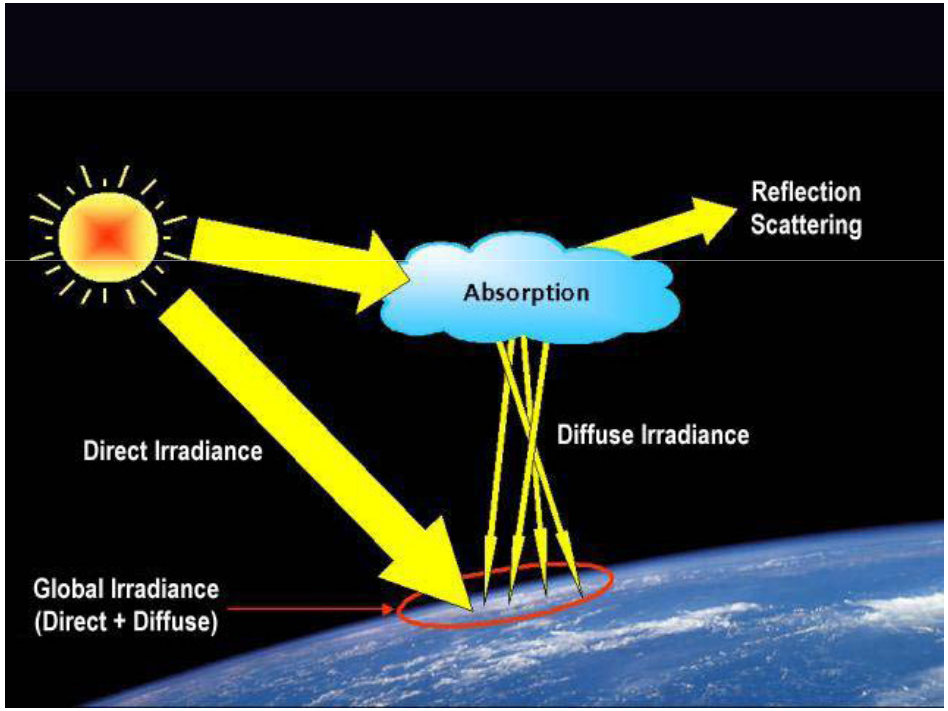
Measurement of Solar Radiation; Calibration of PV cells



Dr. Daniel Cotfas
Transilvania University of Brasov
The Physics department
dtcotfas@unitbv.ro

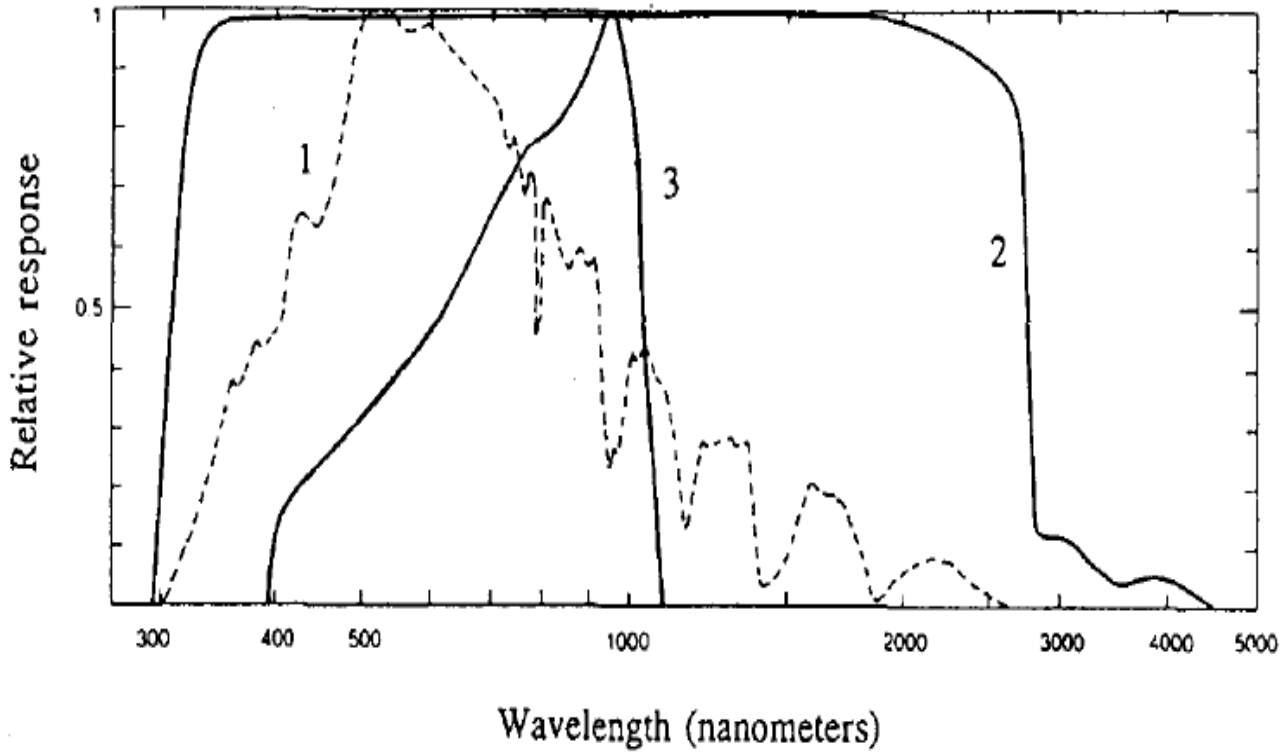
Measurement of Solar Radiation

- The global solar radiation has two components namely direct and diffuse radiation. The global radiation is measured with the pyranometers, and the direct radiation with pyrheliometer.
- The devices use two types of sensors: thermal and photovoltaic.



	The pyranometer with solar cell sensor	The pyranometer with thermal sensor
advantages	•The time of the response is very good 10 μs •cheap; •stability; •ruggedness; •tolerance to soiling.	•nearly constant spectral response on the whole solar spectral range; •highly used.
disadvantages	•the limited spectral response; •the nonuniform spectral response; •the temperature influence upon the response.	•The response time is a disadvantage, in the order of seconds; •Introduces significant errors for instantaneous measurements (clear-cloudy); •are expensive.

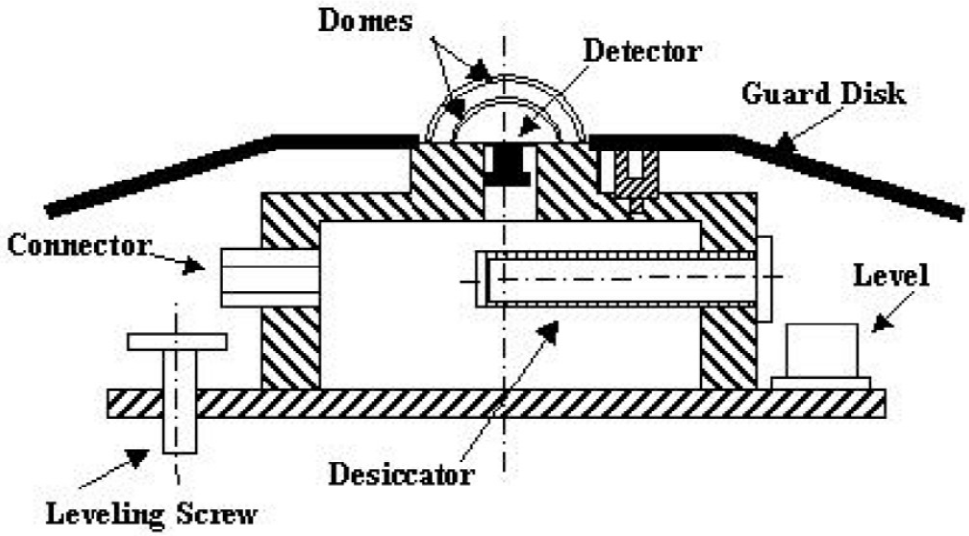
The advantages and disadvantages of the two types pyranometers

