The program moves the detector to the first *x* and *y* position and takes the detector to monitor signal ratio measurement (eq (3.23)). The program scans the detector from top to bottom and left to right. That is, the *x,y* movement is from the top left to the bottom right (or top right depending on the number of columns measured). The program displays a *quasi* three dimensional graph of the signal ratios. The absolute value of the ratio data is plotted in case the polarity of the diode is reversed. This graph is updated after each data point measurement. Also displayed are the current horizontal and vertical positions. The ratio and percent standard deviation data from each *x,y* position are combined into arrays and added to the output file saved on the hard disk. After the spatial scan is complete a record of the operator inputs and a spatial graph of the signal ratios is printed.

The responsivity spatial uniformity output data file is an ASCII text array that is tab delimited. The file consists of "header" lines and data lines. The "header" lines contain information about the measurement parameters, operator comments, laboratory temperature, humidity, etc., and detector temperature (if provided). The data lines consist of *y* rows and *x* columns of the test detector to monitor detector signal ratios. The first data point (array cell) corresponds to the upper left *x,y* scan position. That is, the array corresponds to looking at the detector where the left side of the array is the left side of the detector, the top of the array is the top of the detector, etc. Following the ratio data array is a similar array containing the corresponding relative standard deviations.

7. Uncertainty Assessment

The assessment of the uncertainties for the detector responsivity measurement is explained in this section. First the uncertainty is evaluated for the measurement equation developed earlier in this document. In addition to the uncertainty terms that come directly from the measurement equation there are indirect terms due to the wavelength uncertainty of the monochromator, long-term stability of the working standards, and the assumptions and approximations made during the development of the measurement equation. Second, the uncertainty for each group of working standards and the transfer to customer detectors is given in detail. The uncertainty analysis follows the method outlined in Ref. [7]. A general discussion of the sources of error in radiometry can be found in Refs. [50 and 51]. A detailed explanation of the evaluation and expression of measurement uncertainty is given in Ref. [52].

7.1 Uncertainty Components

In general, a measurement result *y* can be expressed as a functional relationship *f* of N input quantities x_i given by,

$$y = f(x_1, x_2, ..., x_N). \tag{7.1}$$

The combined standard uncertainty $u_c(y)$ is given by the law of propagation of uncertainty as the following sum,

$$u_c(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \cdot u(x_i) \right)^2} \,, \tag{7.2}$$

where the partial derivatives $\partial f / \partial x_i$ are the sensitivity coefficients and $u(x_i)$ are the standard uncertainties of each input x_i which are assumed to be uncorrelated. This method is also called the root-sum-of-squares or "RSS" method.

When the functional relationship involves products and quotients, as the measurement equation described in this document, the relative combined standard uncertainty $u_c(y)/y$ is more convenient, and is given by

$$u_{c,\,r}(y) \equiv \frac{u_c(y)}{y} = \sqrt{\sum_{i=1}^{N} \left(\frac{1}{y} \cdot \frac{\partial f}{\partial x_i} \cdot u(x_i) \right)^2} \,, \tag{7.3}$$

where $(1/y) \cdot (\partial f / \partial x_i)$ is the relative sensitivity coefficient. The expanded uncertainty U is obtained by multiplying $u_c(y)$ by a coverage factor k,

$$U = k \cdot u_c(y) \,, \tag{7.4}$$

where k is chosen on the basis of the level of confidence desired. Replacing $u_c(y)$ with the relative combined standard uncertainty $u_{c,\,r}(y)$ gives the relative expanded uncertainty $U_r \equiv U/y$. The coverage factor $k = 2$ was used in this document and it is assumed that the possible estimated values of spectral responsivity are approximately normally distributed with approximate standard deviation u_c, thus, the interval defined by U has a level of confidence of approximately 95 %.

To help clarify the following discussion of uncertainties, an arbitrary uncertainty $u_0(S_{ws})$ in the working standard spectral responsivity is defined. The uncertainty $u_0(S_{ws})$ can be derived directly from the measurement equation in eq (3.27), repeated below, by using the propagation of standard uncertainty relationship in eq (7.2). The measurement equation is

$$S_{ws} = \frac{R_{ws}}{R_s} \cdot \frac{G_s}{G_{ws}} \cdot S_s \ [\mathrm{A \cdot W^{-1}}]. \tag{7.5}$$

The uncertainty $u_0(S_{ws})$ is

$$u_0(S_{ws}) = \left[\left(\frac{\partial S_{ws}}{\partial R_{ws}} \cdot u(R_{ws}) \right)^2 + \left(\frac{\partial S_{ws}}{\partial R_s} \cdot u(R_s) \right)^2 + \left(\frac{\partial S_{ws}}{\partial G_s} \cdot u(G_s) \right)^2 + \left(\frac{\partial S_{ws}}{\partial G_{ws}} \cdot u(G_{ws}) \right)^2 + \left(\frac{\partial S_{ws}}{\partial S_s} \cdot u(S_s) \right)^2 \right]^{1/2} \ [\mathrm{A \cdot W^{-1}}]. \tag{7.6}$$

The relative uncertainty $u_0(S_{\mathrm{ws}})/S_{\mathrm{ws}}$ is

$$\frac{u_0(S_{\mathrm{ws}})}{S_{\mathrm{ws}}} = \sqrt{\left(\frac{u(R_{\mathrm{ws}})}{R_{\mathrm{ws}}}\right)^2 + \left(\frac{u(R_{\mathrm{s}})}{R_{\mathrm{s}}}\right)^2 + \left(\frac{u(G_{\mathrm{s}})}{G_{\mathrm{s}}}\right)^2 + \left(\frac{u(G_{\mathrm{ws}})}{G_{\mathrm{ws}}}\right)^2 + \left(\frac{u(S_{\mathrm{s}})}{S_{\mathrm{s}}}\right)^2}, \tag{7.7}$$

where $u(R_{\mathrm{ws}})$ is the standard deviation of the mean of *i* ratios of the working standard and the monitor, $u(R_{\mathrm{s}})$ is the standard deviation of the mean of *i* ratios of the calibration standard and the monitor, $u(G_{\mathrm{s}})$ is the calibration standard amplifier gain uncertainty, $u(G_{\mathrm{x}})$ is the working standard amplifier gain uncertainty, $u(S_{\mathrm{s}})$ is the calibration standard uncertainty, and *i* is the number of ratio measurements taken.

The calibration standard uncertainty, $u(S_{\mathrm{s}})$, is determined previously by the HACR transfer measurements. The amplifier gains, G_{s} and G_{x}, are calibrated using a precision current source and DVM. The amplifier gain uncertainties, $u(G_{\mathrm{s}})$ and $u(G_{\mathrm{x}})$, are the RSS of the uncertainties from the precision current source and DVM.

The first two terms contribute uncertainty due to the measurement statistics (Type A uncertainties). The remaining terms are Type B uncertainties. If more than one scan is taken during a measurement (typically three scans are taken), then a weighted average of the mean, R_{w}, of the ratio $R = R_{\mathrm{ws}}/R_{\mathrm{s}}$ is calculated [40] using the RSS of $u(R_{\mathrm{ws}})$ and $u(R_{\mathrm{s}})$ from each scan as weighting factors. An uncertainty term $u(R_{\mathrm{w}})$ is calculated for the weighted average and is an indication of the measurement repeatability.

There is also a statistical uncertainty term $u(R_{\mathrm{r}})$ reflecting the reproducibility of the measurements (e.g., setting up the measurement again the next day). The relative uncertainty term, $u(R_{\mathrm{r}})/R_{\mathrm{r}}$ is combined by RSS with $u(R_{\mathrm{w}})/R_{\mathrm{w}}$ to get the relative measurement uncertainty, $u(R_{\mathrm{m}})/R_{\mathrm{m}}$. The relative measurement uncertainty contains the temperature and uniformity variations since it is the result of repeated measurements at different temperatures and alignments and is an indication of the measurement reproducibility.

