Biospherical Instruments Inc.

APPLICATION NOTE:

Calculating PAR from Measurements of Multi-Channel Instruments

Application Note #: AN-2014-0001-Rev1
BSI DCN 006587KA

5340 Riley Street
SanDiego, CA 92110-2621 USA

Vox: +1.619.686.1888
Fax: +1.619.686.1887

Net: sales@biospherical.com
Web:www.biospherical.com

Calculating PAR from Measurements of Multi-Channel Instruments

Photosynthetically Active Radiation[1] (PAR) designates the spectral range of electromagnetic radiation with wavelengths between 400 and 700 nanometers (nm) that photosynthetic organisms are able to use in the process of photosynthesis. An instrument that is designed to measure PAR is equally sensitive to photons between 400 and 700 nm and insensitive to photons outside this region. Biospherical Instrument (BSI) offers several sensors with this spectral response, such as Q-series sensors. An alternative method to determine PAR is to measure radiation at discrete wavelengths between 400 and 700 nm and compute PAR from these measurements. In this Application Note, a method is presented, and its uncertainty assessed, to calculate PAR from measurements of multi-channel radiometers such as BSI's Compact Optical Profiling Systems (C-OPS), Profiling Reflectance Radiometer (PRR), or Ground-Based UV-Visible radiometers (GUVis-3511) that may not have a PAR channel.

The aforementioned mentioned instruments have in common that they have 10 to 14 channels with wavelengths in the PAR range. These instruments may be equipped with a flat receiver, scalar irradiance collectors, or radiance front optics. While the procedure introduced below does not depend on collector geometry, results have different units depending on the collector type. Here we discuss PAR measurements derived from spectral irradiance measurements of instruments equipped with a flat receiver (or "cosine collector"), such as the Es channels of a C-OPS radiometer. For this geometry, the resulting PAR measurement is often referred to as "Photosynthetic Photon Flux Density" (PPFD) and expressed here in units of µE cm^{-2} s^{-1}. (The symbol "E" stands for the unit Einstein, which denotes one mole of photons: 1 E = 6.022 × 10^{23} photos, where 6.022 × 10^{23} is the Avogadro constant N_A.) Please see our application note on light quantities, units, and conversion factors (BSI, 2012) for different collector geometries and additional information on PAR measurements.

The blue line in Figure 1 shows a spectrum of solar irradiance simulated for a solar zenith angle (SZA) of 30° using the radiative transfer model UVSPEC (Mayer and Kylling, 2005). The spectrum is the sum of the direct irradiance from the solar beam and the irradiance from scattered sky irradiance. This quantity is often referred to as "spectral global irradiance" and for example measured with a C-OPS surface reference sensor. The modeled spectrum has a resolution of 1 nm, which is more than adequate for accurate PPFD retrievals. PPFD was calculated from this spectrum via:

$$\mathrm{PPFD} = \frac{10^{-9}}{N_A} \int_{\lambda=400}^{700} E(\lambda) \frac{\lambda}{hc} d\lambda \,, \qquad (1)$$

where
- $E(\lambda)$ is spectral global irradiance,
- λ is wavelength in nm,
- h is the Planck constant (h = 6.626 × 10^{-34} Js),
- c is the speed of light (c = 2.997 × 10^{-8} ms^{-1}), and
- N_A is the Avogadro constant (N_A =6.022 × 10^{23} mol^{-1}).

The term $\lambda/(hc)$ is the inverse of the energy of a photon with wavelength λ and converts the radiometric quantity $E(\lambda)$ to a quantum unit. The factor 10^{-9} scales wavelengths provided in nm to m.

The channels of BSI's instruments have approximately a bandwidth of 10 nm full width at half maximum (FWHM). The modeled spectrum was convolved with a boxcar[2] function of 10 nm FWHM to simulate measurements of instruments with this bandwidth. The convolved spectrum is denoted $\tilde{E}(\lambda)$ and indicated by a red line in Figure 1. The PPFD, calculated with this function using Eq. (1), is denoted $\mathrm{PPFD}_{10\mathrm{nm}}$.

Because multi-channel radiometers have only a limited number of channel, $\tilde{E}(\lambda)$ can only be measured at a few wavelengths within the PAR range. The spectrum is therefore "undersampled," which has consequences on the abil-

[1] The term "Photosynthetically Available Radiation" is sometimes used instead of Photosynthetically Active Radiation.