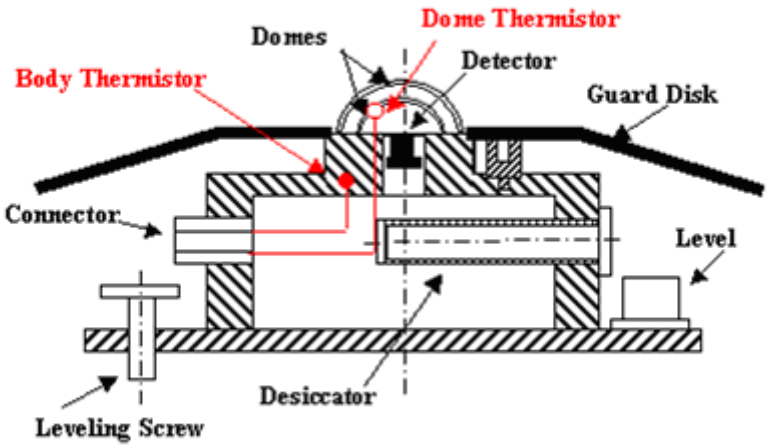


Silicon pyranometer and thermopile pyranometer spectral responses.
1.Spectral distribution of solar radiation at sea level for a 1 air mass
2. Relative spectral response for thermopile pyranometer (Kipp & Zonen CM-11)
3. Relative spectral response for photovoltaic sensor (Licor 200~SZ)

Precision Spectral Pyranometer (PSP)

- The inner and outer domes, their role is to filter out infrared radiation coming from the atmosphere and the surroundings and to allow shortwave radiation coming from the sun to reach the detector.
- The detector is a thermopile made with more than 40 thermocouples connected in series. The hot junction of the thermopile is coated with a highly absorbing material.
- The body of the instrument is a cylindrical piece of brass painted white to reduce the absorption of solar irradiance. The electrical circuit is mounted inside. The body is used as heat sink for the cold junction of the thermopile.
- The guard disk is a circular piece of metal painted white. It shields the instrument body from downwelling solar radiation.
- The instrument also contains a desiccant to remove the humidity inside the body to protect the circuitry, and a bubble level to guide the leveling of the absorber surface.

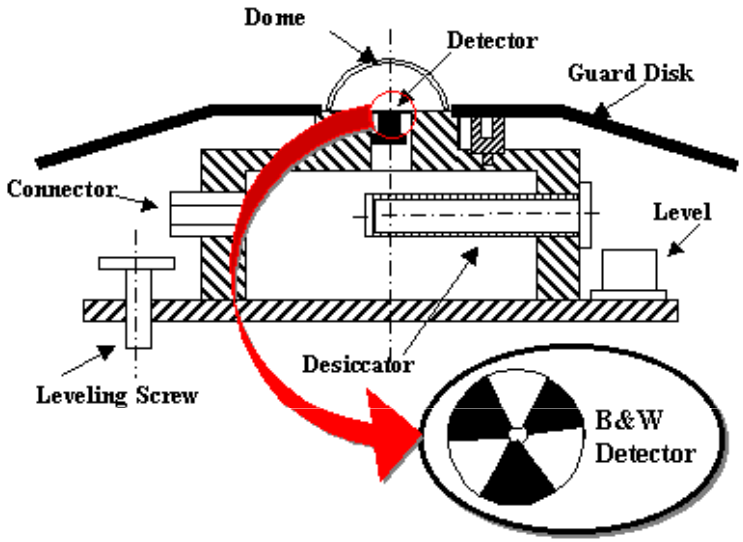




The modified PSP

Eppley B&W Pyranometer

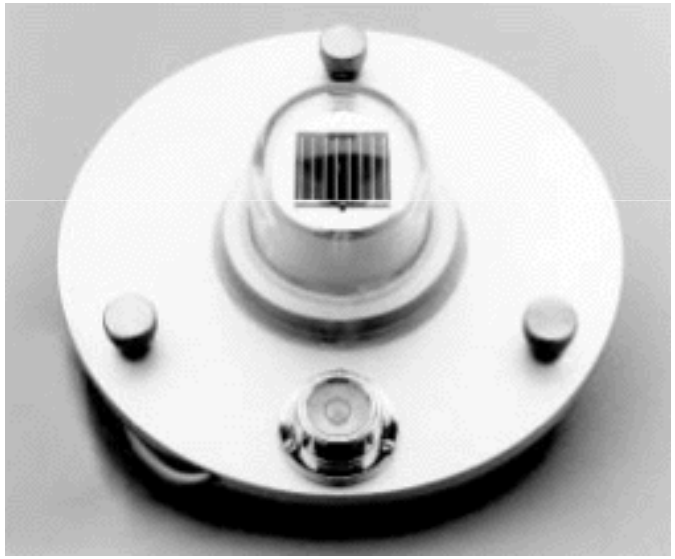
- The Black and White (B&W) pyranometer is an instrument designed to measure diffuse broadband solar irradiance.
- The difference between PSP and B&W are:



1. It has only one dome to filter out IR radiation coming from the atmosphere;
2. The detector is coated with white and black paint;
3. It has much less thermal mass.

Silicon Cell Pyranometer

- The sensor is a silicon photovoltaic cell which absorbs radiation from 0.35 to 1.15 microns.
- The silicon cell converts this light energy directly into electrical energy, and the output voltage (approximately 70 $mV/W/m^2$) is essentially linear with light intensity.
- Full-scale response time is less than 1 millisecond due to the fact that the instrument is light sensitive, not heat sensitive as the thermopile pyranometers are.
- If the output is integrated over a daily period, the accuracy of the value is within +/-3%. Accuracy of instantaneous values is +/-5%.
- Temperature compensation is provided from 4° to 60°C.

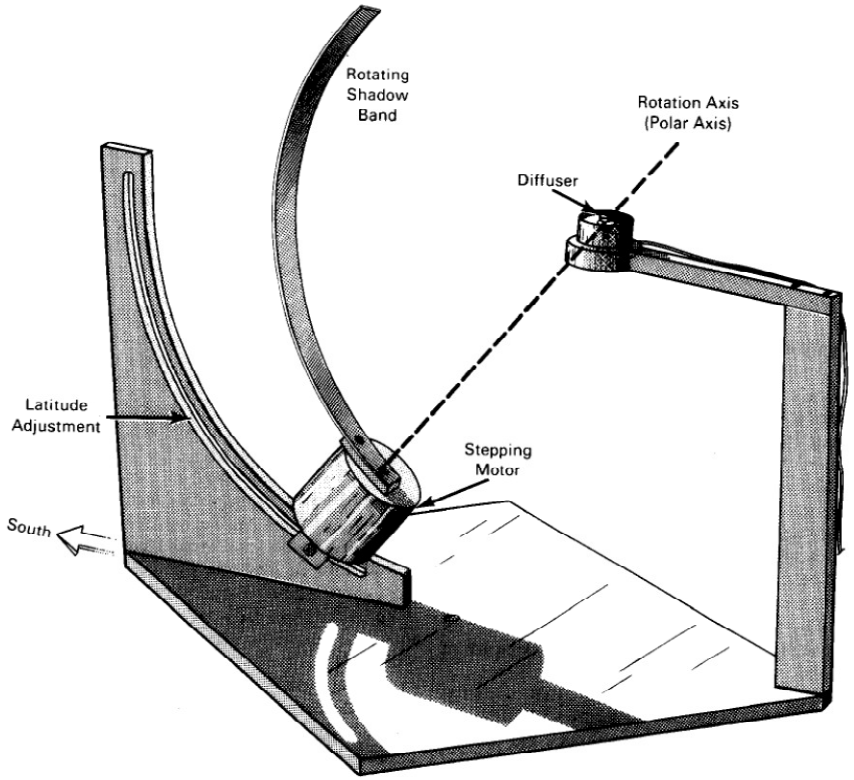


Eppley Normal Incident Pyrheliometer (NIP)

- A pyrheliometer is an instrument that measures the direct component of the solar beam at normal incidence. Therefore a pyrheliometer must be mounted on a device called a solar tracker that orients the pyrheliometer perpendicular to the solar beam during the day.
- The detector of a NIP is a thermopile located at the base of a tube with an aperture-to-length ratio of 1/10, subtending $5^0 43'30''$

- A pyranometer shaded from direct solar radiation can be used to measure diffuse radiation. One implementation uses a band stretching from the eastern to the western horizon that is oriented according to the solar declination to shade the pyranometer with the plane of the band parallel to the celestial equator. Since the solar declination changes, this band must be adjusted with a frequency that depends on accuracy requirements and time of year.