By calculating the ratios of the test to monitor and standard to monitor signals, we take into consideration the correlation of the signals due to source fluctuations, thus the covariance is not included in the *R* uncertainty term. The standard deviation of the ratio of the detector to monitor signals is less than the standard deviation of either by themselves, as shown in figure 6.1.

The combined uncertainty $u_{\mathrm{c}}(S_{\mathrm{ws}})$ in the spectral responsivity of the working standard is determined by calculating the RSS of the uncertainty terms thus far discussed and the uncertainty terms from the assumptions and approximations made in the measurement equation and so-called "indirect" effects that are not explicitly shown in the measurement equation as expressed in eq (7.5) such as, the monochromator wavelength uncertainty, DVM uncertainty, and long-term stability of the working standards.

The relative combined uncertainty $u_c(S_{ws})/S_{ws}$ is

$$\frac{u_c(S_{ws})}{S_{ws}} = \left[\left(\frac{u(R_m)}{R_m}\right)^2 + \left(\frac{u(G_s)}{G_s}\right)^2 + \left(\frac{u(G_{ws})}{G_{ws}}\right)^2 + \left(\frac{u(S_s)}{S_s}\right)^2 + \left(\frac{u(S_l)}{S_l}\right)^2 + \left(\frac{u(V)}{V}\right)^2 + \left(\frac{u(S_{lt})}{S_{lt}}\right)^2 + \left(\frac{u(g)}{g}\right)^2 + \left(\frac{u(R_{sl})}{R_{sl}}\right)^2 + \left(\frac{u(S_{bw})}{S_{bw}}\right)^2\right]^{1/2}, \tag{7.8}$$

where $u(S_l)/S_l$ is the monochromator wavelength relative uncertainty, $u(V)/V$ is the DVM relative uncertainty, $u(S_{lt})/S_{lt}$ is the relative uncertainty due to the long-term stability of the working standards, $u(g)/g$ is the scaling factor relative uncertainty for the relative responsivity measurements, $u(R_{sl})/R_{sl}$ is the relative uncertainty due to stray light, and $u(S_{bw})/S_{bw}$ is the relative uncertainty due to the bandwidth-effect. These uncertainty terms are explained below.

7.1.1 "Indirect" Uncertainty Components

Several uncertainty components are not explicitly contained in the measurement equation as expressed in eq (7.5) and thus far have not been discussed as part of the uncertainty analysis. These are the wavelength uncertainty in the monochromator setting, DVM uncertainty, long-term stability, and the scaling factor for the relative responsivity measurements. Each of these is discussed below and is evaluated in sections 7.2 and 7.3.

<u>Wavelength Uncertainty</u>

The wavelength uncertainty is the uncertainty in the measured spectral responsivity due to the uncertainty of the set wavelength of the monochromator. The repeatability of that wavelength setting is negligible compared to the wavelength uncertainty and is considered part of the relative measurement uncertainty. The wavelength uncertainty of the monochromator $u(l)$ introduces an uncertainty proportional to the slope of the responsivity dS_x/dl [53]

$$u(S_l) = \frac{dS_l}{dl}\cdot u(l) = \frac{d}{dl}\left[\frac{R_{ws}}{R_s}\cdot G\cdot S_s\right]\cdot u(l) \text{ [U·W}^{-1}\text{], where} \tag{7.9}$$

$$S_l = S_x = \frac{R_x}{R_s}\cdot G\cdot S_s \text{ [U·W}^{-1}\text{]}, \tag{7.10}$$

and $G = G_s/G_x$ is the ratio of the amplifier gains, which is a constant with respect to wavelength. Carrying out the differentiation gives

$$u(S_l) = \left[\frac{S_s}{R_s^2}\cdot\left(R_s\cdot\frac{dR_x}{dl} - R_x\cdot\frac{dR_s}{dl}\right) + \frac{R_x}{R_s}\cdot\frac{dS_s}{dl}\right]\cdot u(l) \text{ [U·W}^{-1}\text{]}. \tag{7.11}$$

The wavelength uncertainty of the monochromator $u(l)$ is the standard deviation of the residuals to a fit of the wavelength calibration.

The relative uncertainty can be shown to be

$$\frac{u(S_l)}{S_l} = \frac{u(l)}{G \cdot S_s} \cdot \frac{R_s}{R_x} \cdot \frac{\mathrm{d}S_x}{\mathrm{d}l} = \frac{u(l)}{G} \cdot \left[\frac{1}{R_x} \cdot \frac{\mathrm{d}R_x}{\mathrm{d}l} - \frac{1}{R_s} \cdot \frac{\mathrm{d}R_s}{\mathrm{d}l} + \frac{1}{S_s} \cdot \frac{\mathrm{d}S_s}{\mathrm{d}l} \right] \text{[unitless].} \tag{7.12}$$

Typically the gain ratio G equals unity since the same gain range is used for the same detector type (model). For the same type of detector $R_x = R_s$ and $G = 1$, eq (7.12) reduces to

$$\frac{u(S_l)}{S_l} = \frac{u(l)}{S_s} \cdot \frac{\mathrm{d}S_s}{\mathrm{d}l} \text{ [unitless].} \tag{7.13}$$

While the wavelength uncertainty typically is not a large contribution to the measurement uncertainty, it can be significant if the responsivity slope is large. This is especially noticeable with filter and detector packages where the responsivity curve can be very steep in the cut-on and cut-off regions of the filter. A good example is a photometer.

DVM Uncertainty

The values R_{ws} and R_s are the ratio of the difference of four signals which were all taken by DVMs. It follows that the measurement uncertainty of the DVMs are to be included. An uncertainty is calculated for each of the eight signal measurements taken with a DVM (Type B uncertainties) and combined by RSS (ignoring the covariances due to using two DVMs) to give the overly conservative DVM relative uncertainty, $u(V)/V$.

Long-term Stability

The long-term stability is a component of the uncertainty analysis. The relative uncertainty $u(S_{lt})/S_{lt}$ is the relative difference of the measured responsivity over approximately a one year time period. The long-term stability numbers presented in the uncertainty tables could be influenced by temperature changes. For most of the spectral region the temperature effect is less than the stated long-term uncertainty. In the near-IR spectral region (> 960 nm for the Hamamatsu S1337) the temperature effect may be larger than the stated long-term uncertainty. A more thorough investigation could increase these numbers. However, using recently acquired temperature-controlled fixtures for the silicon working standards is expected to reduce the temperature effect significantly, and could reduce the uncertainty component for long-term stability in this spectral region.

The long-term changes in the germanium working standards are not understood, but could be due to reflections from the wedged window reflecting off of the baffle or incident on the monitor detector. This is being studied.

Scaling factor

The scaling factor g is the ratio of absolute responsivity and relative responsivity measurements. The scaling factor enters the measurement equation with the relative responsivity s_p of the pyroelectric detector. The scaling factor relative uncertainty $u(g)/g$ is the relative standard deviation of the mean of the g's calculated in the spectral region of i wavelengths where the measured responsivities overlap.

7.1.2 Uncertainty Components due to Assumptions and Approximations

Stray Light

Stray light does not add error to measurements when the test and standard detectors have identical responsivity curves. But when the test and standard detectors have different responsivity curves then the error introduced by stray light must be taken into account. This is often very difficult to do, since the slit-scattering function is needed and is very difficult to measure practically; thus it has to be estimated or measured indirectly [54] over the entire spectral range of the monochromator or the responsivity spectral range of the detectors used in operation.

