total power incident on a small area of the PV device (or the power density over the entire PV device) and the current produced at that wavelength. The major sources of uncertainty are the detector calibration used to measure the power (typically μW) and the errors in measuring a small AC current (typically μA or less) produced by the chopped monochromatic light, in the presence of a large DC offset (mA to A) from the broadband bias light. Because a reference cell calibrated using equation (16.21) will be fully illuminated when used to set a solar simulator or measure E_{tot} in natural sunlight, variations in the responsivity over the sample surface may result in an error in I_{SC}. Most groups use a high-current, low-noise operational amplifier with a gain of 10 to 10 000 as the current-to-voltage converter because commercial current amplifiers saturate around 10 mA. Some groups employ a laser to more accurately measure the absolute response of a reference cell at one wavelength because the light power is in the milliwatt range, instead of microwatt, associated with diffraction-grating or filter-based systems and because reference detectors used to measure the monochromatic light power can be more accurately calibrated for laser lines.

A primary reference cell can be calibrated under natural sunlight using equation (16.19) and a thermal detector [1, 2, 9, 66, 82, 83]:

$$CV = \frac{I^{T,S}}{E_{tot}} \frac{\int_{\lambda_1}^{\lambda_2} E_{Ref}(\lambda) S_T(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{Ref}(\lambda)\, d\lambda} \frac{\int_{\lambda_1}^{\lambda_2} E_S(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} E_S(\lambda) S_T(\lambda)\, d\lambda} \tag{16.22}$$

where the cell short-circuit current ($I^{T,S}$) the solar spectra ($E_S(\lambda)$), and the total irradiance (E_{tot}) are measured at the same time. The spectral responsivity of the reference detector is constant, so $S_R(\lambda)$ is constant and drops out of equation (16.22). The incident irradiance E_{tot} is measured with a thermal detector that is traceable to the world radiometric reference scale, such as an absolute-cavity radiometer or pyranometer. The solar constant and solar power density in units of Wm^{-2} for solar applications are based on the world radiometric reference scale, which is derived from a family of primary absolute-cavity radiometers that are maintained at the World Radiation Research Center in Davos, Switzerland [84]. The field of view for the cell and spectroradiometer must be matched. Some investigators prefer to use a pyranometer mounted coplanar to the spectroradiometer and solar cell(s) on a horizontal surface [9, 85]. The investigators at the National Renewable Energy Laboratory (NREL) use an absolute-cavity radiometer because it is the primary instrument used to calibrate pyranometers and has a field of view of 5°, minimizing field-of-view-related error sources [1, 68, 82, 86]. A spectral model was developed to extend the measured direct-beam spectrum to encompass the limits of the reference spectra to minimize the errors in equation (16.21) [68, 83, 86]. The pyranometer-based calibration method requires the measurement of the spectral irradiance over a wavelength range of 300 to 2500 nm [9, 85]. Typically, CV is an average of many measurements taken over several days. This method only requires that the relative spectral response and spectral irradiance be known, thereby eliminating all error sources that are not wavelength-dependent.

If the absolute spectral irradiance $E_S(\lambda)$ of the light source in the test plane is known, as is the case for a standard lamp, black-body or absolute spectral irradiance