[2] A boxcar function is zero except for an interval where it is a constant. In the case discussed here, the function is one between -5 and +5 nm.

ity to accurately calculate PPFD if the source spectrum varies considerably between the wavelengths of the channels.

For demonstrating the method, a radiometer was chosen that has channels at the following wavelengths: 305, 320, 330, 340, 380, 412, 443, 465, 490, 510, 532, 555, 589, 625, 665, 683, 694, 710, and 780 nm. The spectral irradiances $\tilde{E}(\lambda)$ at these wavelengths are indicated by yellow circles in Figure 1, and these values are connected by a black line. The function represented by this line is denoted $\bar{E}(\lambda)$. Note that $\bar{E}(\lambda)$ is equal to $\tilde{E}(\lambda)$ at the wavelengths of the instrument but different between these wavelengths. For example between 412 and 443 nm, $\bar{E}(\lambda)$ overestimates $\tilde{E}(\lambda)$ because the Sun's Fraunhofer line at 430.7 nm is not resolved by the course wavelength spacing of the instrument. The pattern is reversed between 443 and 465 nm, with $\tilde{E}(\lambda)$ being larger than $\bar{E}(\lambda)$.

The approximate PPFD derived from $\bar{E}(\lambda)$ is denoted $\mathrm{PPFD}_{\mathrm{approx}}$ and can be calculated by substituting $E(\lambda)$ with $\bar{E}(\lambda)$ in Eq. (1). In practice, the integral is evaluated numerically using the trapezoidal rule (e.g., http://en.wikipedia.org/wiki/Trapezoidal_rule). For this procedure, it is first necessary to determine $\bar{E}(400)$ and $\bar{E}(700)$. The two quantities are calculated by linear interpolation from the adjacent wavelengths:

$$\begin{aligned}\bar{E}(400) &= \bar{E}(380) + \frac{\bar{E}(412) - \bar{E}(380)}{412 - 380}(400 - 380) \\ \bar{E}(700) &= \bar{E}(694) + \frac{\bar{E}(710) - \bar{E}(694)}{710 - 694}(700 - 694)\end{aligned} \quad (2)$$

Using the trapezoidal rule and $\bar{E}(\lambda)$ at 400 and 700 nm and at wavelengths with the PAR range of the instrument (i.e., 412 – 694 nm), $\mathrm{PPFD}_{\mathrm{approx}}$ can be calculated:

$$\begin{aligned}\mathrm{PPFD}_{\mathrm{approx}} = \frac{10^{-9}}{N_A} \times & \\ \Bigg[0.5 \times & \left(\frac{\bar{E}(400) \times 400}{hc} + \frac{\bar{E}(412) \times 412}{hc} \right) \times (412 - 400) \\ + 0.5 \times & \left(\frac{\bar{E}(412) \times 412}{hc} + \frac{\bar{E}(443) \times 443}{hc} \right) \times (443 - 412) \\ + \cdots + \frac{0.5}{N_A} \times & \left(\frac{\bar{E}(694) \times 694}{hc} + \frac{\bar{E}(700) \times 700}{hc} \right) \times (700 - 694) \Bigg]\end{aligned} \quad (3)$$

Note that only the first two and the last term of the summation are displayed in Eq. (3).

Table 1 presents the results of the calculations. It can be seen that $\mathrm{PPFD}_{\mathrm{approx}}$ agrees to within 0.07% with PPFD calculated from the full-resolution spectrum.

Table 1: Result of PPFD calculations.

Quantity	Result [µE cm^{-2} s^{-1}]	Bias
PPFD	0.19378	—
$\mathrm{PPFD}_{10\mathrm{nm}}$	0.19366	-0.06%
$\mathrm{PPFD}_{\mathrm{approx}}$	0.19392	+0.07%

The result of the integration depends somewhat on the wavelengths of the radiometer. To quantify the effect, the calculation was repeated with the following set of wavelengths, which are also often used in C-OPS systems: 320, 340, 380, 395, 412, 443, 465, 490, 510, 532, 555, 560, 625, 665, 670, 683, 710, and 780 nm. With this set of wavelengths, $\mathrm{PPFD}_{\mathrm{approx}}$ was calculated to 0.19350 µE cm^{-2} s^{-1}, which is only 0.14% smaller than the ideal result of 0.19378 shown in Table 1.