In principle, the stray light is very small when using a double monochromator. Typically this is verified by measurements with various cut-off filters, and the stray light is considered to be a negligible source of error. For this uncertainty analysis, an estimation of the stray light was calculated; and its contribution to the measurement uncertainty was shown to be negligible for almost all of the measurements.

The error due to stray light can be estimated by letting $V_x(l_0)$ be the signal (in U units) from a detector x when the monochromator is set to wavelength l_0

$$V_x(l_0) = V_{x,bw}(l_0) + V_{x,sl}(l_0) \text{ [U]}, \tag{7.14}$$

where $V_{x,bw}(l_0)$ is the signal due to light within the full-width bandpass Δl and $V_{x,sl}(l_0)$ is the signal due to stray light. Using eqs (3.3) and (3.4), the measurement equation for the detector signal due to the light within the bandpass Δl is

$$V_{x,bw}(l_0) = \int_{\Delta l} S_x(l) \cdot F_{D,l}(l, l_0) \cdot \mathrm{d}l \text{ [U]}. \tag{7.15}$$

Similarly, the signal due to stray light is

$$V_{x,sl}(l_0) = \int_{l \neq \Delta l} S_x(l) \cdot F_{D,l}(l, l_0) \cdot \mathrm{d}l \text{ [U]}, \tag{7.16}$$

where the integral spans the detector responsivity spectral range but is not inclusive of the bandpass Δl. The incident flux $F_{\mathrm{D},l}(l, l_0)$ on the detector from the monochromator can be expressed as a product with the slit-scattering function

$$F_{\mathrm{D},l}(l, l_0) = z(l_0 - l) \cdot F_{\mathrm{f},l}(l) \text{ [W]}, \tag{7.17}$$

where $z(l_0 - l)$ is the same slit-scattering function introduced in eq (3.6), and $F_{\mathrm{f},l}(l)$ is the spectral radiant flux on the detector at l_0. (Note: the term $F_{\mathrm{f},l}(l)$, in this situation, implicitly includes the transmittance of the optics and atmosphere unlike in sec. 3.1.) The measurement equation for the detector at wavelength l_0 is thus

$$V_{\mathrm{x}}(l_0) = \int_{\Delta l} S_{\mathrm{x}}(l) \cdot z(l_0 - l) \cdot F_{\mathrm{f},l}(l) \cdot \mathrm{d}l + \int_{l \neq \Delta l} S_{\mathrm{x}}(l) \cdot z(l_0 - l) \cdot F_{\mathrm{f},l}(l) \cdot \mathrm{d}l \text{ [U]}. \tag{7.18}$$

Similarly, the measurement equation for a working standard detector s is

$$V_{\mathrm{s}}(l_0) = \int_{\Delta l} S_{\mathrm{s}}(l) \cdot z(l_0 - l) \cdot F_{\mathrm{f},l}(l) \cdot \mathrm{d}l + \int_{l \neq \Delta l} S_{\mathrm{s}}(l) \cdot z(l_0 - l) \cdot F_{\mathrm{f},l}(l) \cdot \mathrm{d}l \text{ [U]}. \tag{7.19}$$

For estimating the stray light contribution to the measured signal, the slit-scattering function is assumed to have the computationally convenient form

$$z(l_0 - l) = \begin{cases} 1 & \textit{for} \quad l_0 - \Delta l \leq l \leq l_0 + \Delta l \\ 10^{-7} & \textit{otherwise} \end{cases} . \tag{7.20}$$

The error due to stray light is estimated by converting the integrals to summations and taking the difference between the ratio of the measured signals from the test and working standard detectors, R_{T}, and the ratio R_{bw} of the signals due to light within the bandpass Δl. The relative error due to stray light when the monochromator is set to l_0 is estimated as

$$\frac{\delta R_{\mathrm{sl}}(l_0)}{R_{\mathrm{sl}}(l_0)} \approx \frac{R_{\mathrm{T}}(l_0) - R_{\mathrm{bw}}(l_0)}{R_{\mathrm{bw}}(l_0)} \text{ [unitless]}, \tag{7.21}$$

where $$R_{\mathrm{T}}(l_0) = \frac{V_{\mathrm{x}}(l, l_0)}{V_{\mathrm{s}}(l, l_0)} \text{ and } R_{\mathrm{sl}}(l_0) = R_{\mathrm{bw}}(l_0) = \frac{V_{\mathrm{x,bw}}(l, l_0)}{V_{\mathrm{s,bw}}(l, l_0)} . \tag{7.22a,b}$$

The relative error was calculated over the measurement spectral range at 5 nm intervals of l_0 and will be shown below. Because these errors are small, a correction is not applied, but instead the component of relative standard uncertainty is assumed equal to the relative error. It can be seen from tables 7.1 to 7.7 that this component makes a negligible contribution to the combined standard uncertainty.

Bandwidth-effect

As mentioned in section 3.2.4, the bandwidth of the monochromator output flux causes an error in the measurement when the monochromator wavelength scale is calibrated using the peak wavelength of the bandpass and the responsivity curves of the test and standard detectors do not have the same slope. This error can be approximated for the uncertainty analysis. Consider the case of a pyroelectric detector used as a standard. The responsivity for the standard is assumed constant (flat) and the responsivities for the test and monitor detector are assumed linear over the bandpass. This is the situation when measuring the relative responsivity of working standard photodiodes. Following the development of eq (17) in Ref. [53] it can be shown that the measurement equation for spectral responsivity, taking into consideration the bandwidth of the monochromator,

$$S_x = \frac{R_x}{R_s} \cdot S_s - \frac{b \cdot b^2}{6} \cdot \frac{\mathrm{d}S_x}{\mathrm{d}\,l} \ [\mathrm{U \cdot W^{-1}}], \tag{7.23}$$

where the ratio of signals is now replaced by the ratio of test to monitor and standard to monitor signal ratios. Note the change in responsivity and bandwidth notation from Ref. [53]. The other terms are defined as $2b = \Delta\, l =$ full-width bandpass ($b = \Delta\, l/2 =$ FWHM for triangular bandpass)

$$b = \frac{s}{F_D - l_0 \cdot s} \ [\mathrm{m^{-1}}], \text{ where } s = \frac{\mathrm{d}F_D}{\mathrm{d}\,l} \ [\mathrm{W \cdot m^{-1}}], \tag{7.24a,b}$$

and $\mathrm{d}F_D$ is the change in flux reaching the detector (i.e., s = slope of the output flux function). This assumes a triangular bandpass for the monochromator and that the flux varies linearly over the bandpass.

When the responsivity of the standard also changes spectrally, it can be shown that the measurement equation is similar to eq (18) in Ref. [53],

$$S_x = \frac{R_x}{R_s} \cdot \left[S_s + \frac{b \cdot b^2}{6} \cdot \frac{\mathrm{d}S_s}{\mathrm{d}\,l} \right] - \frac{b \cdot b^2}{6} \cdot \frac{\mathrm{d}S_x}{\mathrm{d}\,l} \ [\mathrm{U \cdot W^{-1}}], \tag{7.25}$$

where all the terms and conditions are the same as before. This is the general test situation. The bandwidth-effect error component, using eq (7.23), is

$$\delta S_{bw} = C_{bw} = -\frac{b \cdot b^2}{6} \cdot \frac{\mathrm{d}S_x}{\mathrm{d}\,l} \ [\mathrm{U \cdot W^{-1}}]. \tag{7.26}$$