- Weseley introduced an instrument that uses a rotating shadowband with a fast response silicon cell pyranometer. An inexpensive constant speed motor drives the shadowband continuously, thus periodically shading the pyranometer.
- It was considered desirable for the shadowband to have the following features:

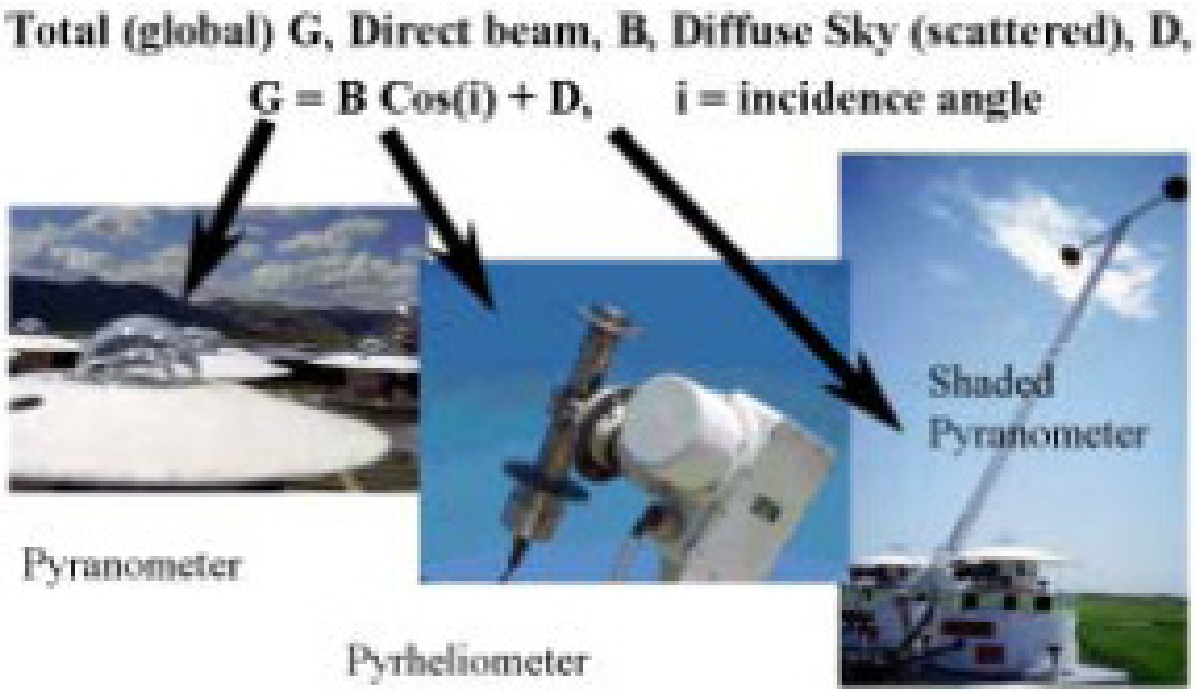


- the same angle should be subtended for all positions of the shadowband;
- the instrument should work at all latitudes;
- the construction should be simple;
- the shadowband should move completely from the field of view for the total horizontal measurement;
- the computation for the position of the shadowband should be simple

SPN1 Sunshine Pyranometer

- The Sunshine Pyranometer uses an array of seven, miniature thermopile sensors and a computer-generated shading pattern to measure the direct and diffuse components of incident solar radiation.
- All seven thermopiles receive an equal amount of diffuse light. From the individual thermopile readings, a microprocessor calculates the global and diffuse horizontal irradiance and from these values an estimate of sunshine state is made.

Instruments for measuring solar radiation components



Albedo

The albedo is a measure of the reflectivity of surfaces. It is an important parameter for different research domains, such as: the photovoltaic domain, the atmospheric sciences, climatology, the agriculture, the forestry and the building energy science.

The empirical models for solar radiation

- The computation of the solar global-radiation can be derived basically from the correlation between the monthly average daily global solar-radiation and the sunshine duration using Angströms simple linear-regression formula

$$H = H_0\left(a + b\frac{S}{S_0}\right)$$

- where H is the monthly average daily global irradiation, H_0 is the monthly average daily extraterrestrial irradiation, S is the monthly average daily hours of bright sunshine, S_0 is the monthly average daily maximum possible daily sunshine hours, and a, b are regression constants, which are dependent upon local climate and topography.

- the mean expected hourly global solar radiation can be determined with the model based on the function:

$$I_g\left(h, n_j\right) = \alpha + \beta \cos\left(\frac{2\pi h}{24}\right)$$

A SIMPLE METHOD TO ESTIMATE GLOBAL RADIATION

- A simple method to estimate daily global radiation relating the difference between maximum and minimum temperature to global radiation (Hargreaves *et al.*) is:

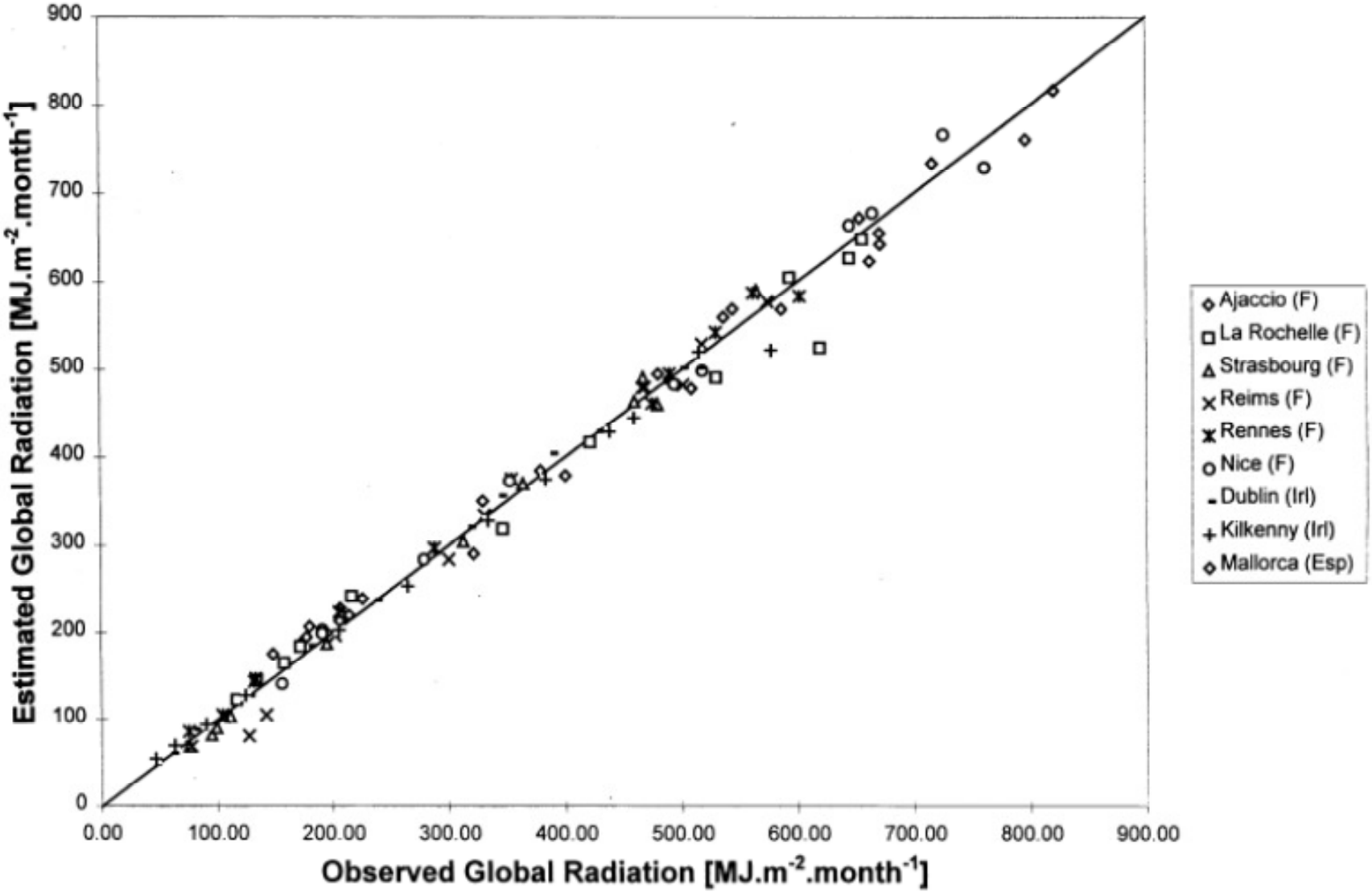
$$H = aH_o\sqrt{(T_{max} - T_{min})} + c$$

- where T_{max} is the maximum temperature (°C), T_{min} is the minimum temperature (°C), *a* and *c* are empirical constants. This model has been validated for the Senegal River Basin
- The advantage of this model is that temperature observations are always available on the GTS. However, the estimation accuracy, applying this model for locations in Europe is limited (Choisnel et al.)

