Lesson 1
The Solar Radiation

Mara Bruzzi

Università degli Studi di Firenze

OUTLINE

- Introduction
- The Electromagnetic radiation
- Photoelectric Effect – the Photon
- The Black Body Approximation
- The Solar Spectrum
- Artificial Light Spectra
- Measuring Irradiance and Illuminance

Introduction

Demand for primary energy on Earth is ever increasing. More than a quarter of the world's population, about 1.6 billion people, still have no access to commercial energy sources.

Current energy systems present inherent risks related to potential damage to the environment, availability and possible international conflicts related to their geographical distribution.

Public opinion as well as several international organizations are therefore heading for a transformation into more sustainable mix.

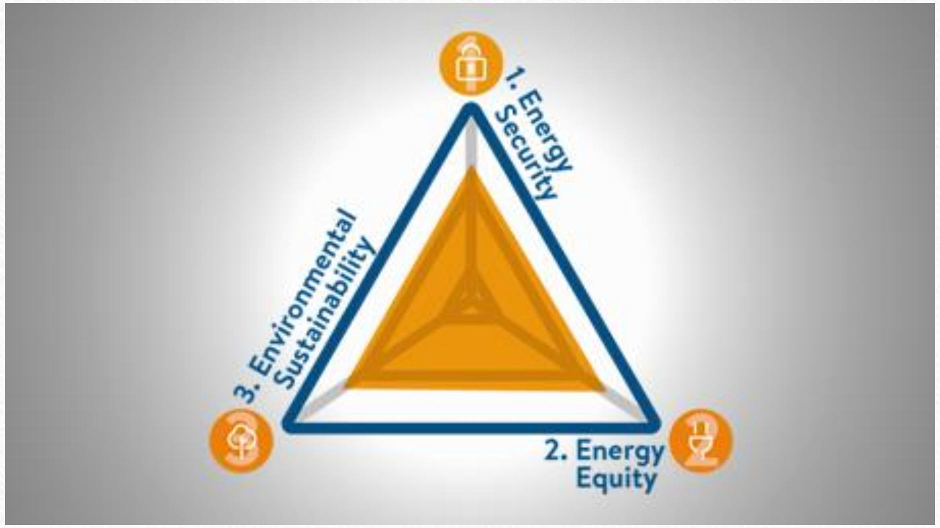
A significant contribution to this transformation will undoubtedly come from solar radiation.

https://youtu.be/M3DLJur7HjQ

The energy trilemma

The World Energy Council is the principal impartial network of leaders and practitioners promoting an affordable, stable and environmentally sensitive energy system for the greatest benefit of all.

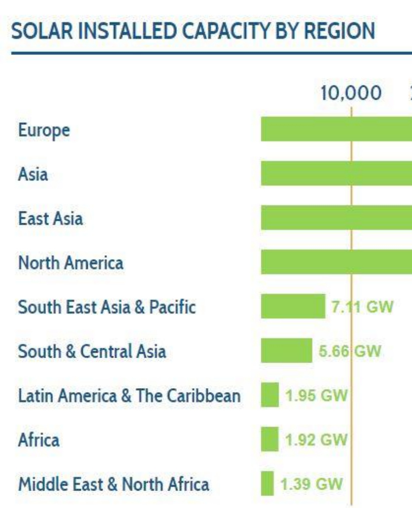
https://youtu.be/a4sp3L8kYI0



https://youtu.be/yWwQGyjX2_c

https://www.worldenergy.org

Solar Energy resources



http://www.irena.org/

* International Renewable Energy Agency (2016) represents the values at the end of year 2015.

https://youtu.be/EkILKYA3Kr8

Two main types of solar energy technologies:

- photovoltaic : convert solar radiation directly into electricity, without the use of any heat engine, and are increasingly popular in building integration purposes (such as using photovoltaic tiles as roof shingles) as well as for small- and large-scale devices, from watches to satellites.

- thermal collectors: used for domestic heating and hot water, but large solar collection plants can also be used for industrial heat purposes or for electricity generation based on the same mechanisms as fossil fuels.

*Global installed capacity for solar-powered electricity has seen an exponential growth, reaching around 227 GWe at the end of 2015. It produced 1% of all electricity used globally. Germany has led PV capacity installations over last decade and continues as a leader followed by China, Japan, Italy and the United States. Concentrated Solar Power (CSP) remains with very limited capacity at 4 GW today.

The Solar Constant

Total Solar Power Density outside atmosphere

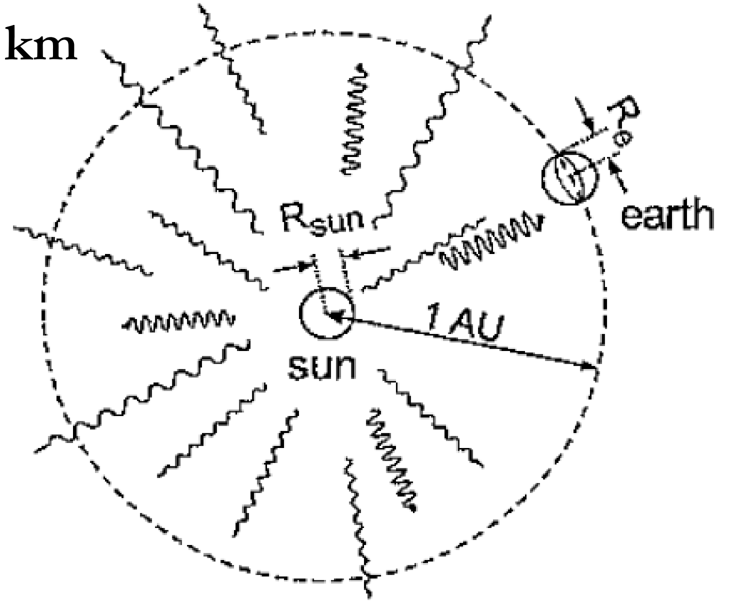
$$P_{sun}^{total} = \sigma_S \cdot T_S^4 \cdot 4\pi \cdot R_{sun}^2$$

$T_s \approx 5778$ K
$R_{sun} \approx 6.96 \times 10^5$ km
σ_s = Stefan Boltzmann constant

$\Rightarrow P^{total}_{Sun} = 3.85 \times 10^{26}$ W

Fraction of Power impinging Earth: $\approx 1.8 \times 10^{14}$ kW ($R_e \approx 6.4 \times 10^3$ km)

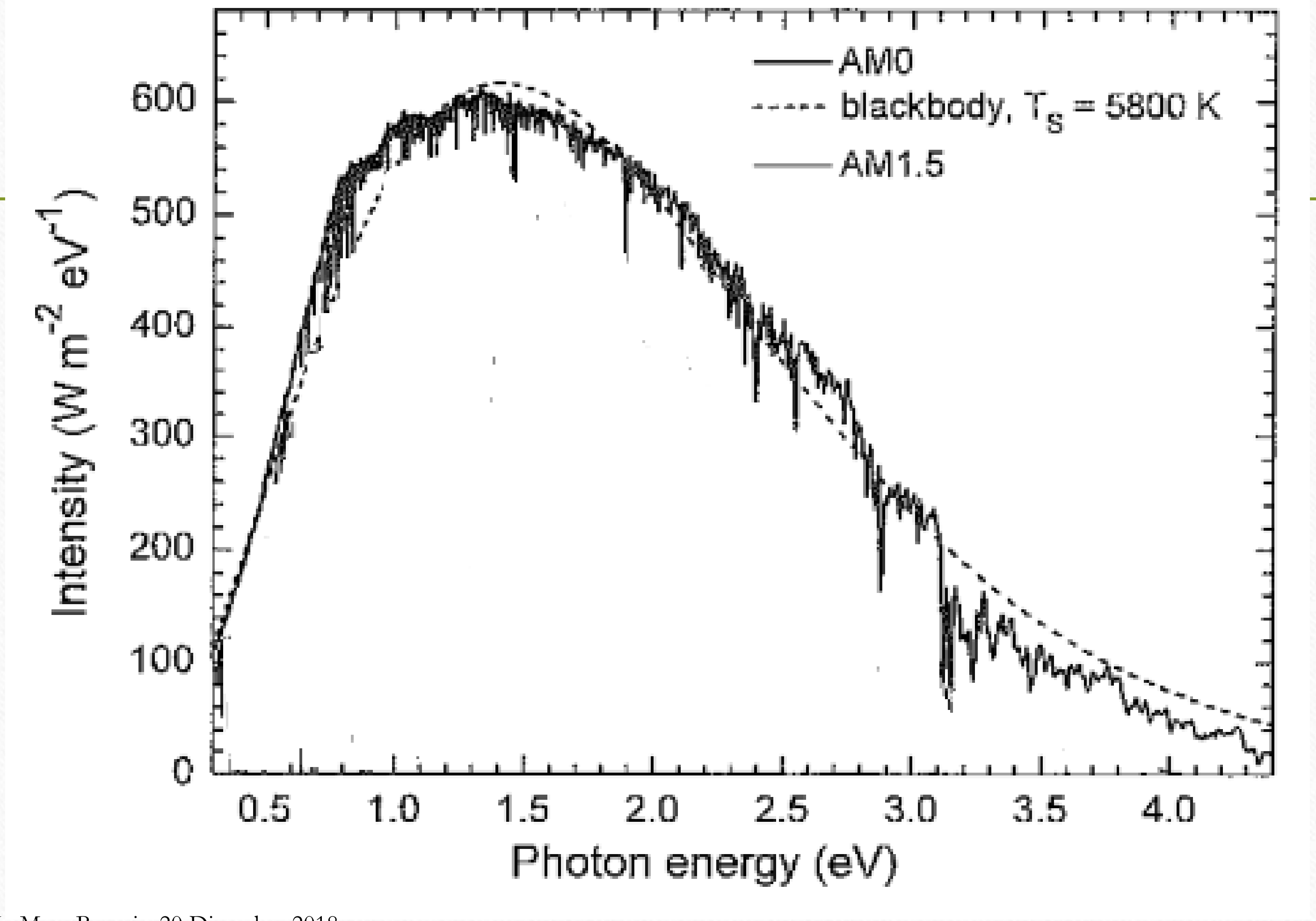
1 AU = 1 astronomic unit = Earth – Sun distance = 1.47 -1.52 10^8 km