The relative error is

$$\frac{\delta S_{bw}}{S_{bw}} = \frac{\delta S_{bw}}{\frac{R_x}{R_s} \cdot S_s} \ [\text{unitless}], \tag{7.27}$$

and

$$\frac{\delta S_{\mathrm{bw}}}{S_{\mathrm{bw}}} = \frac{\delta S_{\mathrm{bw}}}{S_{\mathrm{s}}} \cdot \frac{R_{\mathrm{s}}}{R_{\mathrm{x}}} = \frac{-b \cdot b^{2}}{6 \cdot S_{\mathrm{s}}} \cdot \frac{R_{\mathrm{s}}}{R_{\mathrm{x}}} \cdot \frac{\delta_{\mathrm{x}} S}{\mathrm{d}\, l} \text{ [unitless].} \tag{7.28}$$

Similarly, for eq (7.25) the relative error is eq (7.27) where the bandwidth-effect uncertainty component is

$$\delta S_{\mathrm{bw}} = C_{\mathrm{bw}} = \frac{R_{\mathrm{x}}}{R_{\mathrm{s}}} \cdot \frac{b \cdot b^{2}}{6} \cdot \frac{\mathrm{d}S_{\mathrm{s}}}{\mathrm{d}\, l} - \frac{b \cdot b^{2}}{6} \cdot \frac{\mathrm{d}S_{\mathrm{x}}}{\mathrm{d}\, l} \text{ [U·W}^{-1}\text{]}, \tag{7.29}$$

and

$$\frac{\delta S_{\mathrm{bw}}}{S_{\mathrm{bw}}} = \frac{\delta S_{\mathrm{bw}}}{S_{\mathrm{s}}} \cdot \frac{R_{\mathrm{s}}}{R_{\mathrm{x}}} = \frac{b \cdot b^{2}}{6 \cdot S_{\mathrm{s}}} \cdot \left[\frac{\mathrm{d}S_{\mathrm{s}}}{\mathrm{d}\, l} - \frac{R_{\mathrm{s}}}{R_{\mathrm{x}}} \cdot \frac{\mathrm{d}S_{\mathrm{x}}}{\mathrm{d}\, l} \right] \text{ [unitless].} \tag{7.30}$$

As stated in Ref. [53] and in section 3.2.4, the effect of the bandwidth could be treated as a correction term C_{bw}, but since it is small for the measurements described here it is applied as an uncertainty component. Numerical results are presented in tables 7.1 to 7.7 and it can be seen that this component makes a negligible contribution to the combined standard uncertainty.

7.1.3 Other Factors Considered and Neglected

Several other factors that could contribute uncertainty components were mentioned in section 3.1.1 and are discussed here. Stable detector responsivities are fundamental for detector-based radiometry. Detector responsivity stability has been the subject of several past and present studies reported [55]; and, for this application, short-term instability has not been observed. Long-term stability has already been discussed. Effects of polarization have been studied and found to be negligible for the typical situation, where the detectors are measured at normal incidence to the optical axis (and the detector surfaces are isotropic). The effect of the converging beam angle on the reflectance (and transmittance) from the detector surface (and window) is small compared to the variance of repeated measurements and is typically neglected. Water condensation (onto the detector or window) and the effects of water absorption have not been observed and are neglected.

The responsivity temperature coefficient can be significant, especially for wavelengths near the bandgap of a photodiode. Typically, the temperature variation is small over the measurement time and is accounted for in the relative measurement uncertainty since the measurement consists of multiple scans. Temperature variation was considered in the long-term stability estimation. Therefore no explicit term is included in the uncertainty estimate for the responsivity temperature dependence. As mentioned earlier, diffraction and coherence effects are negligible for these comparator systems.

The responsivity spatial uniformity is typically measured but not explicitly used in the uncertainty analysis. Instead, like the temperature variations, it is considered part of the relative measurement uncertainty and long-term stability uncertainty components since the spatial

uniformity directly affects these measurements (i.e., the reproducibility). The same holds true for the monochromator beam profile and shape.

Geometrically scattered (stray) light is light scattered out of the nominal monochromator beam and is thought to be primarily due to imperfections in the optics. The geometrically scattered light cancels when the test and standard detectors are large enough to collect all of the radiation from the monochromator over an area of uniform responsivity. This is the typical measurement condition and thus the geometrically scattered light is neglected. Background radiation (sometimes called diffuse stray light) has been measured and found to be negligible.

The reflected beam from the test detector(s) and working standard detectors travels "backwards" along the optical axis and assumed to be scattered inside the monochromator. Any of this reflected beam that returns to the detector is considered as part of the geometrically scattered light discussed above. The reflected beam from the monitor is not returned along the same path and is diffusely scattered inside the enclosure on the opposite side of the baffle from the test detector and working standard detectors. It contributes to the background radiation previously mentioned.

Effects of detector nonlinearity have been discussed in the literature [32, 34, 56]. The detector linearity has been measured for the Hamamatsu S1337-1010BQ and the UDT Sensors UV100 silicon photodiodes and is discussed in section 9. At the power levels used for routine measurements, nonlinearity is not a consideration.

The frequency response of the detector and amplifier is important to consider when comparing absolute measurements between chopped (optically modulated or ac) and dc measurements. But since the chopped (pyroelectric comparison) measurements are relative measurements, corrections due to frequency response effects are not considered.

7.2 Transfer from Traps (HACR) to Working Standards

In this section, a detailed listing of the uncertainty components for each type of working standard is provided along with a description of how each component was obtained. The data was calculated at 5 nm intervals as shown in the figures; abbreviated numerical tables are provided. The relative measurement uncertainty was determined by calculating the RSS of the weighted uncertainties from multiple measurements. The amplifier calibration uncertainties are all identical because identical amplifiers are used and they are calibrated using the same equipment and procedure. Stray light, bandwidth-effect, and wavelength calibration uncertainties were all calculated as described above using typical data. All components were considered independent and combined by RSS to get the relative combined standard uncertainty shown.

7.2.1 Visible Silicon Working Standards

Table 7.1 lists the uncertainty components for the three calibrations used for the visible silicon working standards. The UV and Ge working standard calibration uncertainties are the combined standard uncertainties from tables 7.3 and 7.2, respectively. The trap uncertainties are from the HACR transfer [21]. The long-term stability is the typical data for a visible working standard

over a one year period. All the components were combined by RSS to get the relative combined standard uncertainty shown at 5 nm intervals in figure 7.1.

Table 7.1. Visible Working Standard Uncertainty

Transfer from Traps, UV WS, and Ge WS

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	UV WS calibration	UV WS amplifier gain	Visible WS amplifier gain	Wavelength calibration (± 0.1 nm)	Stray light	Bandwidth-effect	Visible WS long-term stability	**Relative combined standard uncertainty**
Type	A	B	B	B	B	B	B	B	A	**[%]**
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(S_{UV})/S_{UV}$	$u(G_{UV})/G_{UV}$	$u(G_{Vis})/G_{Vis}$	$u(S_l)/S_l$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$u(S_{lt})/S_{lt}$	$\boldsymbol{u_c(S_{Vis})/S_{Vis}}$
Wavelength [nm]	Estimated value [%]									**Root-sum-of-squares**
350	0.87	0.56	0.83	0.04	0.04	0.04	0.000	-0.001	0.06	**1.33**
400	0.23	0.12	0.71	0.04	0.04	-0.03	0.000	0.001	0.03	**0.76**