- a simple empirical model which can be considered a ccombination of the Worner and Hargreaves *et al*. model:

$$H = H_o[a\sqrt{(T_{max} - T_{min})} + b\sqrt{(1 - C_w/8)}] + c$$

- where C_w is the mean of the total cloud cover of the daytime observations (octa) and *a*, *b* and *c* are empirical constants.



Monthly total values of global radiation, estimated with the proposed method, plotted against observed values for various locations in France (F), Ireland (Irl) and for one location in Spain (Esp)

Iqbal model C

- The direct normal irradiance I_n (Wm^{-2}) in model C described by Iqbal is given by:

$$\dot{I}_{\mathrm{n}} = 0.9751 E_{\mathrm{o}} \dot{I}_{\mathrm{sc}} \tau_{\mathrm{r}} \tau_{\mathrm{o}} \tau_{\mathrm{g}} \tau_{\mathrm{w}} \tau_{\mathrm{a}}$$

- where the factor 0.9751 is included because the spectral interval considered is 0.3–3 µm; I_{sc} is the solar constant which can be taken as 1367 Wm^{-2}. E_o (dimensionless) is the eccentricity correction-factor of the Earth's orbit and is given by:

$$E_{\mathrm{o}} = 1.00011 + 0.034221\cos\Gamma + 0.00128\sin\Gamma + 0.000719\cos 2\Gamma + 0.000077\sin 2\Gamma$$

Iqbal model C

- Where $$\Gamma = 2\pi\left(\frac{N-1}{365}\right)$$

- τ_r, τ_o, τ_g, τ_w, τ_a (dimensionless) are the Rayleigh, ozone, gas, water and aerosols scattering-transmittances respectively.

$$\tau_r = e^{-0.0903 m_a^{0.84}\left(1+m_a-m_a^{1.01}\right)}$$

$$\tau_o = 1 - \left[0.1611 U_3 (1 + 139.48 U_3)^{-0.3035} - 0.002715 U_3 \left(1 + 0.044 U_3 + 0.0003 U_3^2\right)^{-1}\right]$$

$$\tau_g = e^{-0.0127 m_a^{0.26}}$$

$$\tau_w = 1 - 2.4959 U_1 \left[(1 + 79.034 U_1)^{0.6828} + 6.385 U_1\right]^{-1}$$

$$\tau_a = e^{-l_{ao}^{0.873}\left(1+l_{oa}-l_{ao}^{0.7808}\right) m_a^{0.9108}}$$

- where m_a (dimensionless) is the air mass at actual pressure and m_r (dimensionless) is the air mass at standard pressure (1013.25 mbar). They are related by

$$m_a = m_r\left(\frac{p}{1013.25}\right)$$

- where p (mbar) is the local air-pressure.
- U_3 (cm) is the ozone's relative optical-path length under the normal temperature and surface pressure (NTP) and is given by

$$U_3 = l_{oz} m_r$$

- where l_{oz} (cm) is the vertical ozone-layer thickness.
- U_1 (cm) is the pressure-corrected relative optical-path length of precipitable water, as given by

$$U_1 = w m_r$$

where w (cm) is the precipitable water-vapour

Diffuse radiation

- theoretically, the diffuse radiation can be calculated in terms of the clearness index, K, using empirical equations derived by Liu and Jordan and Klein:

$$\frac{H_d}{G} = A + BK + CK^2 + EK^3$$

- where $K = G / H_0$; H_d is the estimated local diffuse-radiation (kWh/m^2/day); G is the daily local global-radiation (kWh/m^2/day); H_0 is the extraterrestrial daily radiation (kWh/m^2/day); and A, B, C, E are constants determined from the different values of K using a multiple correlation.

- Ulgen and Hepbasli (2002) developed the following empirical correlations for the city of Izmir, Turkey, based on the measurements made in the Meteorological Station of Solar Energy Institute, Ege University, Izmir, Turkey over a 5-yr period from 1994 to 1998:

$$\frac{I_D}{I} = \begin{cases} 0.68 & \text{for } k_T < 0.32 \\ 1.0609 - 1.2138k_T & \text{for } 0.32 < k_T < 0.62 \\ 0.30 & \text{for } k_T > 0.62 \end{cases}$$

$$\frac{I_D}{I} = \begin{cases} 0.68 & \text{for } k_T < 0.32 \\ 0.0743 - 19.343k_T + 206.91k_T^2 & \\ \quad -719.72k_T^3 + 1053.4k_T^4 - 562.69k_T^5 & \text{for } 0.32 < k_T < 0.62 \\ 0.30 & \text{for } k_T > 0.62 \end{cases}$$

- Various approaches have been proposed to simulate radiation over horizontal surfaces. The main group is of the spectral type, which considers the full spectrum of solar radiation using the radiative transfer equations. The MODTRAN, SPECTRAL 2, and SMARTS 2 are representatives of this group.

Code name	Code developer(s)	Code processing method	Code description
6S	D. Tanré et al.	Single-scattering	6S is one of the best codes for satellite spectral radiance simulations with heavy documentation. Available from ftp://loaser.univ-lille1.fr/ or ftp://kratmos.gsfc.nasa.gov/6S/
ATRAD	W. Wiscombe	Adding doubling	W. Wiscombe does not support this code any more. The code is based on the adding and doubling technique.
CliRad SW and CliRad LW	M.D. Chou	2-stream 1-D	Radiative transfer codes used in global circulation models and mesoscale models developed at NASA, Goddard.
Column radiation model (CRM)	NCAR		CRM is a stand-alone version of the radiation model used in the NCAR community climate model (CCM).
DISORT	K. Stamnes, S.C. Tsay, W. Wiscombe	1-D discrete ordinates method (DOM)	DISORT is a solver only. Available from ftp://climate.gsfc.nasa.gov/pub/wiscombe/Disc_Ord. Description of the code: http://imk-msa.fzk.de/msa-public/softaware-tools/modtran/science/disort.htm
DOM	J. Haferman	DOM	The code is available from ftp://iihr.uiowa.edu/pub/hml/haferman
Discrete ordinates optical simulator (DOORS)	C. Godsalve	DOM	DOORS uses aerosol data from LOWTRAN (see below) and gaseous absorption data from 6S (see above).
FASCODE	AFGL	Line-by-line	Instructions and download at http://www2.bc.edu/~sullivab/soft/fascode.html
FluxNet	J. Key	Neural networks	FluxNet is the neural network version of STREAMER (see below). Given a set of input data consisting of surface, cloud and atmospheric characteristics, FluxNet calculates upwelling and downwelling surface flux in either short wave or long wave. While it is not as flexible as STREAMER, FluxNet is faster by two to four orders of magnitude, making it ideal for large batch jobs and image processing.

