INSTRUMENTATION FOR MEASURING AND TRANSMISSION THE SOLAR RADIATION THROUGH EARTH'S ATMOSPHERE

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Abstract
The Sun's energy is distributed over a broad range of the electromagnetic spectrum and Sun behaves approximately like a "blackbody" radiating at a temperature of about 5800 K with maximum output in the green-yellow part of the visible spectrum, around 500 nm. Not all solar radiation reaching the top of the atmosphere reaches Earth's surface due to a various optical phenomena in regard to solar radiation crossing the Earth's atmosphere. In order to investigate them, there are two general categories of instruments used to measure the transmission of solar radiation through Earth's atmosphere: instruments that measure radiation from the entire sky and instruments that measure only direct solar radiation. Within each of these categories, instruments can be further subdivided into those that measure radiation over a broad range of wavelengths and those that measure only specific wavelengths.

Keywords: pyranometer **,** *sun photometer, pyrheliometers* **,** *thermopile, silicon-based solar cell, LED***.**

1. OPTICAL PHENOMENA IN REGARD TO SUNLIGHT CROSSING THE EARTH'S ATMOSPHERE

The total amount of solar radiation reaching Earth's surface is called the insolation or solar irradiance and consists of two basic parts: radiation directly from the Sun and diffuse radiation from the rest of the sky. Figure 1 shows the spectral distribution of insolation for a so-called standard atmosphere (an "average" atmosphere with specified characteristics) compared to the extraterrestrial radiation at the average Earth - Sun distance. The relationship between direct and diffuse radiation depends on the position of the Sun in the sky, defined by the *relative air mass* (Young, 1994):

$$m = \frac{1}{\sin\theta} \qquad (1),$$

where θ is the solar elevation angle. The Sun in Figure 1 is at an elevation angle of about 42º, giving a relative air mass of about 1.5. If the Sun is directly overhead, the relative air mass is 1.
The optical phenomena in regard to sunlight crossing the Earth's atmosphere are **scattering and absorbtion** (Liou, 2002).
Scattering of light by molecules is called Rayleigh scattering after the British physicist John William Strutt, the third Baron Rayleigh (1842 – 1919) who first described this phenomenon mathematically (Bucholtz, 1995).
Scattering of light by aerosol is called Mie scattering after the German physicist Gustav Mie (1868 - 1957) who first described this phenomenon mathematically. Aerosol particles have sizes in the same range as the wavelength of light (~100-1000 nm), so they scatter light differently than molecules, which are much smaller (Hodkinson, Greensleaves, 1963).

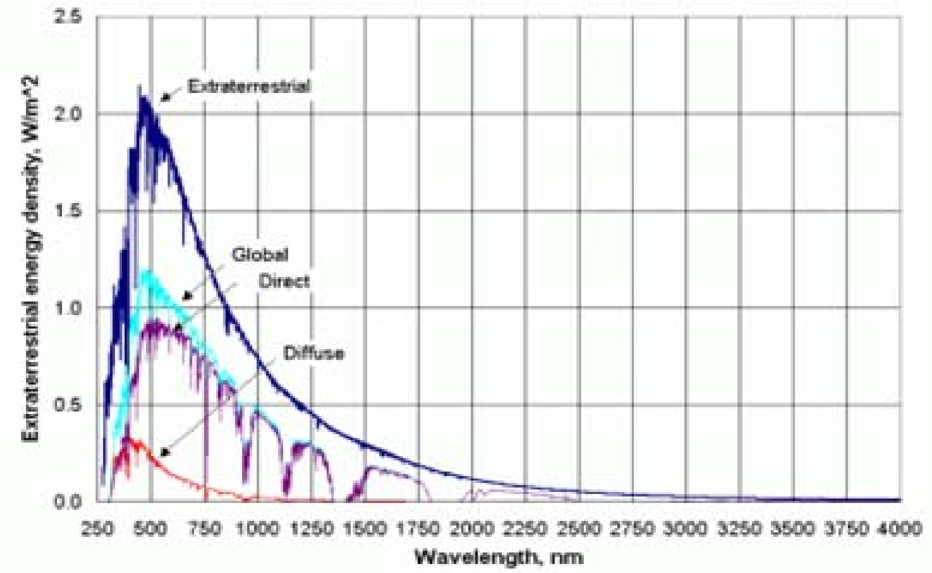

Figure 1. Direct, diffuse and total insolation for a standard atmosphere with relative air mass of 1.5 (Birds, Riordan, 1994)