These calculations confirm that PPFD can be calculated with excellent accuracy from measurements performed at the wavelengths provided by BSI's multi-channel instruments. The recommended procedure to calculate PPFD is therefore to substitute the simulated spectral irradiances $\bar{E}(\lambda)$ with the measured spectral irradiances of these channels, and calculated PPFD using Eqs. (2) and (3). The procedure is implemented in µProfiler software, but can also be executed manually using a spreadsheet.

References

BSI (2012). *Application Note: Light Quantities, Units, and Conversion Factors*, Biospherical Instruments, AN-2012-0001-Rev1, 6 pp. available from the Support section at www.biospherical.com.

Mayer, B., and A. Kylling. (2005). Technical Note: The libRadtran software package for radiative transfer calculations: Description and examples of use. *Atmos. Chem. Phys.*, **5**:1855-1877.

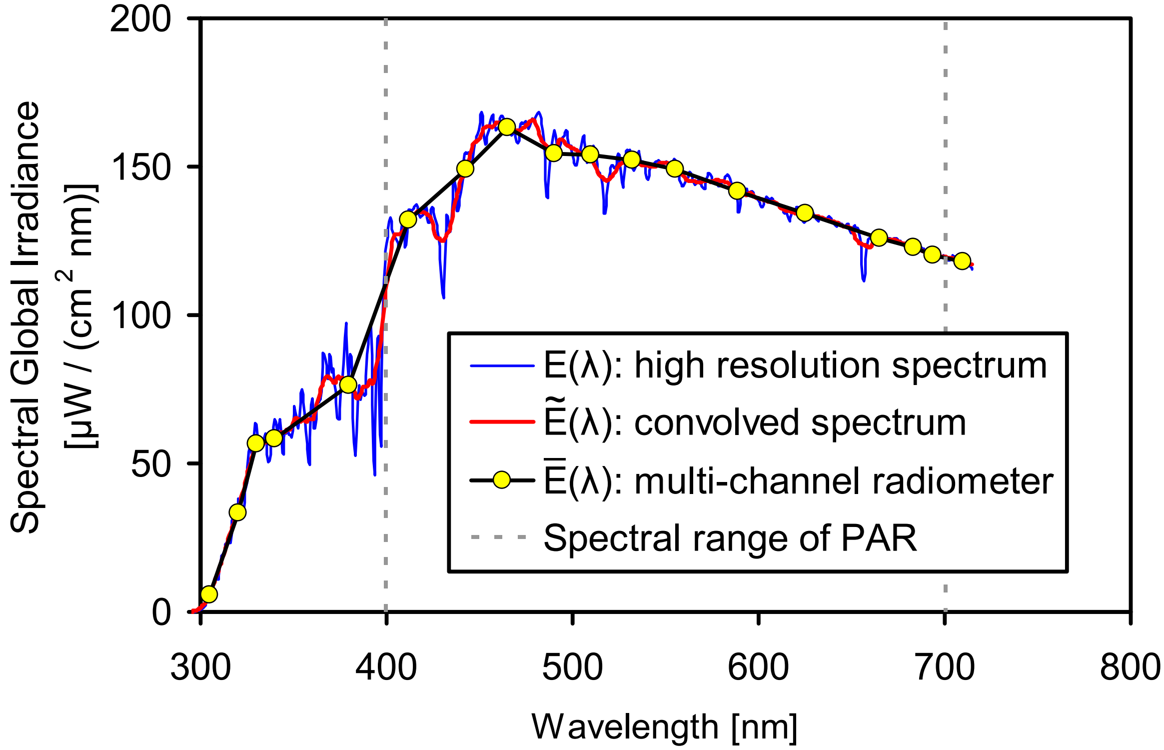

Figure 1. Comparison of a high-resolution solar spectrum ($E(\lambda)$), with the same spectrum convolved with a boxcar function of 10 nm FWHM ($\tilde{E}(\lambda)$), and the simulated measurements of a multi-channel instrument with 12 wavelengths in the PAR range ($\overline{E}(\lambda)$).