Fu-Liu v. 0602b	Q. Fu, K.N. Liou	K-distribution, two-stream	The code was popular in the past but has poor documentation. It is a two-stream solver with good molecular package. Available from http://snowdog.larc.nasa.gov/rose/flp/ (on-line computation) or http://snowdog.larc.nasa.gov/rose/fu0602/ (documentation and source code download).
GENSPECT	University of Toronto, atmospheric physics (now as a commercial product)	Line-by-line	GENSPECT is a radiative transfer toolbox under MATLAB to calculate gas absorption and emissivity, emission and transmission for a wide range of atmospheric gases from NUV to NIR. For more information, see http://www.genspect.com
Line-by-line radiative transfer model (LBLRTM)	Atmospheric and environmental research inc.		Documentation and download of LBLRTM from http://www.rtweb.aer.com/lblrtm_frame.html. The code needs some input data, which can be taken from the output of the LNFL code (http://www.rtweb.aer.com).
libRadtran	A. Kylling and B. Mayer		libRadtran is a collection of C and FORTRAN functions and programmes for calculation of solar and thermal radiation in the earth's atmosphere. Free download of source code and instructions are available from http://www.libradtran.org
LidarPC			Information is available from http://www.optics.arizona.edu/Palmer/PDF/atmosoft.pdf
LOWTRAN	AFGL	Band model approximation of line-by-line	LOWTRAN is a lower-resolution code than its successor, MODTRAN. One should prefer to use MODTRAN instead. LOWTRAN source code is freely available from http://www1.ncdc.noaa.gov/pub/software/lowtran/
Monte Carlo modelling in multi-layer media (MCML)	L.H. Wang and S.L. Jacques	Monte Carlo	MCML is a steady-state Monte Carlo simulation programme intended for multi-layered turbid media. Each layer has its own optical properties of absorption, scattering, anisotropy and refractive index. MCML code and documentation can be found at http://omlc.ogi.edu/pubs/abs/wang95c.html
MODTRAN	AFGL (Berk et al., 1999)	Band model approximation of line-by-line, and DOM	Newer versions of MODTRAN include multiple scattering. It is considered as one of the best codes because its molecular package (based on HITRAN) is often updated. Older versions can be downloaded from http://www2.bc.edu/~sullivab/soft/instruct.html, where a non-disclosure agreement must be signed. MODTRAN's original report as a postscript file can be found at http://imk-msa.fzk.de/msa-public/software-tools/modtran/science/modrep.htm. Recent versions are distributed on a commercial basis by Ontar Corp., http://www.ontar.com
Moderate spectral atmospheric radiance and transmittance (MOSART)	AFGL	Band-model approximation	MOSART is a unified computer code for calculating atmospheric transmission and radiance at low altitudes for line-of-sight paths within the atmosphere and for paths that intersect the earth's surface. Download of code can be done through http://www2.bc.edu/~sullivab/soft/NDA_MOSART.txt, after a non-disclosure, agreement is signed.

(*continued*)

mc-layer	A. Macke	Monte Carlo	A radiative transfer code for multiple scattering in vertically inhomogeneous atmospheres.
Polarised radiative transfer (PolRadTran)	F. Evans		PolRadTran is a plane-parallel fully polarised atmospheric radiative transfer model. It is available from http://nit.colorado.edu/~evans/polrad.html
SAMM	AFGL		A combination of SHARC and MODTRAN to calculate the IR radiance. The source code is available from http://www2.bc.edu/~sullivab/soft/NDA_SAMM.txt. A non-disclosure agreement must be signed first.
SBDART	P. Ricchiazzi, S. Yang and C. Gautier	1-D code using the DOM	SBDART is a FORTRAN computer code for the analysis of a wide variety of radiative transfer problems in satellite remote sensing and atmospheric energy budget studies. The source code can be downloaded from http://arm.mrcsb.com/sbdart, while a description of SBDART can be found at http://crisp.nus.edu.sg/research/links/rs-arm.html
SCIATRAN	IFE/IUP University of Bremen	Line-by-line or correlated-k methods, plane-parallel mode or pseudo-spherical mode	SCIATRAN has been designed to allow fast and accurate simulation of radiance spectra as measured or expected to be measured from space with the passive remote sensing UV–visible–NIR spectrometers: Global ozone monitoring experiment (GOME) and SCIAMACHY. SCIATRAN is designed to be the forward model for retrieval of atmospheric constituents from GOME/SCIAMACHY satellite data. Available from http://www.iup.physik.uni-bremen.de/sciatran/. A licensing agreement must be signed
Synthetic High-Altitude Radiance Code SHARC	AFGL		Simulates IR high-altitude background radiation. The source code is available from http://www2.bc.edu/~sullivab/soft/NDA_SHARC.txt. A non-disclosure agreement must be signed first.

Spherical harmonics discrete ordinate for 3-D atmospheric radiative transfer (SHDOM)	F. Evans	3-D DOM	This code computes unpolarised monochromatic or spectral-band radiative transfer in a 1-, 2- or 3-D medium for either collimated solar and/or thermal emission sources of radiation. It is probably one of the best 3-D codes available. A description of the code can be found at http://nit.colorado.edu/~evans/shdom
SIG			The source code is available from http://www2.bc.edu/~sullivab/soft/NDA_SIG.txt. A non-disclosure agreement must be signed first.
Simplified method for atmospheric corrections (SMAC)	R. Rahman and G. Dedieu	Semi-empirical approximation	SMAC works over the whole solar spectrum. Available from ftp://www.cesbio.ups-tlse.fr
Simple model of the atmospheric radiative transfer of sunshine (SMARTS)	C. Gueymard	Transmittance parameterisations	The code calculates total as well as partial atmospheric transmittances, irradiances and illuminances. SMARTS and its documentation are available from http://www.nrel.gov/solar/models/SMARTS, after a password is given to download the code and an agreement is signed. A detailed description of early versions of SMARTS can be found in Gueymard (1995b; 2001).
Simple spectral model (SPCTRAL2)	R.E. Bird and C. Riordan	Transmittance parameterisations	Details of the code can be found in Bird (1984). The code is freely available from http://rredc.nrel.gov/solar/models/spectral/spectrl2 and is available in different versions (C, FORTRAN or spreadsheet)
System for transfer of atmospheric radiation (STAR)	H. Schwander, A. Kaifel, A. Ruggaber and P. Koepke		Details of the code can be found in Schwander et al. (2001). The code, as a Java application, is available from http://www.meteo.physik.uni-muenchen.de/strahlung/uvrad/Star/starprog.html. An agreement must be signed first
STREAMER	J. Key	DOM	Radiative transfer model that can be used for computing either radiances or irradiances for a wide variety of atmospheric and surface conditions. It is a 1-D radiative transfer solver with molecular package. Its molecular package is not often updated, however.

Calibration of Solar Cells

- Standard solar cells are used to set the intensity of solar simulators to standard illumination conditions, in order to electrically characterize solar cells with similar spectral response.

The calibration methods of solar cells can be:

1. **Extraterrestrial**

- the high altitude balloon
- the high altitude aircraft

2. **Space Methods**

3. **Terestrial Methods**

- global sunlight
- direct sunlight

High Altitude Balloon

- on board stratospheric balloons flying at altitudes of around 36 km
- the illumination sun conditions are very close to AM0
- the cells are directly exposed to the sun
- the cells mounted on supports with sun trackers

High Altitude Aircraft

- on board of an aircraft capable of flying at altitudes of 15-16 km.
- cells are mounted at the end cap of a collimating tube on a temperature controlled plate
- data are corrected for:

- the ozone absorption
- the geocentric distance
- extrapolated to the air mass value of zero

- The most realistic environment on which calibration of solar cells can be performed is indeed outside the atmosphere. The first constraint of these methods is their relatively high cost compared with the other two extraterrestrial methods and their lower level of maturity.

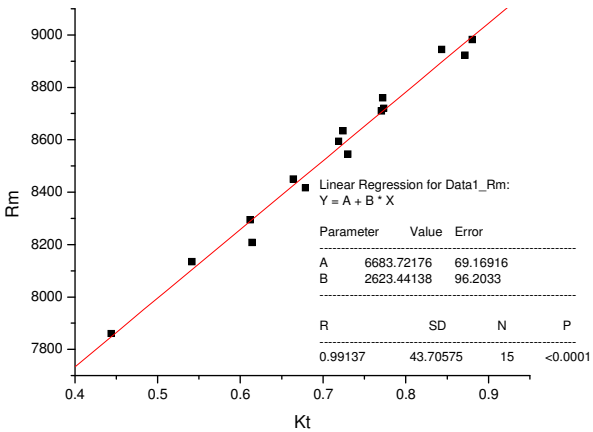
1. Space shuttle: On board the space shuttle, the Solar Cell Calibration Experiment (SCCE) was conducted in two flights in 1983/84, where solar cells from different agencies, institutions and space solar cell industries around the world were calibrated and returned back to Earth.
2. Photovoltaic Engineering Testbed: This is a NASA-proposed facility to be flown in the International Space Station, where after exposure and calibration of cells in the space environment, they are returned back to Earth for laboratory use
3. Lost Twin: This is an ESA-proposed method, based on the flight of several solar cells on a non-recoverable spacecraft. Cells nearly identical to the flight ones are kept on Earth. The orbiting cells are calibrated and these calibrated values are given to their respective twin cells.