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	Trap detector calibration	Trap detector amplifier gain	Visible WS amplifier gain	Wavelength calibration (± 0.1 nm)	Stray light	Bandwidth-effect	Visible WS long-term stability	**Relative combined standard uncertainty**
Type	A	B	B	B	B	B	B	B	A	**[%]**
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(S_T)/S_T$	$u(G_T)/G_T$	$u(G_{Vis})/G_{Vis}$	$u(S_l)/S_l$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$u(S_{lt})/S_{lt}$	$\boldsymbol{u_c(S_{Vis})/S_{Vis}}$
Wavelength [nm]	Estimated value [%]									**Root-sum-of-squares**
405	0.03	0.05	0.05	0.04	0.04	-0.05	0.001	-0.001	0.05	**0.12**
450	0.03	0.02	0.05	0.04	0.04	-0.03	0.000	-0.001	0.01	**0.09**
500	0.03	0.01	0.05	0.04	0.04	-0.02	0.000	0.000	0.01	**0.08**
550	0.03	0.01	0.05	0.04	0.04	-0.02	0.000	0.000	0.01	**0.08**
600	0.02	0.01	0.05	0.04	0.04	-0.02	0.000	0.000	0.01	**0.08**
650	0.03	0.01	0.05	0.04	0.04	-0.02	0.000	0.000	0.01	**0.08**
700	0.03	0.01	0.05	0.04	0.04	-0.01	0.000	0.000	0.01	**0.08**
750	0.03	0.01	0.05	0.04	0.04	-0.01	0.000	0.000	0.02	**0.08**
800	0.02	0.02	0.05	0.04	0.04	-0.01	0.000	0.000	0.03	**0.09**
850	0.02	0.02	0.05	0.04	0.04	-0.01	0.000	0.000	0.04	**0.09**
900	0.02	0.01	0.05	0.04	0.04	-0.01	0.000	0.000	0.04	**0.09**
920	0.02	0.01	0.05	0.04	0.04	-0.01	0.000	0.000	0.05	**0.10**

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	Ge WS calibration	Ge WS amplifier gain	Visible WS amplifier gain	Wavelength calibration (± 0.1 nm)	Stray light	Bandwidth-effect	Visible WS long-term stability	**Relative combined standard uncertainty**
Type	A	B	B	B	B	B	B	B	A	**[%]**
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(S_{Ge})/S_{Ge}$	$u(G_{Ge})/G_{Ge}$	$u(G_{Vis})/G_{Vis}$	$u(S_l)/S_l$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$u(S_{lt})/S_{lt}$	$\boldsymbol{u_c(S_{Vis})/S_{Vis}}$
Wavelength [nm]	Estimated value [%]									**Root-sum-of-squares**
950	0.90	0.02	0.90	0.04	0.04	-0.02	0.002	0.001	0.22	**1.29**
1000	0.39	0.01	0.75	0.04	0.04	0.03	0.001	0.002	0.13	**0.86**
1050	0.43	0.01	0.87	0.04	0.04	0.17	0.000	0.003	0.87	**1.31**
1100	0.40	0.02	0.78	0.04	0.04	0.18	-0.002	0.001	1.86	**2.06**

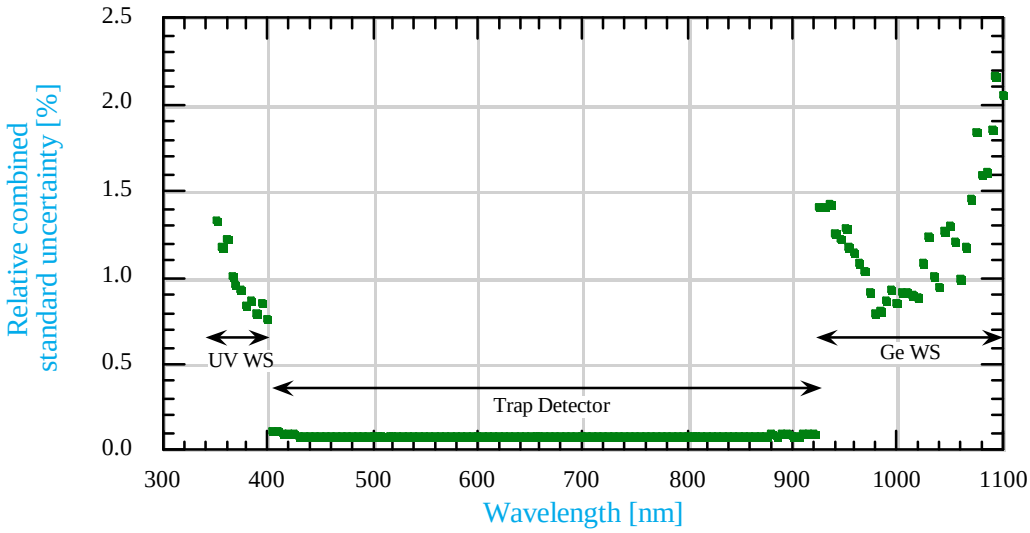


Figure 7.1. Visible Working Standard (Vis WS) relative combined standard uncertainty. The discontinuities in the curve are the result of calibrations with different standards.

7.2.2 Germanium (NIR) Working Standards

Table 7.2 lists the uncertainty components for the relative responsivity measurements using the pyroelectric detector and the absolute responsivity transfer measurement uncertainty components using the HACR-calibrated trap detectors. The absolute measurements are used to scale the relative data of the germanium (NIR) working standards. The low SNR when using the pyroelectric gives rise to larger relative measurement uncertainty values. Also, the long-term stability adds significantly to the germanium working standard uncertainty. The relative combined standard uncertainty was determined by the RSS of all the components. Figure 7.2 shows the relative combined standard uncertainty at 5 nm intervals.

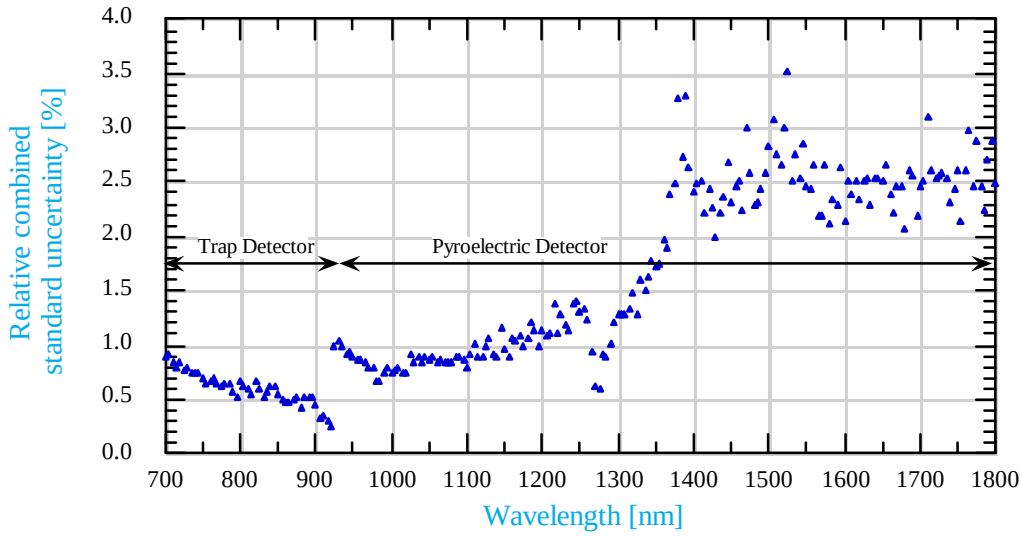


Figure 7.2. Germanium (NIR) Working Standard (Ge WS) relative combined standard uncertainty.

