standardized mounting, data acquisition system, and thermal considerations [90, 91]. See Chapter 10 for further discussion of calibration of reference cells for testing space cells.

16.3.4 Uncertainty Estimates in Reference Cell Calibration Procedures

All measurements have an uncertainty between the measured or derived value and the true value. In the case of terrestrial PV reference cell calibrations, the true value is the value under reference conditions given in Table 16.1. For extraterrestrial calibrations, the true value is determined by the actual solar spectrum, at the time of calibration and not the tabular reference spectrum, as in the case of terrestrial calibrations. Any variation in the primary AM0 calibration because of the varying solar constant is not considered an error. The spectral responsivity of PV cells change as a function of radiation damage. For an accurate assessment of the performance as a function of radiation damage using procedures that assume the spectral correction factor is unity, at least three matched reference cells are required (beginning of life, midlife, and end of life) to minimize the spectral errors.

The uncertainty that is expected to include 95% of results (U_{95}) in a calibration can be expressed in terms of the random error and systematic error component defined below, through the following equation [97]:

$$U_{95} \equiv \sqrt{B^2 + (t_{95}A)^2} \tag{16.25}$$

where A is the statistical component applied to a series of repeated determinations and is often expressed as a standard deviation. Type B error sources are associated with the instruments used in the measurement process and their associated calibration uncertainties. Student's t value for 95% coverage (t_{95}) is approximately 2.0 for an average of more than 20 measurements. The elemental error sources are composed of J random and systematic error components. The *systematic* error is

$$A \equiv \sqrt{\sum_{i=1}^{J} (\Theta_i A_i)^2} \tag{16.26}$$

The term *systematic error* is sometimes used synonymously with bias or nonrandom error. The sensitivity coefficient (Θ_i) is obtained by partial differentiation of the result with respect to one of the parameters in the result. If A_i is expressed in units of percent error, then Θ_i is unity. The *random* error is

$$B \equiv \sqrt{\sum_{i=1}^{J} (\Theta_i B_i)^2} \tag{16.27}$$

An example of an uncertainty analysis of equation (16.22) using the NREL direct-beam calibration method is given in Table 16.6 [98, 99]. Detailed uncertainty analysis using Monte Carlo methods indicates that the uncertainty in the spectral correction factor is 10%