SOLAR CONSTANT :

$$J_s = \frac{P_{sun}^{total}}{4\pi \cdot (AU)^2} \approx 1360 \text{ W/m}^2$$

Comparison between solar spectrum measured outside atmosphere (AM0) and black body spectrum at Ts = 5800K

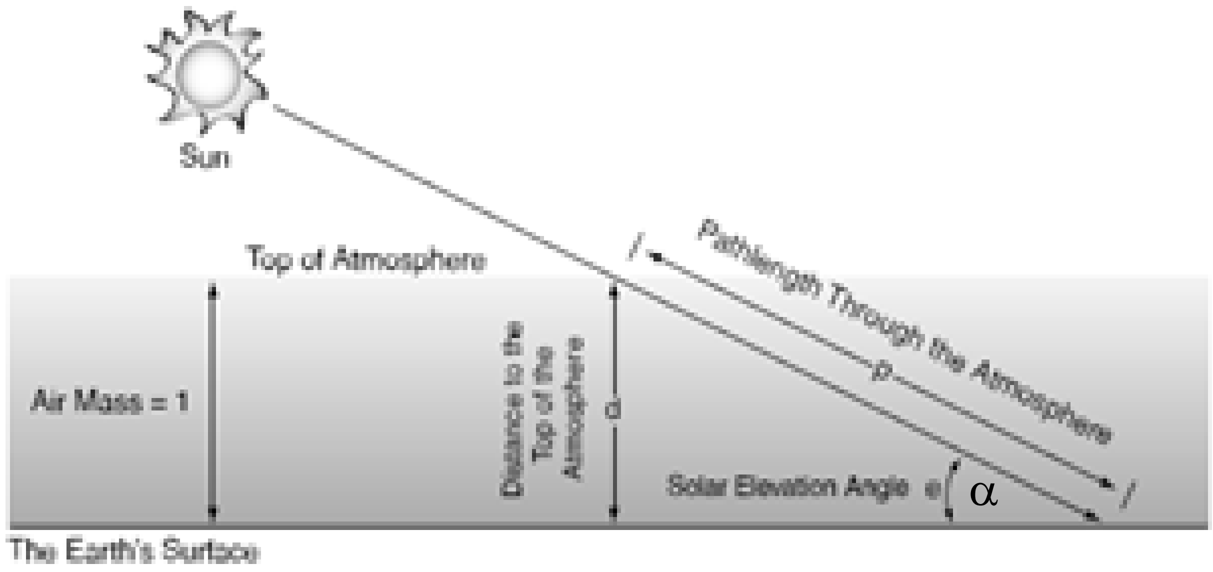


Atmospheric attenuation

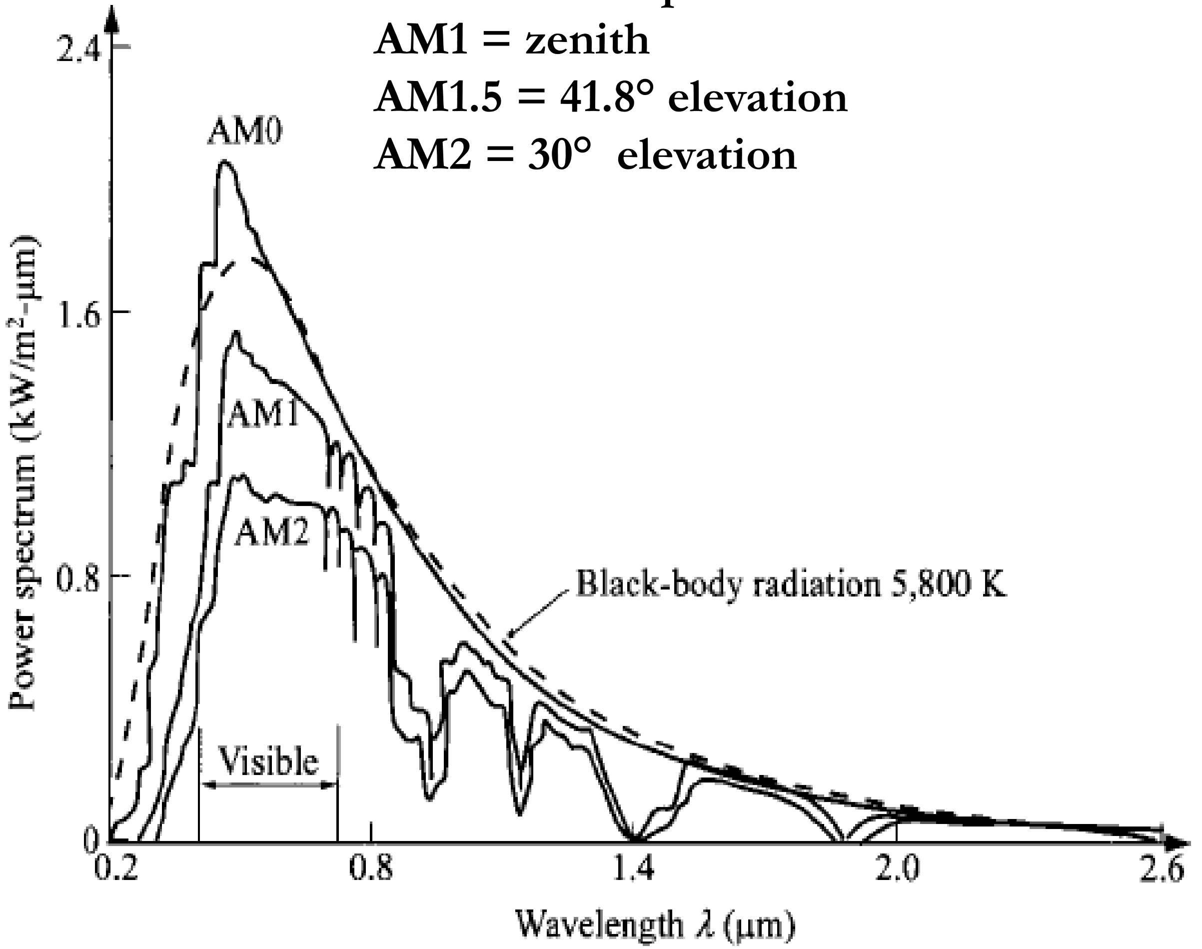
Atmospheric attenuation is measured by the numerical factor AIR MASS

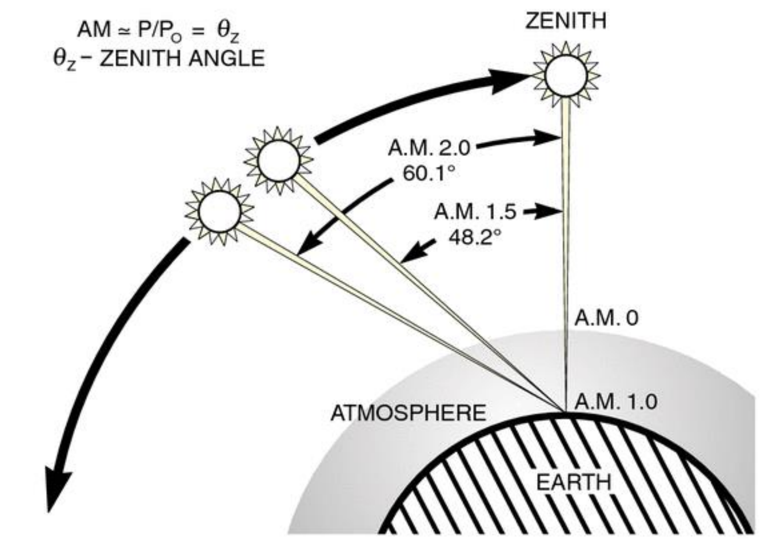
$$AIR\ MASS = AM = \frac{Pathlength\ through\ the\ atmosphere}{distance\ to\ the\ top\ of\ the\ atmosphere} = \frac{1}{\sin\alpha}$$

