direct and AM0 reference spectra have no angular dependence, and measurements are normally performed at normal incidence, so the angular dependence in equation (16.16) drops out. If the angular dependence of the reference detector used to measure E_{tot} and the global reference spectra follow an ideal cosine response, then equation (16.16) simplifies to [66, 67]:

$$M = \frac{\int_{\lambda_1}^{\lambda_2} E_{\text{Ref}}(\lambda) S_{\text{R}}(\lambda)\, \text{d}\lambda}{\int_{\lambda_1}^{\lambda_2} E_{\text{Ref}}(\lambda) S_{\text{T}}(\lambda)\, \text{d}\lambda} \frac{\int_{\lambda_1}^{\lambda_2} E_{\text{S}}(\lambda) S_{\text{T}}(\lambda)\, \text{d}\lambda}{\int_{\lambda_1}^{\lambda_2} E_{\text{S}}(\lambda) S_{\text{R}}(\lambda)\, \text{d}\lambda}. \tag{16.17}$$

If the reference detector is a thermal detector, S_{R} is independent of the wavelength and drops out. The source spectral irradiance (E_{S}) and spectral responsivity of S_{R} and S_{T} need only be relative in equation (16.17), since any multiplicative error sources will drop out. Ideally, the limits of integration λ_1 and λ_2 in equation (16.17) should encompass the range of the reference detector and reference spectrum, or else an error can arise [68]. If the spectral irradiance of the light source is the same as the reference spectrum or if the relative spectral responsivity of the reference detector matches the relative spectral responsivity of the test device, then M is unity. Manufacturers of PV cells and modules for multimillion dollar satellites require the lowest possible measurement uncertainty; so they require primary balloon or space-calibrated reference cells of the same manufacturing lot, and purchase solar simulators with the closest spectral match to AM0 that is technically possible so that they can assume that M is unity.

The short-circuit current of the reference cell under the source spectrum ($I^{\text{R,S}}$) is used to determine the effective irradiance using the following equation:

$$E_{\text{tot}} = \frac{I^{\text{R,S}} M}{CV} \tag{16.18}$$

where CV is the calibration value of the instrument used to measure the incident irradiance in units of AW^{-1}m^2. If a thermal detector is used, then CV has the units of VW^{-1}m^2 and $S_{\text{R}}(\lambda)$ is constant.

16.3.2 Simulator-based $I-V$ Measurements: Theory

The short circuit current of a test device ($I^{\text{T,R}}$) at the reference total irradiance (E_{Ref}) can be written as [2, 4, 67]:

$$I^{\text{T,R}} = \frac{I^{\text{T,S}} E_{\text{Ref}} CV}{I^{\text{R,S}} M} \tag{16.19}$$

where $I^{\text{T,S}}$ is the short-circuit current of the test device measured under the source spectrum, M is from equation (16.17), and $I^{\text{R,S}}$ is the measured short-circuit current of the reference cell under the source spectrum. This is the standard simulator-based calibration procedure. Many groups assume M is unity because of the difficulty of obtaining a spectral irradiance of the source spectrum and knowledge of the spectral responsivities of the