Table 7.2. Germanium Working Standard Uncertainty

Transfer from pyroelectric (relative) and scaling with trap (absolute)

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	Trap detector calibration	Trap detector amplifier gain	Ge WS amplifier gain	Wavelength calibration (± 0.1 nm)	Stray light	Bandwidth-effect	Ge WS long-term stability	**Relative combined standard uncertainty**
Type	A	B	B	B	B	B	B	B	A	**[%]**
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(S_T)/S_T$	$u(G_T)/G_T$	$u(G_{Ge})/G_{Ge}$	$u(S_l)/S_l$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$u(S_{lt})/S_{lt}$	$\boldsymbol{u_c(S_{Ge})/S_{Ge}}$
Wavelength [nm]	Estimated value [%]									**Root-sum-of-squares**
700	0.05	0.03	0.05	0.04	0.04	-0.09	0.008	0.002	0.87	**0.88**
750	0.05	0.03	0.05	0.04	0.04	-0.07	0.008	0.002	0.69	**0.70**
800	0.04	0.04	0.05	0.04	0.04	-0.06	0.008	0.001	0.65	**0.66**
850	0.03	0.04	0.05	0.04	0.04	-0.05	0.008	0.001	0.54	**0.55**
900	0.03	0.02	0.05	0.04	0.04	-0.04	0.003	0.001	0.44	**0.45**
920	0.03	0.02	0.05	0.04	0.04	-0.04	0.003	0.001	0.23	**0.25**

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	Pyroelectric relative calibration	Scaling factor g	Wavelength calibration (± 0.1 nm)	Stray light	Bandwidth-effect	Ge WS long-term stability	**Relative combined standard uncertainty**
Type	A	B	B	B	B	B	B	A	**[%]**
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(s_p)/s_p$	$u(g)/g$	$u(S_l)/S_l$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$u(S_{lt})/S_{lt}$	$\boldsymbol{u_c(S_{Ge})/S_{Ge}}$
Wavelength [nm]	Estimated value [%]								**Root-sum-of-squares**
950	0.68	0.02	0.52	0.14	-0.02	0.000	0.001	0.26	**0.90**
1000	0.39	0.01	0.52	0.14	-0.06	0.000	0.000	0.35	**0.75**
1050	0.63	0.01	0.52	0.14	-0.01	-0.001	0.000	0.25	**0.87**
1100	0.56	0.01	0.52	0.14	0.00	-0.001	0.000	0.09	**0.78**
1150	0.78	0.01	0.52	0.14	0.00	-0.001	-0.001	0.15	**0.96**
1200	0.98	0.01	0.52	0.14	0.00	-0.001	0.000	0.18	**1.13**
1250	1.17	0.01	0.52	0.14	-0.03	-0.001	0.000	0.11	**1.30**
1300	1.14	0.01	0.52	0.14	-0.01	-0.001	0.000	0.21	**1.28**
1350	1.64	0.01	0.52	0.14	-0.05	-0.002	0.000	-0.05	**1.73**
1400	2.34	0.02	0.52	0.14	0.02	-0.003	0.000	-0.04	**2.40**
1450	2.25	0.01	0.52	0.14	0.07	-0.003	0.000	-0.11	**2.31**
1500	2.77	0.01	0.52	0.14	0.06	-0.003	0.000	-0.11	**2.83**
1550	2.34	0.02	0.52	0.14	0.08	-0.003	-0.001	0.57	**2.46**
1600	1.47	0.02	0.52	0.14	-0.02	-0.002	0.000	1.47	**2.14**
1650	1.75	0.03	0.52	0.14	0.08	0.000	0.000	1.72	**2.52**
1700	1.69	0.05	0.52	0.14	0.04	0.003	-0.001	1.70	**2.46**
1750	2.10	0.09	0.52	0.14	0.18	0.016	-0.001	1.45	**2.61**
1800	2.12	0.26	0.52	0.14	0.06	0.064	-0.001	1.15	**2.49**

7.2.3 UV Silicon Working Standards

Table 7.3 lists the uncertainty components for the relative responsivity measurements using the pyroelectric detector and the absolute responsivity transfer measurement uncertainty components from the visible working standards which are traceable to the HACR. The absolute measurements are used to scale the relative data of the UV silicon working standards. The pyroelectric relative measurement uncertainty was affected by a low SNR below 250 nm. The long-term stability is also a large component in the uncertainty. As with the previous working standards, the relative combined standard uncertainty was determined by the RSS of each component. Figure 7.3 shows the relative combined standard uncertainty at 5 nm intervals.

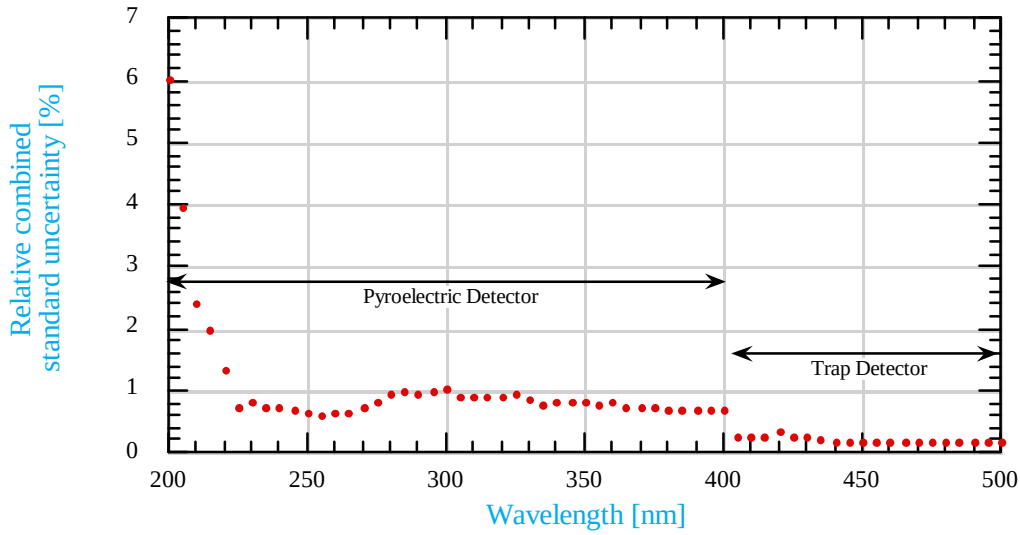


Figure 7.3. Ultraviolet Working Standard (UV WS) relative combined standard uncertainty.

Table 7.3. UV Working Standard Uncertainty

Transfer from Pyroelectric (relative) and Scaling with Visible WS (absolute)

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	Pyroelectric relative calibration	Scaling factor γ	Wavelength calibration (± 0.1 nm)	Stray light	Bandwidth-effect	UV WS long-term stability	**Relative combined standard uncertainty**
Type	A	B	B	B	B	B	B	A	**[%]**
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(s_p)/s_p$	$u(\gamma)/\gamma$	$u(S_l)/S_l$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$u(S_{lt})/S_{lt}$	$\boldsymbol{u_c(S_{UV})/S_{UV}}$
Wavelength [nm]	Estimated value [%]								**Root-sum-of-squares**
200	5.87	0.38	0.52	0.18	-0.98	0.160	0.002	0.72	**6.03**
250	0.34	0.01	0.52	0.18	-0.05	0.001	0.001	-0.19	**0.67**
300	0.38	0.01	0.52	0.18	-0.03	0.000	0.001	0.77	**1.02**
350	0.44	0.01	0.52	0.18	0.03	0.001	0.000	0.44	**0.83**
400	0.42	0.01	0.52	0.18	-0.06	0.000	0.000	0.17	**0.71**

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	Visible WS calibration	Visible WS amplifier gain	UV WS amplifier gain	Wavelength calibration (± 0.1 nm)	Stray light	Bandwidth-effect	UV WS long-term stability	**Relative combined standard uncertainty**
Type	A	B	B	B	B	B	B	B	A	**[%]**
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(S_{Vis})/S_{Vis}$	$u(G_{Vis})/G_{Vis}$	$u(G_{UV})/G_{UV}$	$u(S_l)/S_l$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$u(S_{lt})/S_{lt}$	$\boldsymbol{u_c(S_{UV})/S_{UV}}$
Wavelength [nm]	Estimated value [%]									**Root-sum-of-squares**
450	0.12	0.04	0.09	0.04	0.04	-0.05	0.0000	-0.002	0.00	**0.17**
500	0.11	0.03	0.08	0.04	0.04	-0.04	-0.0001	-0.001	-0.04	**0.16**