α = Solar elevation angle



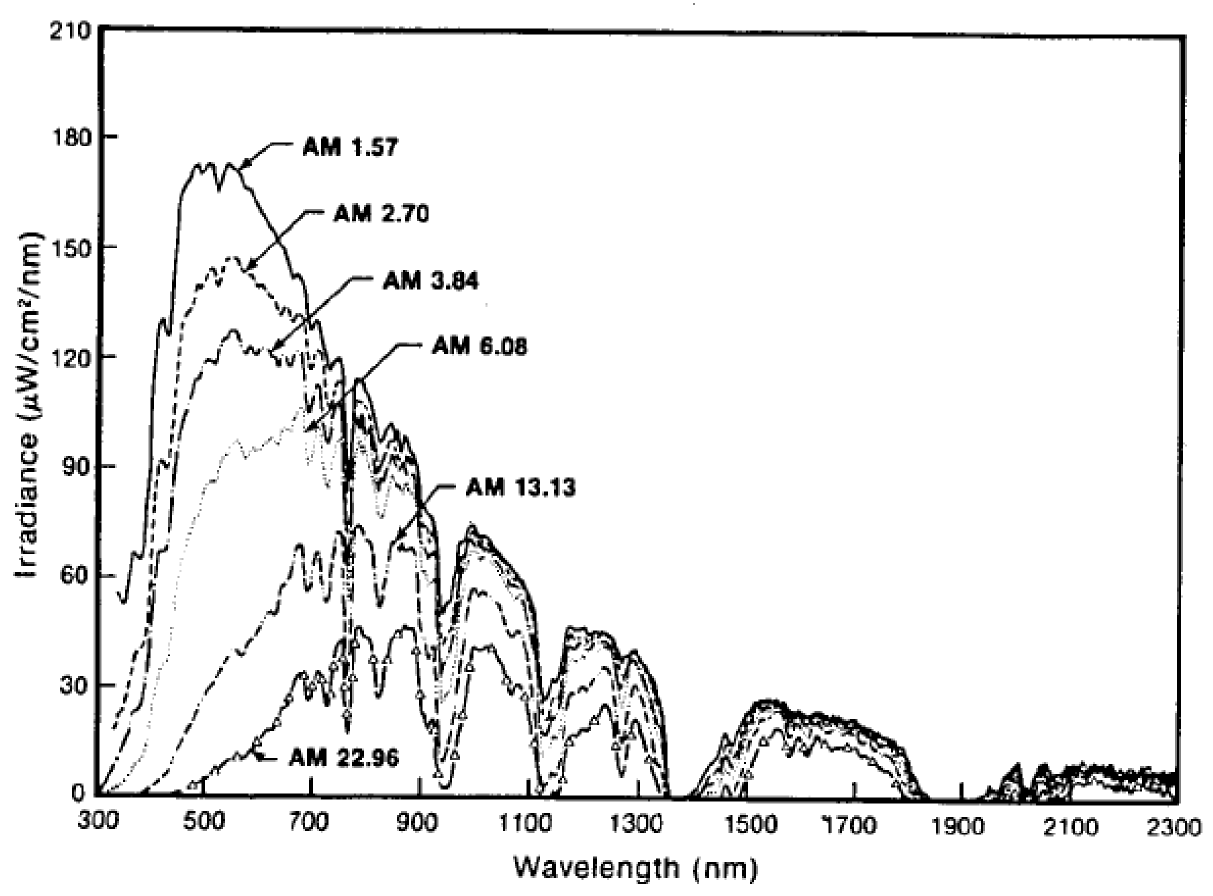
AM0 = Solar spectrum at the limit of atmosphere
AM1 = zenith
AM1.5 = 41.8° elevation
AM2 = 30° elevation





Other attenuation effects :
- **Aerosols in atmosphere**
- **Adsorption from O_2, H_2O, CO_2 gas**

Both solar radiation intensity and shape of the solar spectrum depend strongly on the AM value , which in turn varies during the day , the season and depends on the geographical position

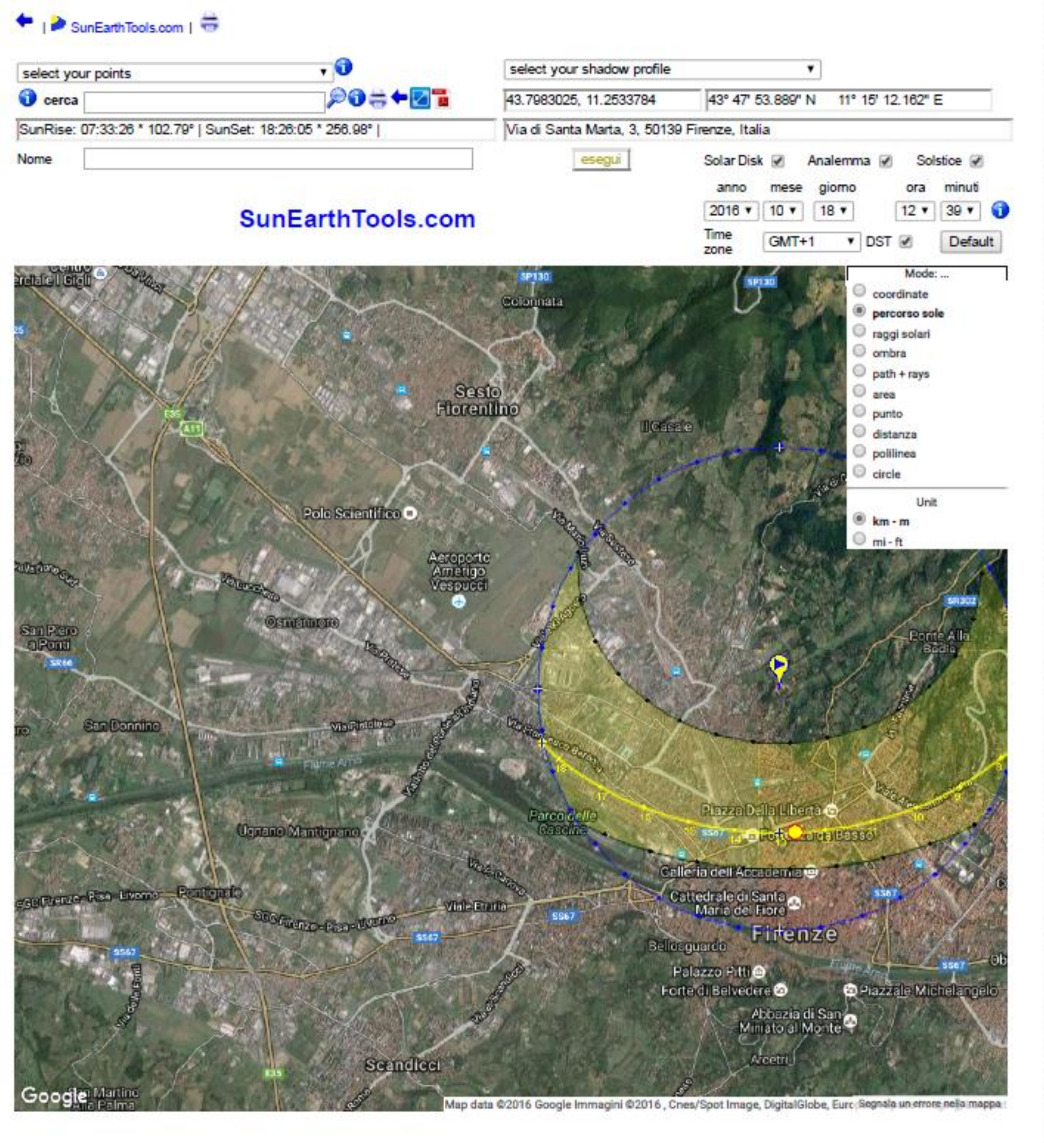


Air Mass Calculation

The AM is calculated from the elevation angle which in turn is determined from the GPS coordinates, time and altitude

Dedicated software open source:

http://www.sunearthtools.com/

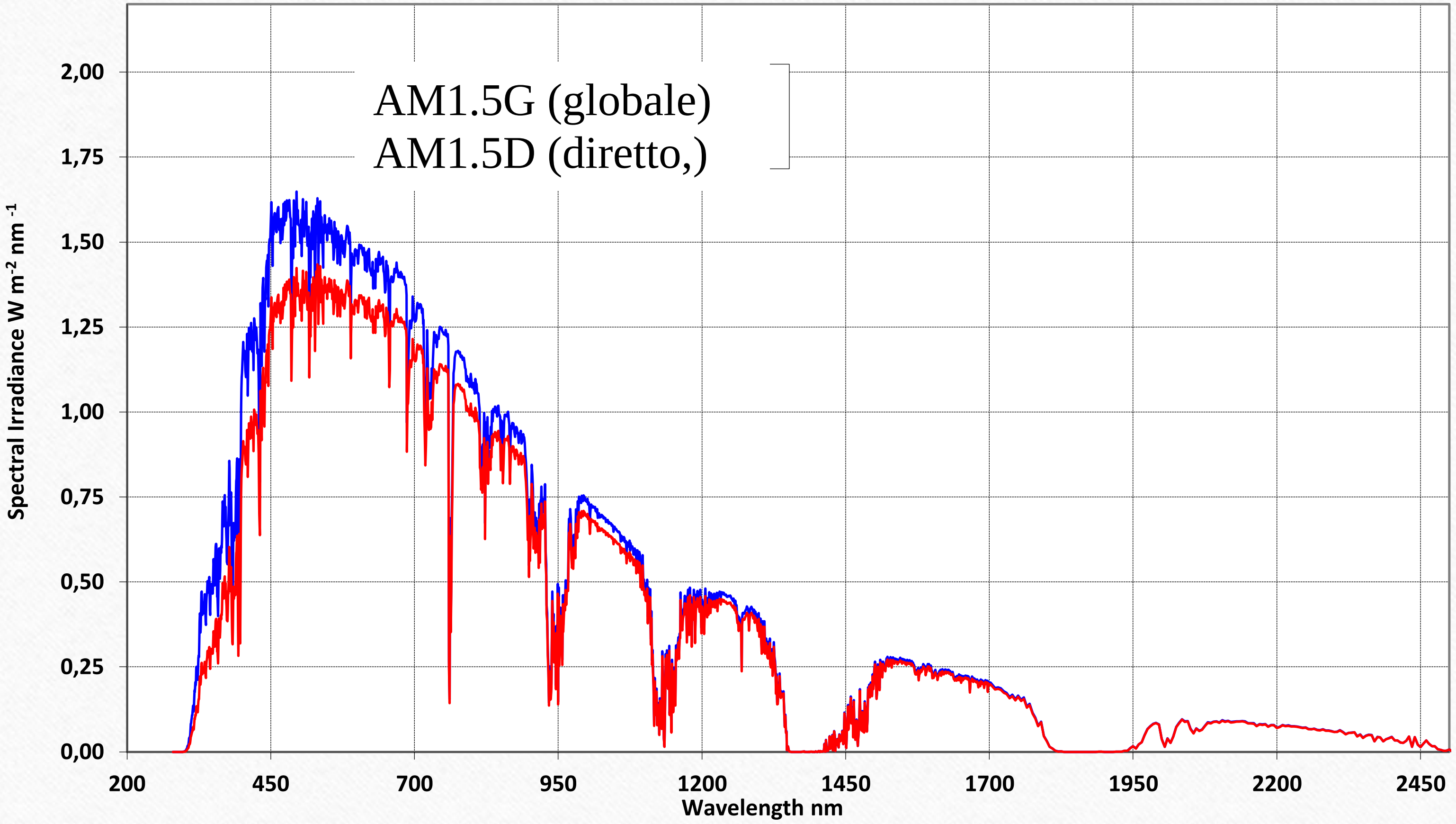


Direct, Diffuse and Global Solar Spectra

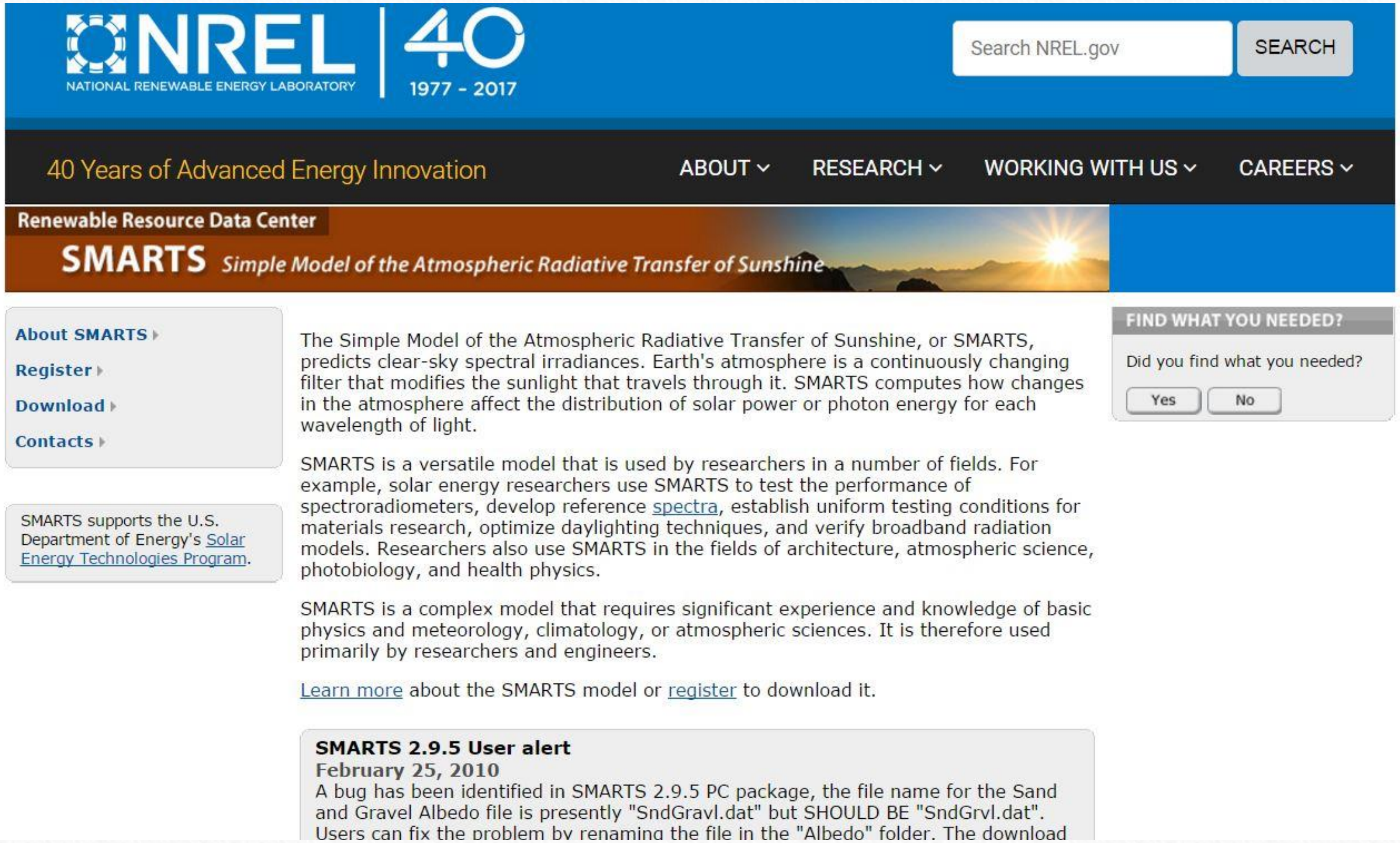
Direct = radiation coming directly from the Sun, impinging normally on the device (**D**)

Diffuse = scattering and diffused components (depending on the environment)

Global = Direct + Diffuse (**G**)