Global Sunlight

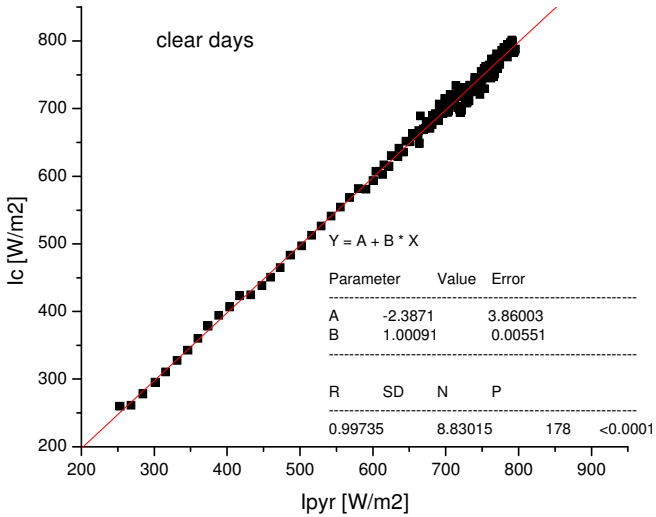
- The cells to be calibrated and a pyranometer are placed on a horizontal surface
- The calibration site environmental conditions need to fulfil several requirements relating to global and diffuse irradiance levels, solar elevation, unobstructed view over a full hemisphere, etc. The calibrated short circuit current of the cell is calculated by means of the following formula:

$$I_{sc} = I_{sg} \frac{\int (k_2 E_{g\lambda}) d\lambda}{E_{glob}} \frac{\int (k_1 s_\lambda) E_{s\lambda} d\lambda}{\int (k_1 s_\lambda)(k_2 E_{g\lambda}) d\lambda}$$

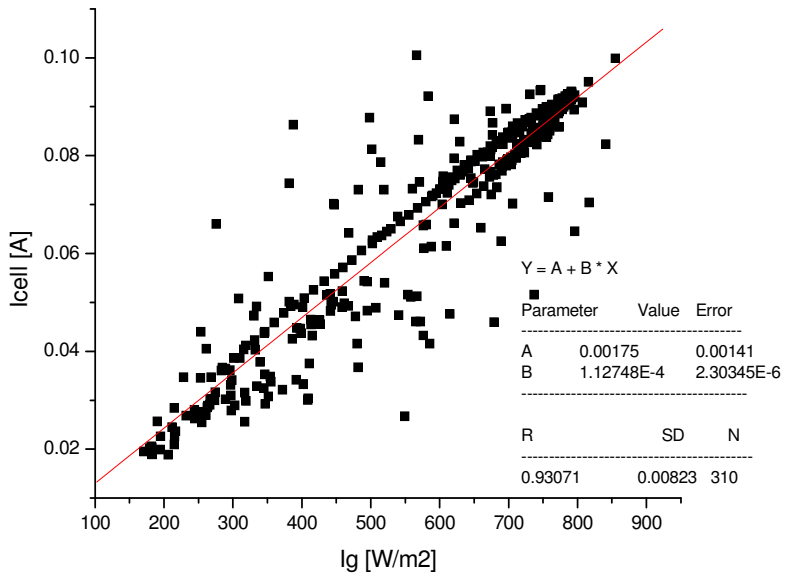
The solar cells calibration under global solar radiation

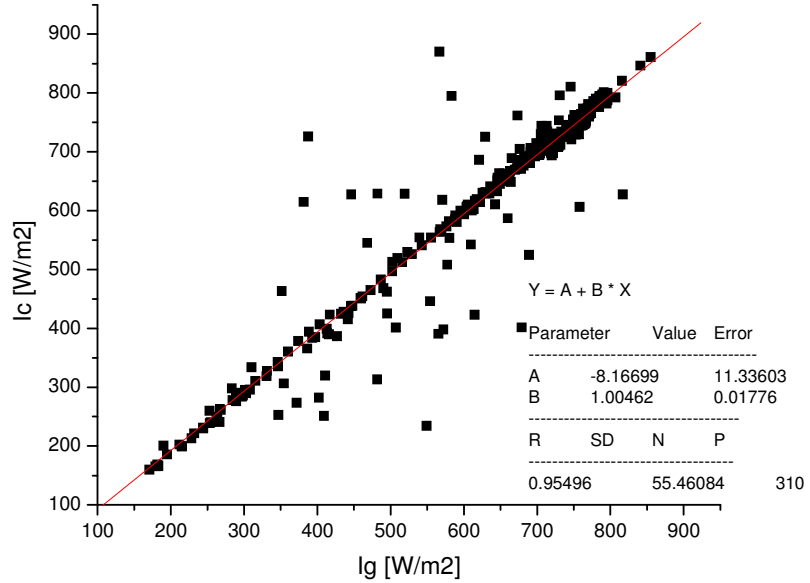


$$R_m = a \cdot K_t + b$$



$$I_c = \frac{b \cdot I_{cell} \cdot I_{ext}}{I_{ext} - a \cdot I_{cell}}$$



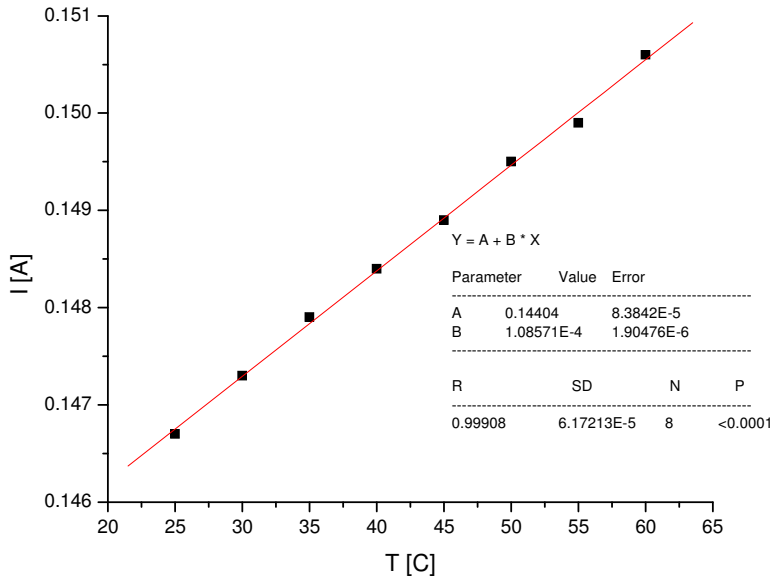


The uncorected and corrected curves Icell vs Ig (measuremtnts taken at five minutes intervals)

$$I_c = \frac{I_{g,ideal} \cdot I_{cell}}{I_{cell,ideal}}$$

Dependence of I_{sc} on T, for the Si solar cell

- As it can be observed the raise of the short circuit current is smaller than the decrease of open circuit voltage. This is the reason why the correction for the calibration function of the temperature variation during measurements becomes a second order factor.