7.3 Transfer to Test (Customer) Detectors

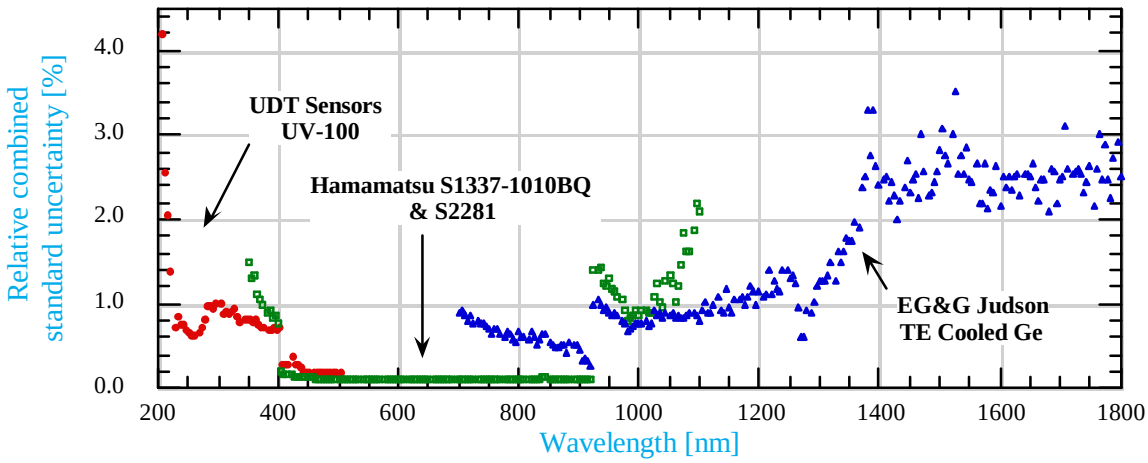
This section details the uncertainty components when transferring the spectral responsivity scale from the working standards to test (customer) detectors. The tables and figures are calculated for specific photodiode models and would, in general, be different for other detectors. These tables and figures serve as a starting point to estimate the minimum uncertainty value possible from this measurement service using the current configuration.

The uncertainty in the spectral responsivity transferred to a test detector is determined similarly to the working standards using eq (7.8). Since, in general, it is not possible to know the details of how a test detector is used, NIST policy [7] is to not include estimates of the uncertainties introduced by transporting the detector or its use by the customer as a reference standard. Examples are uncertainties due to the passage of time (long-term stability) and differences in laboratory environmental conditions.

The stray light and bandwidth-effect are negligible and effects due to wavelength calibration uncertainty are minimized when the working standard and test detector have the same response curve. In the case of an InGaAs photodiode calibrated with the germanium working standards, stray light and bandwidth-effect are almost completely negligible except near the ends of the responsivity spectral range.

As with the transfer to the working standards, abbreviated numerical tables are provided even though the data was calculated at 5 nm intervals; full data sets are shown in the figures. The relative measurement uncertainty was determined by the RSS of the weighted uncertainties from multiple measurements except for the InGaAs example where only one measurement was made and the weighted uncertainties were used. The amplifier calibration uncertainties are all identical because the amplifiers used are identical and calibrated in the same way. Bandwidth-effects, stray light, and wavelength calibration uncertainties were all calculated using typical data as described above. All uncertainty components were considered independent and were combined by RSS to get the relative combined standard uncertainty shown.

Figure 7.4 shows the relative combined standard uncertainty at 5 nm intervals for three types of transfer measurements routinely provided to customers. Note that the NIST policy is to report to customers the uncertainty using a expansion factor of $k = 2$. The expanded uncertainties are shown in figure 2.1.



(Note: Relative standard uncertainty at 200 nm is 6.5 %.)

Figure 7.4. Transfer to test (customer) detectors relative combined standard uncertainty.

7.3.1 UV Silicon Transfer

Table 7.4 lists the uncertainty components for the transfer comparison measurements for test UV silicon photodiodes using the UV working standards. The UV working standard calibration uncertainties are the combined standard uncertainties from table 7.3. The transfer relative combined standard uncertainty was determined by the RSS of the components.

Table 7.4. Transfer Uncertainty to Test (Customer) UV100 Silicon Photodiodes

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	UV WS calibration	UV WS amplifier gain	Test detector amplifier gain	Wavelength calibration (± 0.1 nm)	Stray light†	Bandwidth-effect†	**Relative combined standard uncertainty [%]**
Type	A	B	B	B	B	B	B	B	
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(S_{UV})/S_{UV}$	$u(G_{UV})/G_{UV}$	$u(G_{Test})/G_{Test}$	$u(S_l)/S_l$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$\mathbf{u_c(S_{Test})/S_{Test}}$
Wavelength [nm]	Estimated value [%]								**Root-sum-of-squares**
200	2.41	0.38	6.03	0.04	0.04	-0.05	0.00	0.00	**6.51**
250	0.09	0.01	0.67	0.04	0.04	-0.05	0.00	0.00	**0.68**
300	0.10	0.01	1.02	0.04	0.04	-0.03	0.00	0.00	**1.03**
350	0.09	0.01	0.83	0.04	0.04	0.03	0.00	0.00	**0.84**
400	0.15	0.01	0.71	0.04	0.04	-0.06	0.00	0.00	**0.73**
450	0.04	0.01	0.17	0.04	0.04	-0.05	0.00	0.00	**0.19**
500	0.05	0.01	0.16	0.04	0.04	-0.04	0.00	0.00	**0.19**

†These terms are zero for identical responsivities.

7.3.2 Visible Silicon Transfer

Table 7.5 lists the uncertainty components for the transfer comparison measurements for test Hamamatsu S1337 and S2281 visible silicon photodiodes using the visible working standards. The visible working standard calibration uncertainties are the combined standard uncertainties from table 7.1. The transfer relative combined standard uncertainty was determined by the RSS of the components.

Table 7.5. Transfer Uncertainty to Test (Customer) S1337 and S2281 Silicon Photodiodes

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	Visible WS calibration	Visible WS amplifier gain	Test detector amplifier gain	Wavelength calibration (± 0.1 nm)	Stray light†	Bandwidth-effect†	**Relative combined standard uncertainty**
Type	A	B	B	B	B	B	B	B	**[%]**
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(S_{Vis})/S_{Vis}$	$u(G_{Vis})/G_{Vis}$	$u(G_{Test})/G_{Test}$	$u(S_l)/S_l$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$\boldsymbol{u_c(S_{Test})/S_{Test}}$
Wavelength [nm]	Estimated value [%]								**Root-sum-of-squares**
350	0.31	0.56	1.33	0.04	0.04	0.01	0.00	0.00	**1.48**
400	0.05	0.12	0.76	0.04	0.04	-0.05	0.00	0.00	**0.78**
450	0.02	0.04	0.09	0.04	0.04	-0.03	0.00	0.00	**0.12**
500	0.01	0.02	0.08	0.04	0.04	-0.02	0.00	0.00	**0.11**
550	0.00	0.02	0.08	0.04	0.04	-0.02	0.00	0.00	**0.10**
600	0.01	0.01	0.08	0.04	0.04	-0.02	0.00	0.00	**0.10**
650	0.01	0.01	0.08	0.04	0.04	-0.02	0.00	0.00	**0.10**
700	0.01	0.02	0.08	0.04	0.04	-0.01	0.00	0.00	**0.10**
750	0.01	0.02	0.08	0.04	0.04	-0.01	0.00	0.00	**0.11**
800	0.02	0.03	0.09	0.04	0.04	-0.01	0.00	0.00	**0.11**
850	0.02	0.03	0.09	0.04	0.04	-0.01	0.00	0.00	**0.11**
900	0.01	0.02	0.09	0.04	0.04	-0.01	0.00	0.00	**0.11**
950	0.01	0.01	1.29	0.04	0.04	-0.01	0.00	0.00	**1.29**
1000	0.01	0.01	0.86	0.04	0.04	0.04	0.00	0.00	**0.86**
1050	0.04	0.02	1.31	0.04	0.04	0.18	0.00	0.00	**1.33**
1100	0.08	0.03	2.06	0.04	0.04	0.23	0.00	0.00	**2.08**

†These terms are zero for identical responsivities.