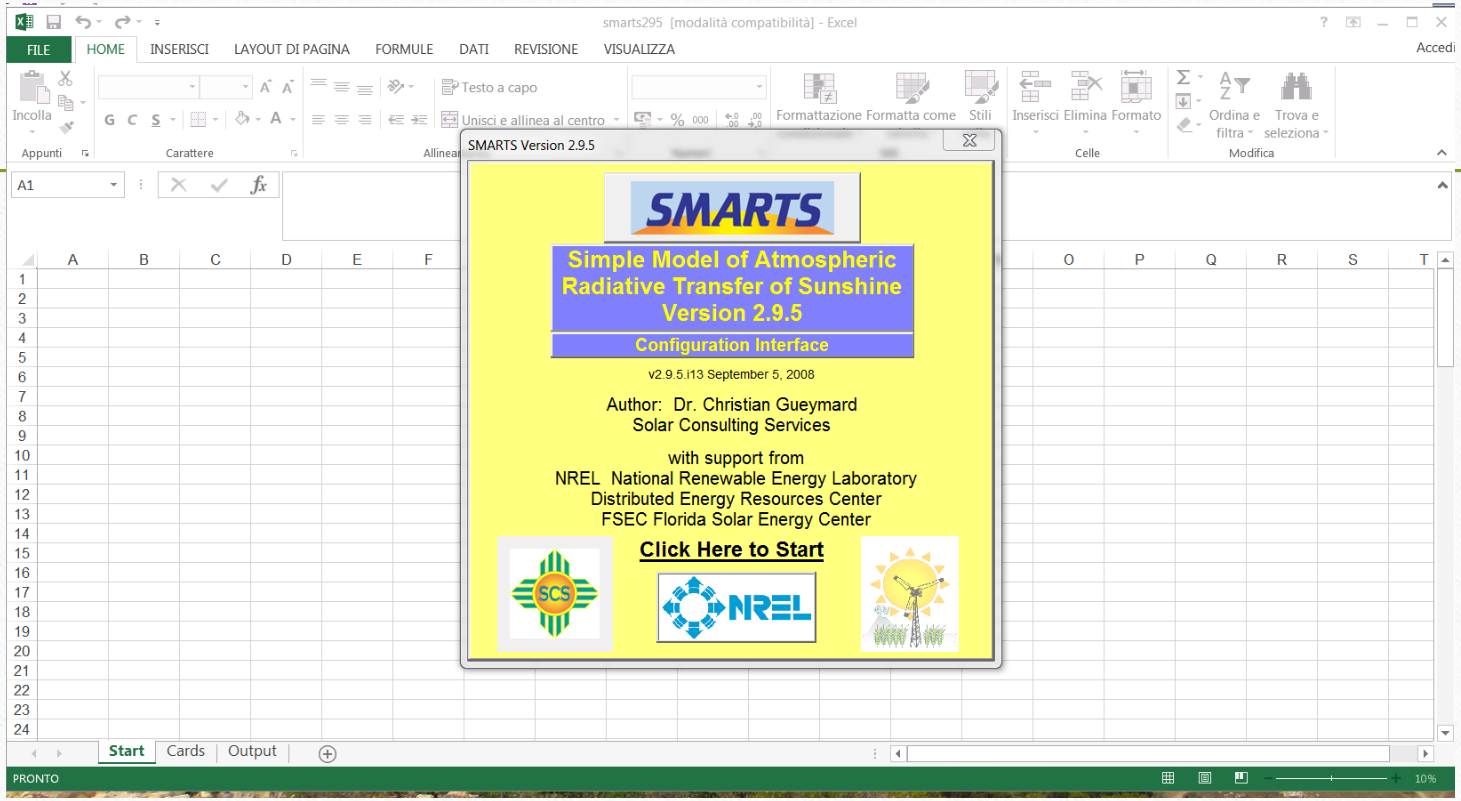


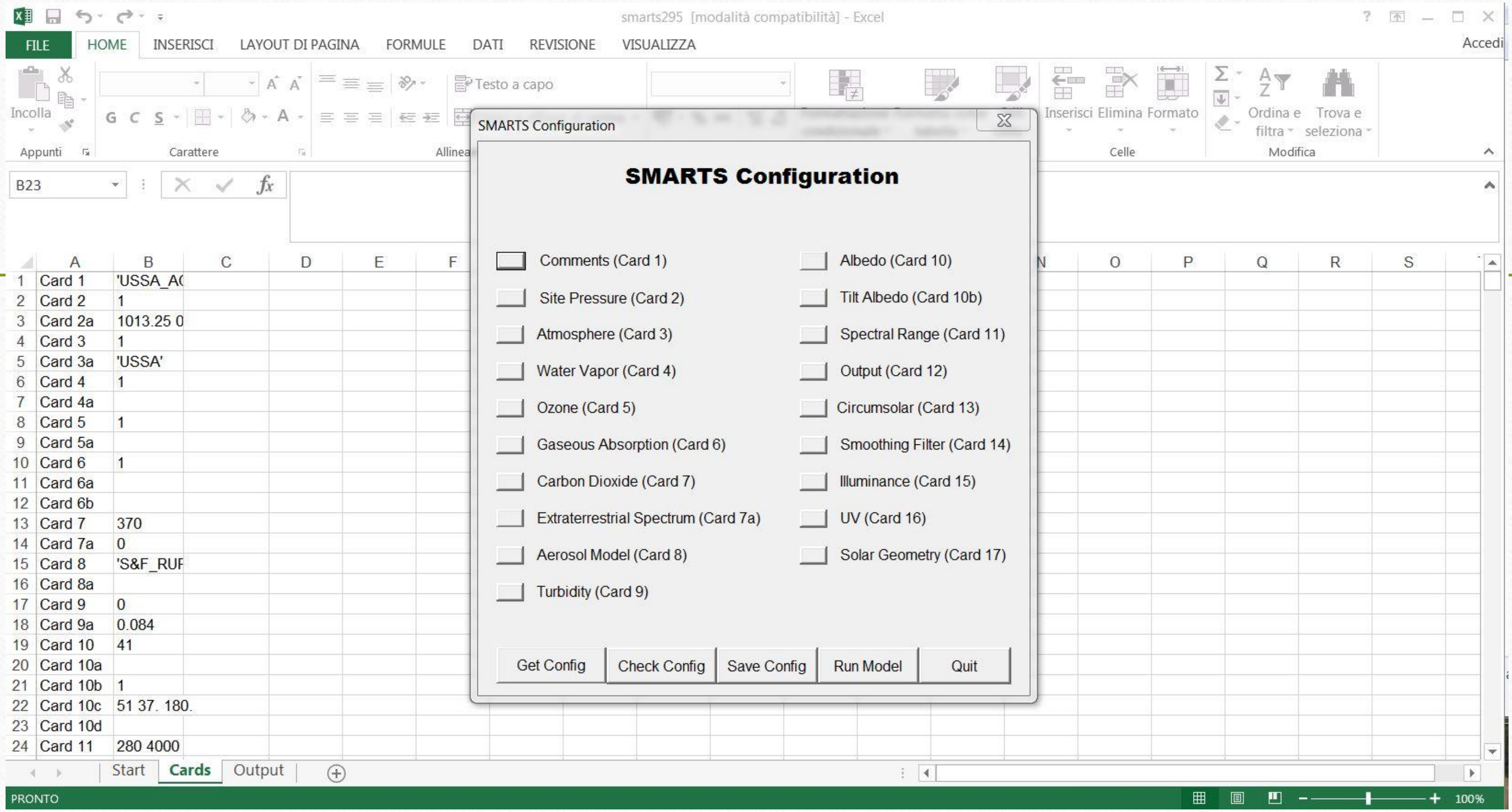
SMARTS: Software open source used to calculate the

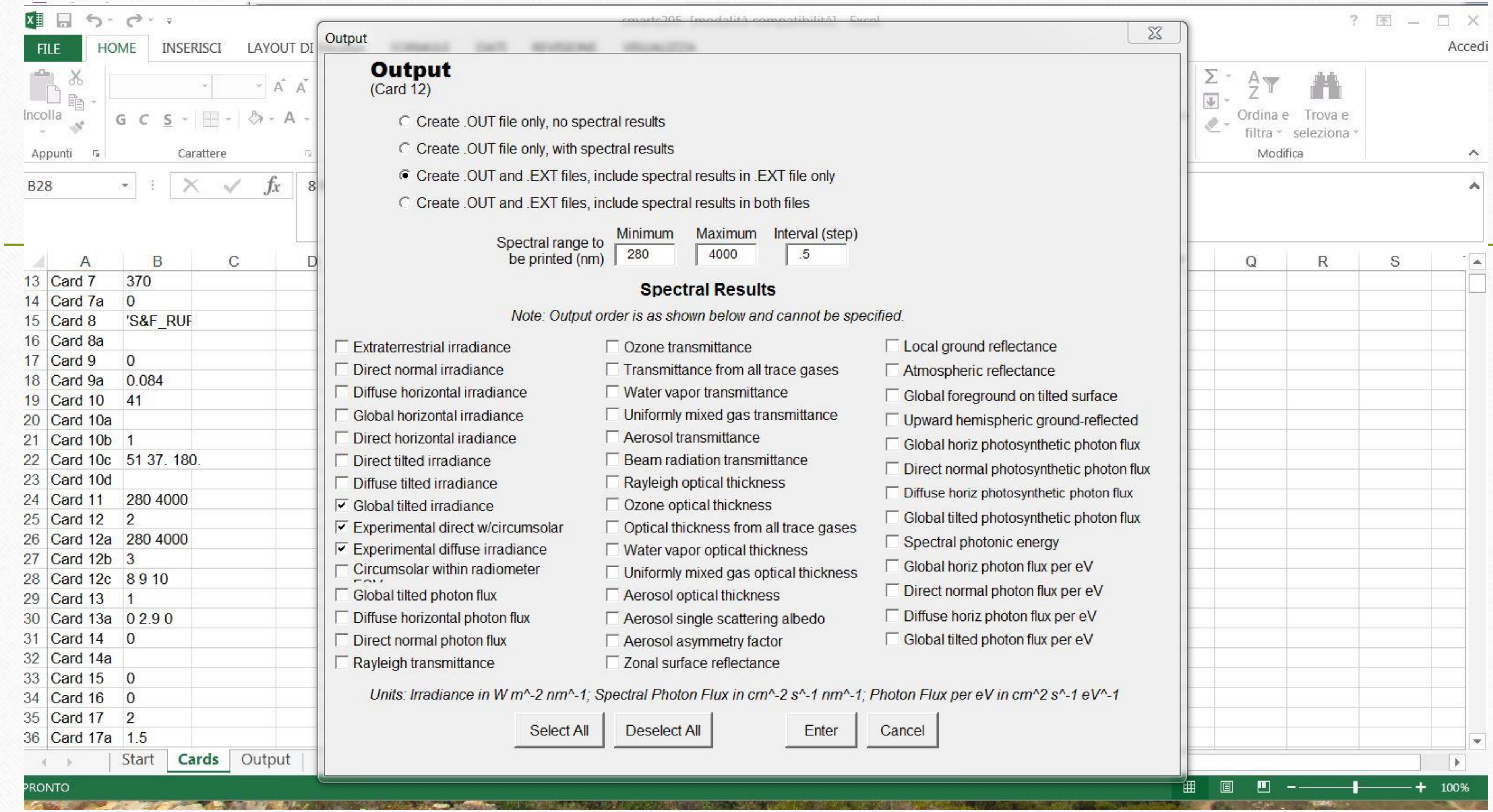


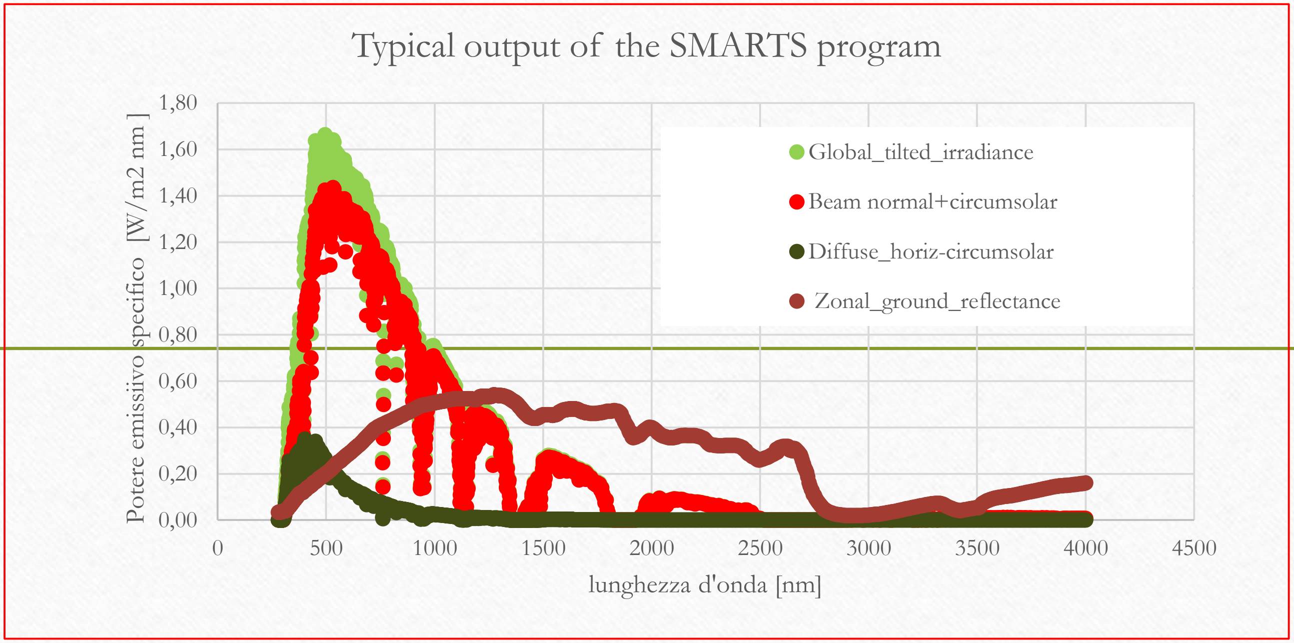
http://www.nrel.gov/rredc/smarts/

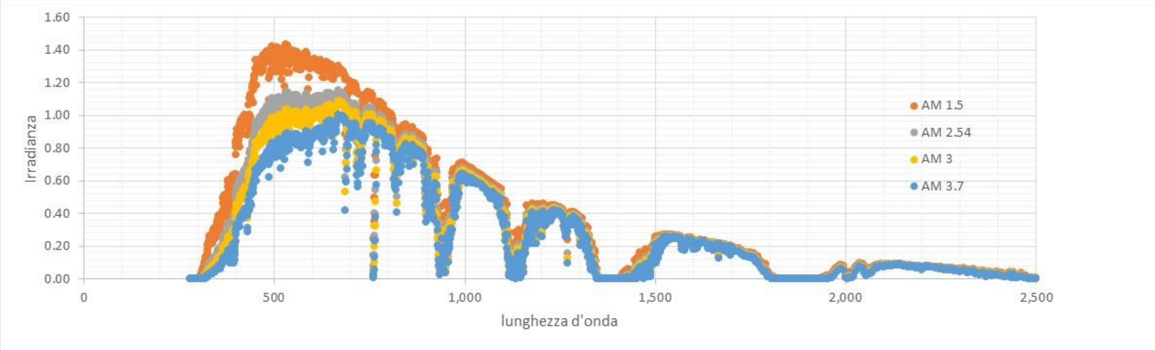
SMARTS: The Simple Model of the Atmospheric Radiative Transfer of Sunshine




