test and reference device. Typically, the simulator is adjusted so that E_{tot} is equal to E_{Ref} from equation (16.18) or

$$I = \frac{E_{\mathrm{Ref}} C V}{I^{\mathrm{R,S}} M} = \frac{I^{\mathrm{R,R}}}{I^{\mathrm{R,S}} M} \tag{16.20}$$

where $I^{\mathrm{R,R}}$ is the calibrated short-circuit current of the reference cell under the reference spectral and total irradiance. Typically, a reference cell is made of the same material and technology as the devices that it will be used to test, causing M to be closer to unity since $S_{\mathrm{R}} \approx S_{\mathrm{T}}$. Ideally, the angular response of the reference package should be similar to the device under test. This is essential for outdoor measurements [2, 69–71]. Consensus standards have been developed, giving guidance for reference cells [72–75]. If the detector package has a window and an air gap between the window and cell, then the package should be completely illuminated and used only with simulators to prevent reflection-related artifacts [29, 76]. Recently, the terrestrial community has proposed a standard package design for the World Photovoltaic Scale [74, 75]. This package was designed by international terrestrial PV calibration laboratories to accommodate their various PV calibration equipment, while having standardized connectors to facilitate international intercomparisons.

16.3.3 Primary Reference Cell Calibration Methods

Perhaps the most straightforward method of determining the short-circuit current with respect to a set of reference conditions is to measure the absolute external spectral responsivity of the test device at the reference temperature, $S_{\mathrm{T}}(\lambda)$, and to integrate it with the reference spectrum, $E_{\mathrm{Ref}}(\lambda)$, at the reference total irradiance, E_{tot}, using the following equation:

$$E_{\mathrm{tot}} C V = I_{\mathrm{SC}} = \frac{E_{\mathrm{tot}} A \displaystyle\int_{\lambda_1}^{\lambda_2} E_{\mathrm{Ref}}(\lambda) S_{\mathrm{T}}(\lambda)\,\mathrm{d}\lambda}{\displaystyle\int_{\lambda_1}^{\lambda_2} E_{\mathrm{Ref}}(\lambda)\,\mathrm{d}\lambda}. \tag{16.21}$$

For I_{SC} to be in units of A, wavelength (λ) must be in units of μm, PV area (A) in m^2, $E_{\mathrm{Ref}}(\lambda)$ in $\mathrm{Wm}^{-2}\mu\mathrm{m}^{-1}$, E_{tot} in Wm^{-2}, and $S_{\mathrm{T}}(\lambda)$ in AW^{-1}. The limits of integration should encompass the range of $E_{\mathrm{Ref}}(\lambda)$. If $E_{\mathrm{Ref}}(\lambda)$ is normalized to integrate to E_{tot}, then the limits of integration should encompass the response range of the device. The relationship between the spectral responsivity and the quantum yield is discussed in 16.4. Equation (16.21) assumes that $S_{\mathrm{T}}(\lambda)$ is uniform over the PV device and that $S_{\mathrm{T}}(\lambda)$ is independent of voltage bias, E_{tot}, and $E_{\mathrm{Ref}}(\lambda)$. These assumptions can be relaxed for single-junction devices by applying an external bias light operating at E_{tot}. Several groups have gone to great lengths to minimize the various errors associated with equation (16.21) [77, 78]. Several intercomparisons show that differences of more than 10% in the absolute spectral response are possible from well-known PV calibration laboratories [74, 79–81]. Accurate spectral response measurements require measuring the