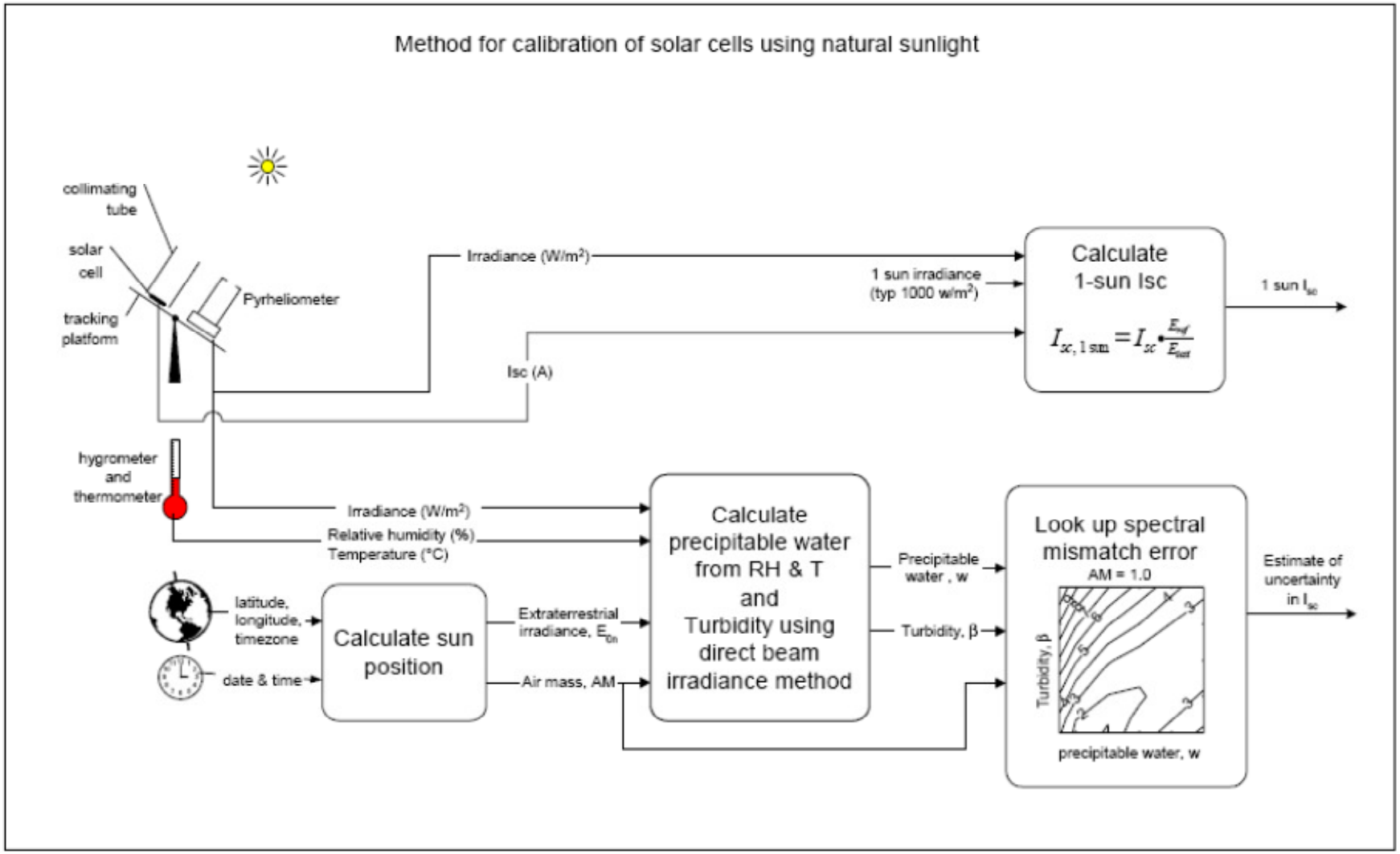


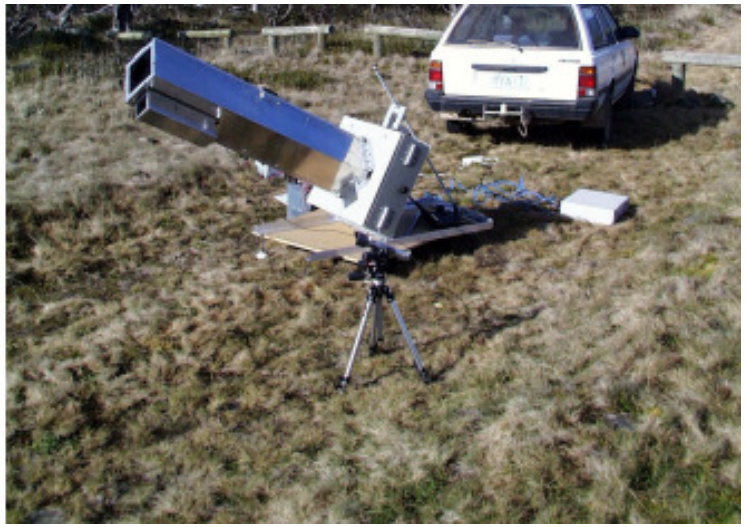
Name of cell	dI_{sc}/dT [A/K] at 1000 W/m^2	dV_{oc}/dT [V/K] at 1000 W/m^2
AstroPower cell covered with glass	$3.28*10^{-5}$	$-2.18*10^{-3}$
uncovered Si cell	$1.08*10^{-4}$	$-1.97*10^{-3}$

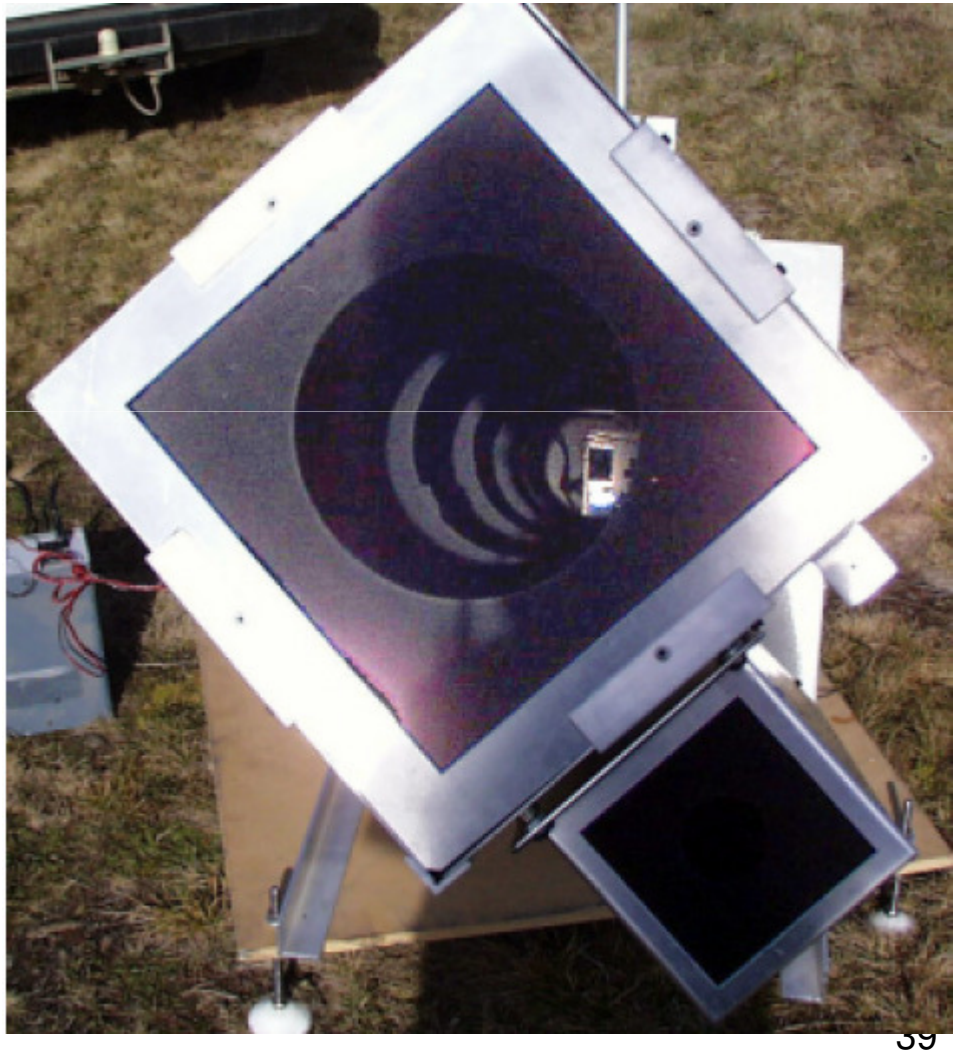
Direct Sunlight

- The cells to be calibrated are placed on the bottom plate of a collimation tube, a normal incidence pyrheliometer and a spectroradiometer are kept pointing to direct sunlight while measurements of short-circuit current, total irradiance and spectral irradiance are recorded.
- Several conditions need to be fulfilled by the calibration site and its environment, i.e. certain irradiance level, stable cell short-circuit readings, ratio of diffuse to direct irradiance, etc.
- The calibrated short circuit current of the cell is calculated by means of the following formula:

$$I_{sc'} = \frac{I_{sd} \int E_{d\lambda} d\lambda \int E_{s\lambda} s_{\lambda} d\lambda}{E_{dir} \int E_{d\lambda} s_{\lambda} d\lambda}$$