smarts295 [modalità compatibilità] - Excel
FILE
HOME
INSERISCI
LAYOUT DI PAGINA
FORMULE
DATI
REVISIONE
VISUALIZZA
Accedi
Incolla
Appunti
Carattere
Testo a capo
Inserisci
Elimina
Formato
Celle
Ordina e filtra
Trova e seleziona
Modifica
B23
SMARTS Configuration
SMARTS Configuration
Comments (Card 1)
Site Pressure (Card 2)
Atmosphere (Card 3)
Water Vapor (Card 4)
Ozone (Card 5)
Gaseous Absorption (Card 6)
Carbon Dioxide (Card 7)
Extraterrestrial Spectrum (Card 7a)
Aerosol Model (Card 8)
Turbidity (Card 9)
Albedo (Card 10)
Tilt Albedo (Card 10b)
Spectral Range (Card 11)
Output (Card 12)
Circumsolar (Card 13)
Smoothing Filter (Card 14)
Illuminance (Card 15)
UV (Card 16)
Solar Geometry (Card 17)
Get Config
Check Config
Save Config
Run Model
Quit
Card 1 'USSA_A(
Card 2 1
Card 2a 1013.25 0
Card 3 1
Card 3a 'USSA'
Card 4 1
Card 4a
Card 5 1
Card 5a
Card 6 1
Card 6a
Card 6b
Card 7 370
Card 7a 0
Card 8 'S&F_RUF
Card 8a
Card 9 0
Card 9a 0.084
Card 10 41
Card 10a
Card 10b 1
Card 10c 51 37. 180.
Card 10d
Card 11 280 4000
Start
Cards
Output
PRONTO
100%


Output
Output
(Card 12)
Create .OUT file only, no spectral results
Create .OUT file only, with spectral results
Create .OUT and .EXT files, include spectral results in .EXT file only
Create .OUT and .EXT files, include spectral results in both files
Spectral range to be printed (nm)
Minimum 280
Maximum 4000
Interval (step) .5
Spectral Results
Note: Output order is as shown below and cannot be specified.
Extraterrestrial irradiance
Direct normal irradiance
Diffuse horizontal irradiance
Global horizontal irradiance
Direct horizontal iradiance
Direct tilted irradiance
Diffuse tilted irradiance
Global tilted irradiance
Experimental direct w/circumsolar
Experimental diffuse irradiance
Circumsolar within radiometer
Global tilted photon flux
Diffuse horizontal photon flux
Direct normal photon flux
Rayleigh transmittance
Ozone transmittance
Transmittance from all trace gases
Water vapor transmittance
Uniformly mixed gas transmittance
Aerosol transmittance
Beam radiation transmittance
Rayleigh optical thickness
Ozone optical thickness
Optical thickness from all trace gases
Water vapor optical thickness
Uniformly mixed gas optical thickness
Aerosol optical thickness
Aerosol single scattering albedo
Aerosol asymmetry factor
Zonal surface reflectance
Local ground reflectance
Atmospheric reflectance
Global foreground on tilted surface
Upward hemispheric ground-reflected
Global horiz photosynthetic photon flux
Direct normal photosynthetic photon flux
Diffuse horiz photosynthetic photon flux
Global tilted photosynthetic photon flux
Spectral photonic energy
Global horiz photon flux per eV
Direct normal photon flux per eV
Diffuse horiz photon flux per eV
Global tilted photon flux per eV
Units: Irradiance in W m^-2 nm^-1; Spectral Photon Flux in cm^-2 s^-1 nm^-1; Photon Flux per eV in cm^2 s^-1 eV^-1
Select All
Deselect All
Enter
Cancel
FILE
HOME
INSERISCI
LAYOUT DI
Incolla
Appunti
Carattere
Ordina e filtra
Trova e seleziona
Modifica
Accedi
B28
Card 7 370
Card 7a 0
Card 8 'S&F_RUF
Card 8a
Card 9 0
Card 9a 0.084
Card 10 41
Card 10a
Card 10b 1
Card 10c 51 37. 180.
Card 10d
Card 11 280 4000
Card 12 2
Card 12a 280 4000
Card 12b 3
Card 12c 8 9 10
Card 13 1
Card 13a 0 2.9 0
Card 14 0
Card 14a
Card 15 0
Card 16 0
Card 17 2
Card 17a 1.5
Start
Cards
Output
PRONTO
100%


Typical output of the SMARTS program
Potere emissivo specifico [W/m2 nm]
1,80
1,60
1,40
1,20
1,00
0,80
0,60
0,40
0,20
0,00
0
500
1000
1500
2000
2500
3000
3500
4000
4500
lunghezza d'onda [nm]
Global_tilted_irradiance
Beam normal+circumsolar
Diffuse_horiz-circumsolar
Zonal_ground_reflectance


Irradianza
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
500
1,000
1,500
2,000
2,500
lunghezza d'onda
AM 1.5
AM 2.54
AM 3
AM 3.7

Exercises

1. Determine the AM value using the GPS coordinates of our building, at present day/time using the dedicated open source software.

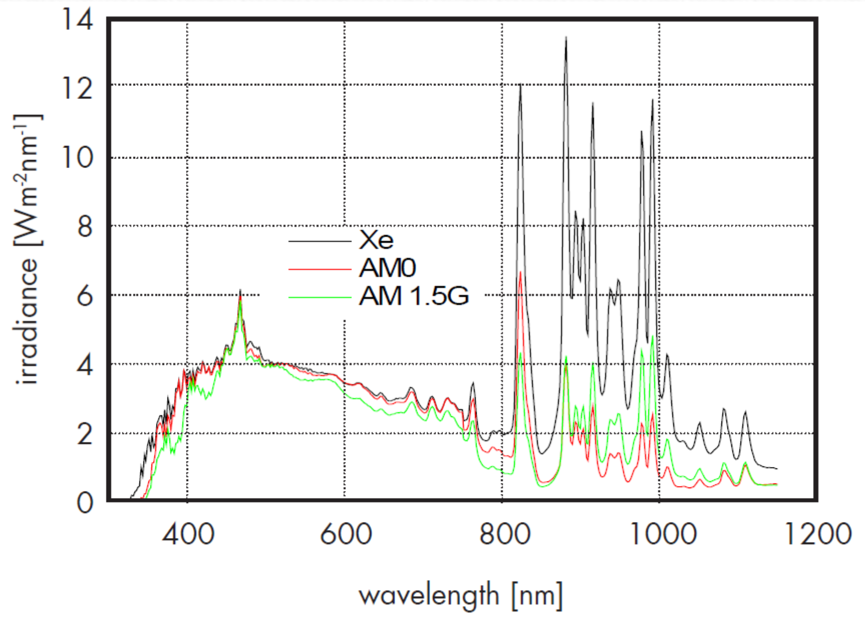
2. Calculate the relative global emission spectrum and plot it as a function of wavelength using the dedicated open source software.