Absorbtion of light by molecules and aerosol is defined by the Lambert - Bouguer law or Lambert - Beer law, named after the French scientist Pierre Bouguer (1698 - 1758) who first measured the moonlight attenuation through the terrestrial atmosphere at 23 November 1725. The basic equation governing the transmission *T* of radiation through an intervening medium is (Petty, 2006):

$$T = \frac{I_\lambda}{I_{0\lambda}} = \exp(-\tau_\lambda) \qquad (2)$$

where $I_{o\lambda}$ is the original source intensity, I_λ is the intensity after radiation passes through a medium of thickness m, and τ_λ is the total atmospheric optical thickness, all at wavelength λ.

Some radiation absorbed by molecules and aerosol is re-emitted as thermal radiation towards the Earth or extraterrestrial space. The nature of the molecular bonds permit the absorbtion of radiation only at specific wavelengths. As a result, insolation is an attenuated specific spectral version of the extraterrestrial radiation.

Water vapor is the major absorber, hence its importance as a greenhouse gas. Its most prominent absorption occurs far out in the infrared part of the solar spectrum, but there are also absorption bands in the near-IR around 720, 820, and 940 nm. (Brooks, Forrest, Levine, Hinton, 2003).

Ozone is the second most important absorber in the UV-visible-Near-IR part of the spectrum. It has a deep bell-shaped absorption band between 210-310 nm (the Hartley band) and less prominent structured bands between 310-350 nm (Huggins band) and 450-850 nm (Chappuis bands). Ozone absorbs almost all UV-C radiation (200-280 nm), roughly 70% or more UV-B (280-320 nm) radiation and a little of UV-A radiation (320-400 nm) (Brooks et. al., 2003).

So the scattering and absorbtion by molecules and particles in the atmosphere leave "fingerprints" on the insolation spectrum that provide a way to measure quantitatively the presence and concentration of those molecules and particles. The effects of scattering and absorption enable scientists to develop ground-based measurement strategies based on this important observation.

2. Full-Sky Instruments

As their name implies, full-sky instruments need an unobstructed view of the entire sky. So, they need sites that have a 360º view of the horizon, without significant obstacles. Corrections can be made for limited horizon obstructions but, the more clear the horizon is, the more accurate measurements will be.

A less obvious requirement for full-sky detectors is that they have good response to the inclination of the sunlight. If sunlight has intensity I_o when the Sun is directly above a horizontal surface, meaning the zenith angle is 0º, then the intensity I at some other zenith angle υ is given by the following formula:

$$I(x) = I_0 \cos \nu \qquad (2),$$

where x is distance between Sun and the previous mentioned horizontal surface (Petty, 2006).

If an ideal detector on a horizontal surface is illuminated by direct light, then its response should be proportional to the cosine of the zenith angle of the light source. Real detectors do not have perfect cosine response. Cosine response corrections can be determined and applied for a direct sunlight, but this issue becomes much more complicated especially under partly cloudy skies, when the radiation incident on a detector is an unknown combination of direct sunlight and diffuse sky radiation, as is the case for full-sky solar radiation.

Full-sky instruments are generally called *radiometers* or, in the particular case of solar monitors, *pyranometers*. Figure 2 shows an Eppley Model PSP pyranometer, a widely used "first class" reference instrument, as defined by the World Meteorological Organization. This instrument is about 15 cm in diameter. The sensor is under the hemispherical glass dome. The glass is specially formulated to transmit solar radiation over a wide range of wavelengths.

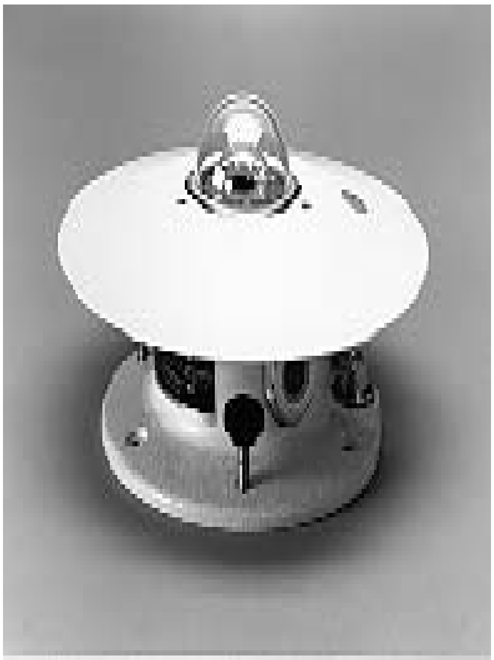

Figure 2. Eppley PSP pyranometer.
(Diak et. al., 1996)