Method for calibration of solar cells using natural sunlight
collimating tube
solar cell
tracking platform
Pyrheliometer
Irradiance (W/m²)
1 sun irradiance (typ 1000 w/m²)
Calculate 1-sun Isc
1 sun Isc
Isc (A)
hygrometer and thermometer
Irradiance (W/m²)
Relative humidity (%)
Temperature (°C)
Calculate precipitable water from RH & T and Turbidity using direct beam irradiance method
Precipitable water , w
Turbidity, β
Look up spectral mismatch error
AM = 1.0
Turbidity, β
precipitable water, w
Estimate of uncertainty in Isc
latitude, longitude, timezone
date & time
Calculate sun position
Extraterrestrial irradiance, E0n
Air mass, AM





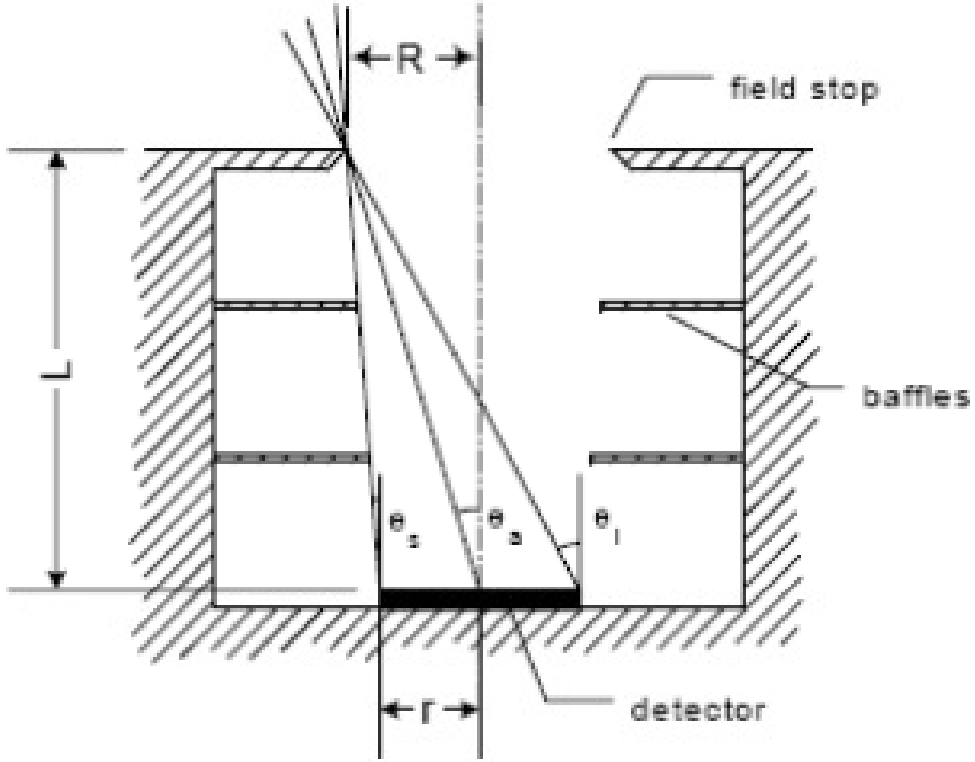
End view of the main collimating tube, with the reference tube on the side. A cell can be seen in the centre of the main tube

Geometry of a cylindrical collimator

A recommended collimator design is the smallest geometry that satisfies $\theta_a \approx 2° - 3°$ and $\theta_s > 1.26°$. For a cell of radius r (for a cell that is not circular, r should be the radius of an enclosing circle – eg for a square, r = ½ the diagonal), this is satisfied by:

$$R > 2r \qquad (\theta_s > 1°)$$

$$\frac{L}{R} = 24 \pm 4 \quad (\theta_a = 2° - 3°)$$



slope angle, θ_s, aperture angle, θ_a, and limit angle, θ_l.

Solar Simulator

- The cell to be calibrated is illuminated by means of a steady-state solar simulator adjusted to AM0 solar constant with a previously calibrated cell or a suitable detector.
- The spectral irradiance of the solar simulator is measured with a spectroradiometer and the relative spectral response of the cell is measured separately.
- The calibrated short circuit current of the cell is calculated as follows:

$$I_{sc} = I_{sm} \frac{\int Es\lambda s_{\lambda} d\lambda}{\int Em\lambda s\lambda d\lambda}$$

CALIBRATION OF SOLAR CELLS BY THE REFERENCE CELL METHOD--THE SPECTRAL MISMATCH PROBLEM

$$K = I/J \quad [\mathrm{mA} \cdot \mathrm{mW}^{-1} \cdot \mathrm{cm}^2]$$

$$K_{CA} = I_{CA}/J_A$$

$$K_{RA} = I_{RA}/J_A$$

$$K_{CA}/K_{RA} = I_{CA}/I_{RA}$$

$$K_{CS}/K_{RS} = I_{CS}/I_{RS}.$$

$$K_{CS}/K_{RS} \stackrel{?}{=} K_{CA}/K_{RA}$$

$$K_{CS}/K_{RS} = M\,K_{CA}/K_{RA}$$

$$I_{CS}/I_{RS} = M\,I_{CA}/I_{RA}.$$

$$I_{CS} = \Sigma\, E_{Si}R_{Ci}\Delta_i \quad [\mathrm{mA}]$$
$$I_{RS} = \Sigma\, E_{Si}R_{Ri}\Delta_i \quad [\mathrm{mA}]$$
$$I_{CA} = \Sigma\, E_{Ai}R_{Ci}\Delta_i \quad [\mathrm{mA}]$$
$$I_{RA} = \Sigma\, E_{Ai}R_{Ri}\Delta_i \quad [\mathrm{mA}]$$

$$\Sigma\, E_{Si}R_{Ci}\Delta_i/\Sigma\, E_{Si}R_{Ri}\Delta_i = M\,\Sigma\, E_{Ai}R_{Ci}\Delta_i/\Sigma\, E_{Ai}R_{Ri}\Delta_i$$

$$M = (\Sigma\, E_{Si}R_{Ci}\Delta_i/\Sigma\, E_{Si}R_{Ri}\Delta_i)/(\Sigma\, E_{Ai}R_{Ci}\Delta_i/\Sigma\, E_{Ai}R_{Ri}\Delta_i).$$

$$R_{Ri} = \alpha_i R_{Ci} \qquad E_{Ai} = \beta_i E_{Si}$$

$$M = (\Sigma\, E_{Si}R_{Ci}\Delta_i/\Sigma\, E_{Si}\beta_i R_{Ci}\Delta_i)/$$

$$(\Sigma\, \alpha_i E_{Si}R_{Ci}\Delta_i/\Sigma\, \alpha_i E_{Si}\beta_i R_{Ci}\Delta_i).$$

$$I_{CA} = I_{CS}/M.$$

- Jenkins, P. et al. 1997. Uncertainty analysis of high altitude aircraft air mass zero solar cell calibration. *Proc. 26th IEEE Photovoltaic Specialists Conf.,* Anaheim, pp. 857-860.
- Suppa, E.G. 1984. Space Calibration of Solar Cells. Results of 2 shuttle flight missions. *Proc. 17th IEEE Photovoltaic Specialists Conf.,* Orlando, pp. 301-305.
- Landis, G.A. et al. 2001. Calibration and measurement of solar cells on the international space station: A new test facility. *Proc. 36th Intersociety Energy Conversion Conf.,* pp. 229-231.
- Davies, M.A.H. and Goodbody, C. 1991. The calibration of solar cells in terrestrial sunlight. *Proc. 2nd European Space Power Conf.,* ESA SP-320,pp. 583-587.
- Garcia-Cervantes, L. et al. 1998. Ground level sunlight calibration of space solar cells. *Proc. 5th European Space Power Conf.,* ESA SP-416,pp. 615-620.
- Kawasaki, O. et al. 1994. Study of solar simulator method and round robin alibration plan of primary standard solar cell for space use. *Proc.1st World Conf. on Photovoltaic Energy Conversion,* Hawaii.