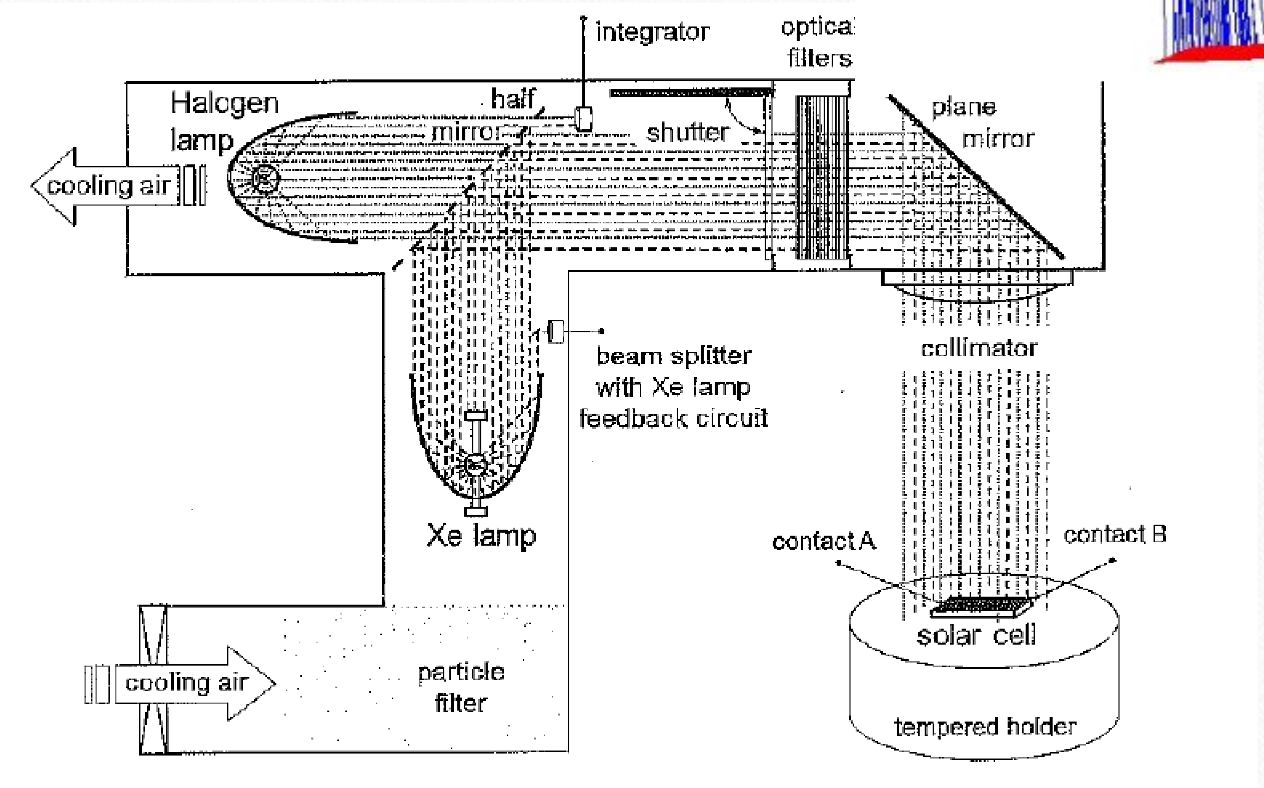
ARTIFICIAL LIGHTS

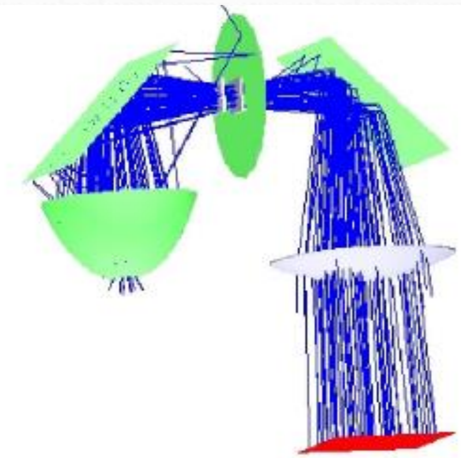
Simulating solar radiation

The Sun Simulator

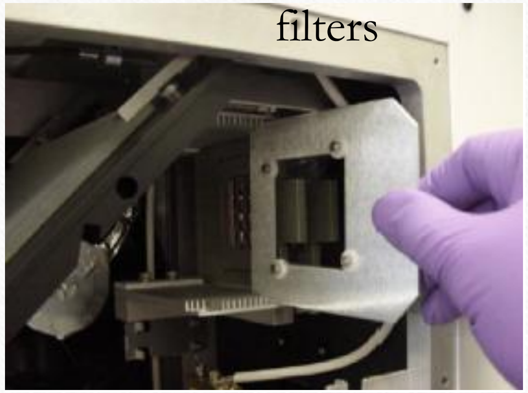
Simulating Sun in laboratory with a lamp producing a similar emission spectrum is important to get a fixed standard when certified measurements of the efficiency of the photovoltaic cells are needed.

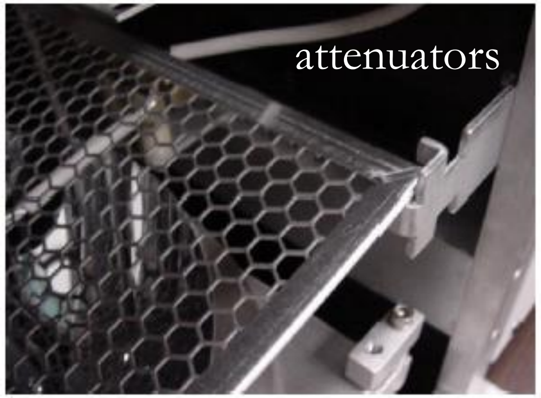






Sun Simulator at Department of Physics and Astronomy, University of Florence





Spectra Xe source and Sun Simulator con filtri AM0/AM1.5G

Artificial lights spectra

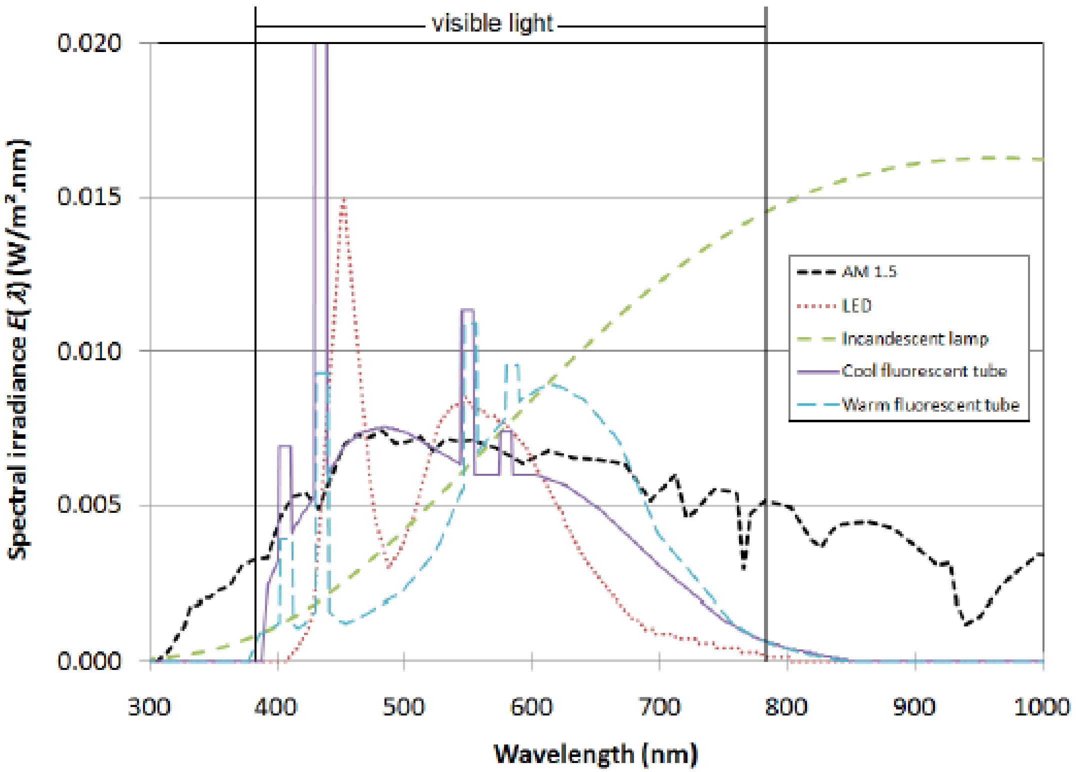
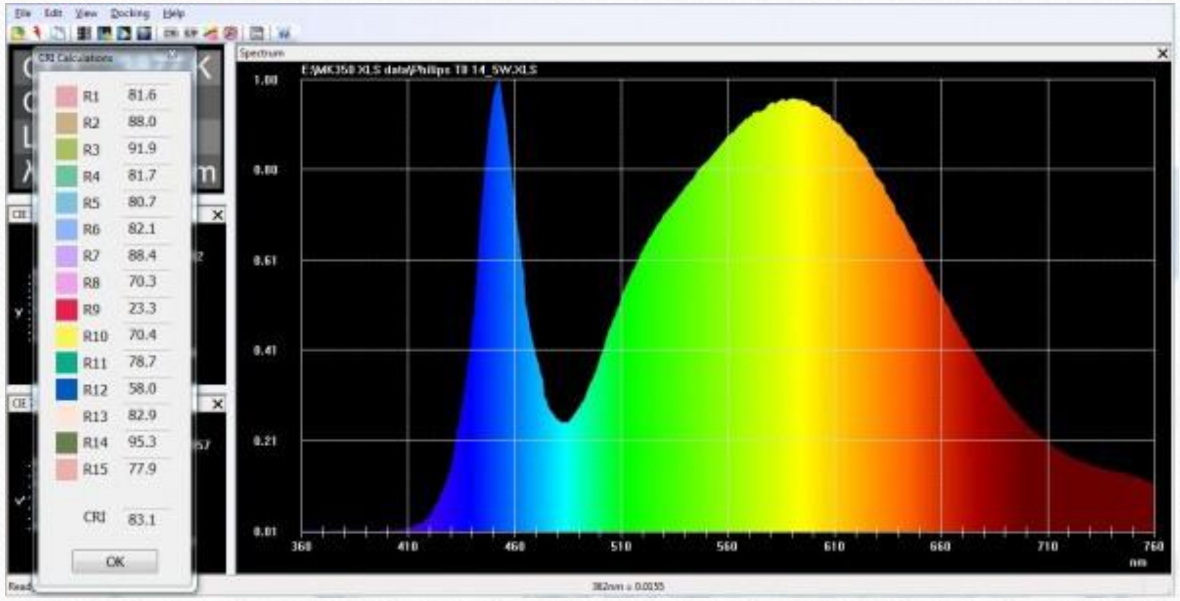
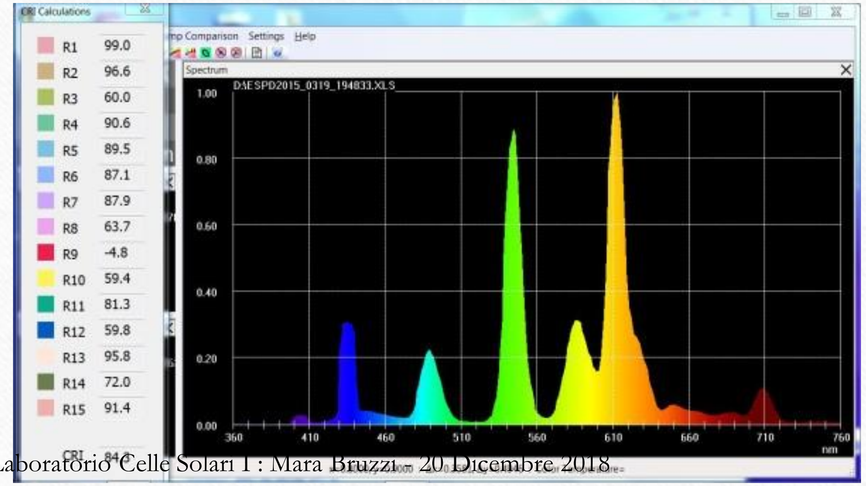


Figure 2. The spectral irradiance of some typical artificial light sources and the solar spectrum AM 1.5 as reference. All light sources, including the solar spectrum AM 1.5, are scaled to 500 lux. The region of the visible light in the spectrum is indicated.