3. Direct Sunlight Instruments

As their name implies, these instruments are designed to view only light coming directly from the Sun. The radiation incident on one or more detectors is restricted to a narrow cone of the sky, the instrument's field of view. The field of view should be as small as possible in order to restrict the amount of scattered light that finds its way to the detector, while still providing enough light for the detector to produce a usable output signal.

Direct Sunlight instruments are called *sun photometers* or, in the case of *broadband solar monitors*, *normal incidence pyrheliometers*. Modern sun photometers are equipped, beside a sensitive

photodetector and a performant auxiliary optical system, with a spectrally filtering device, an automatic Sun tracking device and a data acquisition system (Mims, 2002).
Figure 3 shows a CIMEL sun photometer. The tubes, which limit the field of view, and the detector housing below them, are about 50 cm long. This instrument automatically tracks the Sun under computer control. It is used by the Aerosol Robotic Network (AERONET), developed and managed by NASA's Goddard Space Flight Center, at sites around the world (Holben et al., 1998).

Figure 3. CIMEL Sun photometer.
(Holben et al., 1998)

4. Broadband Detectors

Broadband detectors are required for measuring total solar radiation. They must be sensitive to cover the whole broad range of the electromagnetic spectrum corresponding to solar radiation
High-quality reference pyranometers, such as the Eppley pyranometer shown in Figure 2, use *thermopiles*, meaning *collections of thermocouples*. A thermocouple is a common device useful for measuring with high precision a wide range of temperature, depending on its construction characteristics. It consist of dissimilar metals or alloys, called *A* and *B*, mechanically joined and welded together in two distinct points. One of the welded points is irradiated by the Sun and its temperature raises to a value T_2, while the other welded point is maintained to a lower constant temperature T_1. Between the welded points a small voltage E_{AB}, proportional to the gradient of temperature is generated, according to the law of Seebeck effect:

$$E_{AB} \equiv \int_{T_1}^{T_2} (\alpha_A - \alpha_B) dT \qquad (2),$$

where α_A and α_B are the *Seebeck coefficients* of the metals or alloys *A* and *B*, depending on their nature and also on the temperatures T_1 and T_2. The Seebeck coefficients α_A and α_B have the meaning of absolute thermoelectromotor voltages, usually measured in *mV/K*.

When thermopiles are appropriately arranged and coated with a dull black finish, they serve as nearly perfect "black body" detectors that absorb energy across the entire range of the solar spectrum. These instruments are very expensive and not suitable for routine field work.

An inexpensive alternative is to use *photovoltaic detectors*. *Silicon-based solar cells* are an obvious choice. They generated a small current when they irradiated by sunlight, internal photoelectric effect. Their major disadvantage is that their spectral response is different from the solar spectrum. Typically, they respond to sunlight in the range from 400 to 1100 nm, with a peak response in the near-infrared, around 900 nm. This restricted spectral response represents a subset of the solar spectrum which, under normal outdoor sunlight conditions, introduces a potential error of a few percent. However, reliable and inexpensive solar radiation monitors are so desirable that a great deal of research effort has been dedicated to designing and understanding silicon-based pyranometers. (King and Myers, 1997). Commercial pyranometers that use silicon-based detectors - they might more accurately referred to as "surrogate" pyranometers- are much less expensive than thermopile-based pyranometers. Figure 4 shows a pyranometer that uses two small solar cells with an analog microampermeter. Output from the solar cells is about 0.5 mA in full sunlight.

Figure 4. A solar-cell based pyranometer with an analog microampermeter used for calibration (King and Myers, 1997)

5. Spectrally Selective Detectors

For both full-sky and direct sunlight instruments, some measurements require detectors that respond only to a specific range of wavelengths.

For research instruments the first choice for *spectrally selective detectors* are relatively broadband photodetectors used in combination with interference filters that transmit only a limited range of wavelengths, often only a few nanometers or less. These detectors are expensive, fragile, and subject to unpredictable degradation. Detectors for the shorter UV wavelengths and for IR wavelengths beyond 2000 nm or so tend to be very expensive, with no inexpensive alternatives. These realities impose some important practical limitations on the kinds of spectrally selective measurements that can be made with inexpensive instruments. Nonetheless, there is a great deal of useful atmospheric science that can be done with spectrally selective detectors which lie within the range of roughly 350-1000 nm, corresponding to the most of the UV through the visible and near-IR ranges of the solar spectrum.

The most common used spectrally selective detector is *light emitting diodes (LEDs)*. They are semiconductor diodes, which generate a small electrical current, according to the laws of internal photoelectric effect, and also emit light when light in an appropriate wavelength range shines on them. LEDs are inexpensive, stable, and virtually indestructible if they are use properly.

LEDs have some disadvantages. The main difficulty is that the spectral response of LEDs is often wider than is desirable for certain kinds of atmospheric measurements and the wavelength ranges may not be ideal for the intended measurement. Also, the spectral distribution of an LED's emitted radiation is not the same as its response spectrum. The peak response wavelength is invariably lower than the peak emission wavelength but, as a practical matter, it is not possible to predict the location and shape of the response spectrum based on the emission spectrum The emission spectrum is readily available from the manufacturer, because this is fundamental information required to select an LED for use as a light source. Information about the response spectral distribution is rarely available, because it is typically of no interest to the purchaser of an LED. So, the response spectrum must be measured in order to determine the suitability of an LED as a light detector for a particular application.

Figure 5 shows the normalized generic emission spectrum of a typical "emerald green" LED, as supplied by its manufacturer, compared to its normalized directly measured response spectrum. According to these data, the emission peaks is at 555 nm, but the peak response is around 530 nm, making it a suitable spectrally selective detector for visible range of the solar spectrum.

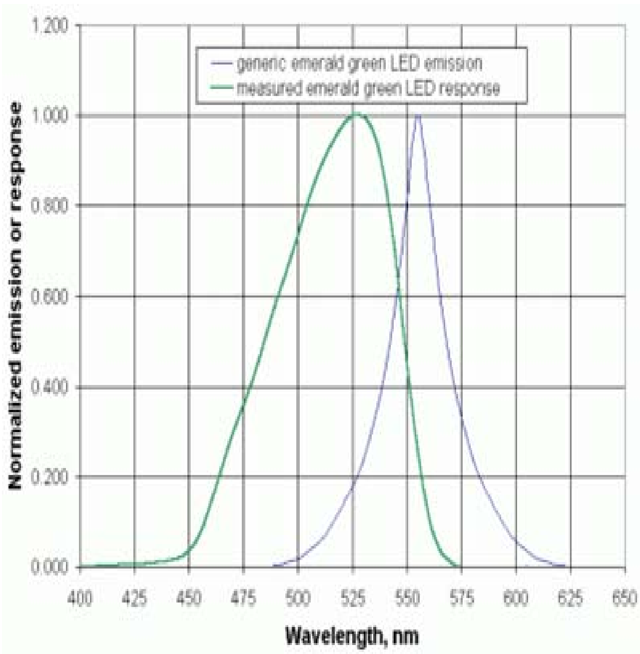

Figure 5. Generic emerald green LED emission compared to measured spectral response.
(Mims, 1992)

Figure 6 shows the response of a blue LED suitable spectrally selective detector for UV range of the solar spectrum. It has a strong peak response around 372 nm, in the UV-A part of the spectrum. Unfortunately, it also has a significant response "shoulder" that extends to higher wavelengths in the visible spectrum.

The solution to this problem is to cover the LED with a "low-pass filter", a coated piece of glass or quartz that is highly transparent to wavelengths below about 380 nm, but does not transmit any radiation at longer wavelengths, over the visible part of the spectrum. A cut-away view of the housing and filter is shown in Figure 7.