4000K white LED spectral distribution (Philips InstantFit T8 LED)



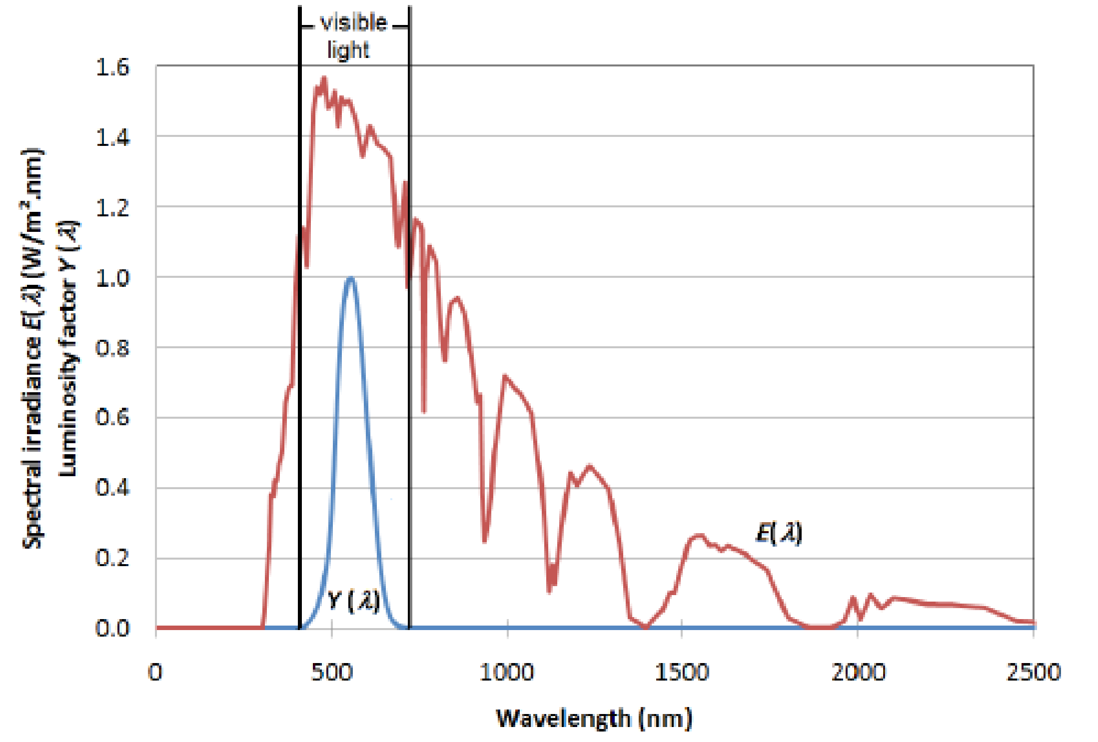


Fluorescent lamp T12 fluorescent lamp: 2900K

Luminous Power: the perception of the human eye

Luminous power is the measure of the **perceived** power of light. It differs from irradiance in that it is adjusted to take into consideration the sensitivity of the human eye to different wavelengths of light.

The CIE photopic luminosity function is a standard function established by the Commission Internationale de l'Eclairage (CIE) and may be used to convert irradiance into luminous power.



The peak of the luminosity function is at 555 nm (green);

For monochromatic light *of this wavelength*, the amount of illuminance for a given amount of irradiance is maximum: 683.002 lux per 1 W/m^2;

the irradiance needed to make 1 lux at this wavelength is about 1.464 mW/m^2.

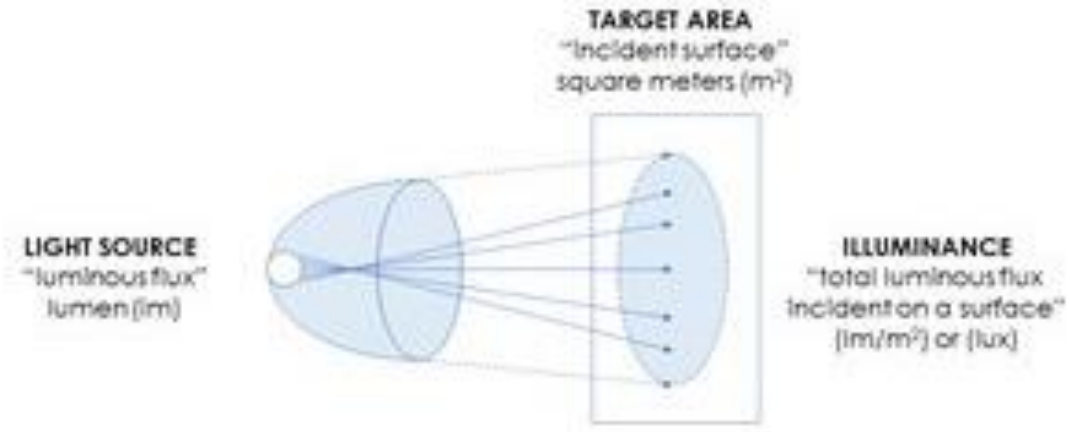
Measuring radiation power density

A black body placed inside a transparent screen absorbs the radiation of the solar spectrum, the temperature of the black body is then measured with respect to a reference value by means of a thermopile, a set of thermocouples placed in series, which provides a difference in output voltage, the appropriately calibrated response provides the power density.

Physics lab pyranometer
CMP3 Kipp-Zonen
Spectral range 300-2800 nm.
Coefficient 15.66μV/W/m^2

It is important to include a cosine correcting head to eliminate measurement errors which may arise when the light source is not directed normally to the sensor, but at any angle within the hemisphere of measurement.

Measuring visible light intensity



Candela (cd) = unit of **luminous intensity** : luminous power per unit solid angle emitted by a point light source in a particular direction.
A common wax candle emits light with a luminous intensity of roughly 1cd.

Lumen (lm) = unit of **luminous flux**, measure the **total quantity** of visible light emitted by a source.

1 lm = 1 cd · sr. A full sphere has a solid angle of 4π steradians, so a light source that uniformly radiates one candela in all directions has a total luminous flux of $1\ \text{cd} \times 4\pi\ \text{sr} = 4\pi\ \text{cd}\cdot\text{sr} \approx 12.57\ \text{lm}$.

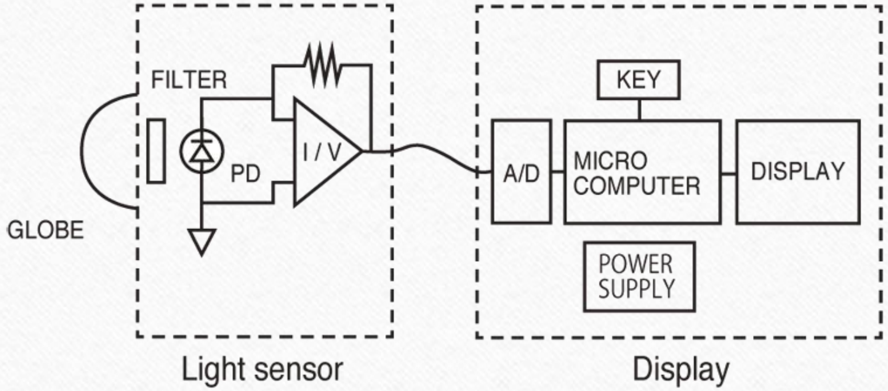
Lux (lx) = unit of **illuminance** and luminous emittance, measuring luminous flux per unit area. $1\ \text{lx} = 1\ \text{lm/m}^2$.

Luminous intensity, flux, illuminance take into account of the contribution of each wavelength is weighted by the standard luminosity function.

Illuminometers - Luxmeters

Illuminometers quantify the brightness of a lit surface by measuring luminous flux per unit of area. The illuminometer's light sensor consists of :

- a photodiode that converts light into an electrical signal,
- an optical filter that ensures the same sensitivity as the human eye,
- and a diffusing globe that facilitates cosine correction.



Block diagram

The JIS C 1609-1 standard defines performance requirements for illuminometers.

How to convert Lx = [lm/m^2] to irradiance [W/m^2] ?

There is no single conversion factor between lx and W/m^2; there is a different conversion factor for every wavelength. To make a conversion we need the spectral composition of the light.
In case λ = 555nm we have the following conversion:

1 lux [lx] = 1.46 x 10^{-07} W/cm² (at 555 nm)

1 W/cm^2 at 555 nm (W·cm^{-2}) = 6.83x10^6 lux.
The wavelength of 555 nm, is chosen as reference.

Example

Lx	W/m2	
2200	9	4000K LED panel in lab
8.20E+04	960	Solar exposition clear sky July h 2pm
9.70E+03	153	Out-door cloudy sky July h 2pm
9.10E+03	108	Out-door shadow July h 2pm