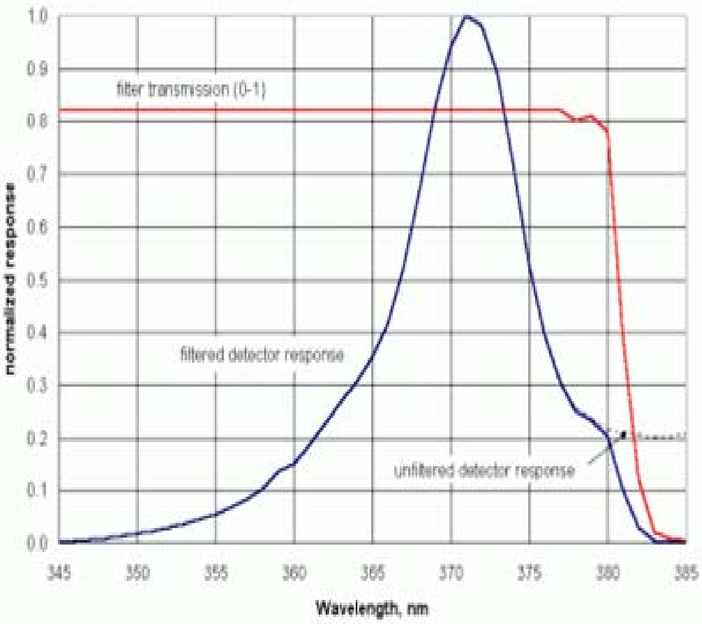

Figure 6. Spectral response of an unfiltered blue LED detector.

Figure 7. UV-A detector assembly with Teflon diffuser.

(Mims, 2003)

The LED detector assembly is covered with a Teflon® disk to diffuse sunlight. This assembly is then attached to the top of the instrument enclosure, as shown in Figure 8. The dark ring around the detector prevents light from leaking through the sides of the housing. The ring can be removed and replaced by a collimating tube with a small hole at one end (the end with the white cap in Figure 8). This tube fits snugly over the housing, giving the detector a field of view identical to a sun photometers discussed previously. Thus, a single instrument can be used to measure either full-sky or direct sun radiation.

Figure 8. GLOBE/GSFC UV - A radiometer and Sun photometer.
(Brooks and Mims, 2001)

6. AUTOMATIC SUN AND SKY SCANNING SPECTRAL RADIOMETER

Most if not all sun photometer networks have had limited success when people are required to make routine observations. Therefore an automatic instrument is a fundamental component for routine network observations. The measurement protocol must be reasonably robust such that unwanted data may be successfully screened from useful data, data quality and instrument functionality may be evaluated and the instrument should be self-calibrating or at the least collects data for its calibration. Following is the assessment of the *CIMEL CE-318 instrument* that meets these criteria of a field hardy, transmitting, sun and sky scanning spectral radiometer which is used in the AERONET program, as it seen in Figure 9.

Figure 9. Standard operational CIMEL platform used by AERONET station.
(http://aeronet.gsfc.nasa.gov/)

The CIMEL Electronique 318A spectral radiometer manufactured in Paris, France is a solar powered weather hardy robotically pointed sun and sky spectral radiometer. This instrument has approximately a 1.2 degree full angle field of view and two detectors for measurement of direct sun, aureole and sky radiance. The 33 cm collimators were designed for 10^{-5} straylight rejection for measurements of the aureole 3 degrees from the sun. The robot mounted sensor head is parked pointed nadir when idle to prevent contamination of the optical windows from rain and foreign particles. The sun/aureole collimator is protected by a quartz window allowing observation with a UV enhanced silicon detector with sufficient signal-to-noise for spectral observations between 300 and 1020 nm. The sky collimator has the same field of view but an order of magnitude larger aperture-lens system allows better dynamic range for the sky radiances. The components of the sensor head are sealed from moisture and desiccated to prevent damage to the electrical components and interference filters. Eight ion assisted deposition interference filters are located in a filter wheel which is rotated by a direct drive stepping motor. A thermister measures the temperature of the detector allowing compensation for any temperature dependence in the silicon detector. The sensor head is pointed by stepping azimuth and zenith motors with a precision of 0.05 degrees. A microprocessor computes the position of the sun based on time, latitude and longitude which directs the sensor head to within approximately one degree of the sun, after which a four quadrant detector tracks the sun precisely prior to a programmed measurement sequence. After the routine measurement is completed the instrument returns to the "park" position awaiting the next measurement sequence. A "wet sensor" exposed to precipitation will cancel any measurement sequence in progress. (www.cimel.fr.).

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