7.3.3 NIR Transfer

The transfer comparison measurement uncertainties for example germanium and indium gallium arsenide (InGaAs) test photodiodes are presented in tables 7.6 and 7.7 respectively. Several of the data columns are detector-dependent, thus these tables are presented as references of typical uncertainties for these types of photodiodes. The reported uncertainties do not include estimates for several components that are unknown for these test photodiodes. The unknown uncertainty components are photodiode responsivity uniformity, polarization sensitivity, linearity, temperature coefficient, and long-term stability. These components could significantly add to the reported uncertainty.

7.3.3.1 Germanium Transfer

Table 7.6 lists the uncertainty components for the transfer comparison measurements for test thermoelectrically cooled germanium photodiodes using the germanium working standards. The germanium NIR working standard calibration uncertainties are the combined standard uncertainties from table 7.2. The transfer relative combined standard uncertainty was determined by the RSS of the components.

The transfer relative combined standard uncertainty presented in table 7.6 is for a Judson EG&G J16TE2-8A6-R05M-SC test photodiode. For different customer-supplied germanium photodiodes the uncertainty is reanalyzed for that device.

Table 7.6. Transfer Uncertainty to Test (Customer) TE Cooled Germanium Photodiodes

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	Ge WS calibration	Ge WS amplifier gain	Test detector amplifier gain	Wavelength calibration (± 0.1 nm)	Stray light†	Bandwidth-effect†	**Relative combined standard uncertainty**
Type	A	B	B	B	B	B	B	B	**[%]**
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(S_{Ge})/S_{Ge}$	$u(G_{Ge})/G_{Ge}$	$u(G_{Test})/G_{Test}$	$u(S_l)/S_l$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$\boldsymbol{u_c(S_{Test})/S_{Test}}$
Wavelength [nm]	Estimated value [%]								**Root-sum-of-squares**
700	0.01	0.05	0.88	0.04	0.04	-0.09	0.00	0.00	**0.89**
750	0.01	0.05	0.70	0.04	0.04	-0.07	0.00	0.00	**0.71**
800	0.03	0.06	0.66	0.04	0.04	-0.06	0.00	0.00	**0.66**
850	0.03	0.06	0.55	0.04	0.04	-0.05	0.00	0.00	**0.56**
900	0.02	0.03	0.45	0.04	0.04	-0.04	0.00	0.00	**0.46**
950	0.02	0.02	0.90	0.04	0.04	-0.03	0.00	0.00	**0.90**
1000	0.01	0.01	0.75	0.04	0.04	-0.03	0.00	0.00	**0.75**
1050	0.01	0.01	0.87	0.04	0.04	-0.03	0.00	0.00	**0.87**
1100	0.01	0.01	0.78	0.04	0.04	-0.02	0.00	0.00	**0.78**
1150	0.01	0.01	0.96	0.04	0.04	-0.02	0.00	0.00	**0.96**
1200	0.01	0.01	1.13	0.04	0.04	-0.02	0.00	0.00	**1.13**
1250	0.01	0.01	1.30	0.04	0.04	-0.01	0.00	0.00	**1.30**
1300	0.01	0.01	1.28	0.04	0.04	-0.01	0.00	0.00	**1.28**
1350	0.02	0.01	1.73	0.04	0.04	-0.01	0.00	0.00	**1.73**
1400	0.03	0.02	2.40	0.04	0.04	-0.01	0.00	0.00	**2.40**
1450	0.02	0.01	2.31	0.04	0.04	-0.01	0.00	0.00	**2.32**
1500	0.03	0.01	2.83	0.04	0.04	-0.01	0.00	0.00	**2.83**
1550	0.03	0.02	2.46	0.04	0.04	0.11	0.00	0.00	**2.47**
1600	0.03	0.02	2.14	0.04	0.04	0.06	0.00	0.00	**2.15**
1650	0.03	0.03	2.52	0.04	0.04	0.06	0.00	0.00	**2.52**
1700	0.03	0.05	2.46	0.04	0.04	0.10	0.00	0.00	**2.46**
1750	0.03	0.09	2.61	0.04	0.04	0.18	0.00	0.00	**2.62**
1800	0.04	0.26	2.49	0.04	0.04	0.20	0.00	0.00	**2.51**

†These terms are zero for identical responsivities.

7.3.3.2 InGaAs Transfer

Table 7.7 lists the uncertainty components for the transfer comparison measurements for test InGaAs photodiodes using the germanium working standards. The weighted uncertainty of one measurement (of three scans) was used as the relative measurement uncertainty. The germanium (NIR) working standard calibration uncertainties are the combined standard uncertainties from table 7.2. The transfer relative combined standard uncertainty was determined by the RSS of the components.

The transfer relative combined standard uncertainty presented in table 7.7 is for an example InGaAs test photodiode. The InGaAs transfer uncertainties are very similar to the germanium transfer uncertainties and were omitted from figure 7.4 for clarity. As with the germanium transfer uncertainty in table 7.6 several of the data columns are detector-dependent, thus this table is presented as a reference representing typical uncertainties for this type of photodiode. For customer-supplied photodiodes the uncertainty is reanalyzed for that device.

Table 7.7. Transfer Uncertainty to Test (Customer) InGaAs Photodiodes

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	Ge WS calibration	Ge WS amplifier gain	Test detector amplifier gain	Wavelength calibration (± 0.1 nm)	Stray light	Bandwidth-effect	**Relative combined standard uncertainty**
Type	A	B	B	B	B	B	B	B	**[%]**
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(S_{Ge})/S_{Ge}$	$u(G_{Ge})/G_{Ge}$	$u(G_{Test})/G_{Test}$	$u(S_l)/S_l$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$\boldsymbol{u_c(S_{Test})/S_{Test}}$
Wavelength [nm]	Estimated value [%]								**Root-sum-of-squares**
700	0.16	0.04	0.88	0.04	0.04	-0.06	0.01	0.00	**0.90**
750	0.18	0.05	0.70	0.04	0.04	-0.06	0.01	0.00	**0.73**
800	0.17	0.06	0.66	0.04	0.04	-0.06	0.01	0.00	**0.69**
850	0.13	0.06	0.55	0.04	0.04	-0.11	0.01	0.00	**0.58**
900	0.11	0.03	0.45	0.04	0.04	-0.11	0.00	0.00	**0.48**
950	0.09	0.02	0.90	0.04	0.04	-0.08	0.00	0.00	**0.91**
1000	0.08	0.01	0.75	0.04	0.04	-0.01	0.00	0.00	**0.76**
1050	0.08	0.01	0.87	0.04	0.04	-0.02	0.00	0.00	**0.87**
1100	0.06	0.01	0.78	0.04	0.04	-0.01	0.00	0.00	**0.78**
1150	0.06	0.01	0.96	0.04	0.04	-0.01	0.00	0.00	**0.96**
1200	0.05	0.01	1.13	0.04	0.04	-0.01	0.00	0.00	**1.13**
1250	0.04	0.01	1.30	0.04	0.04	-0.01	0.00	0.00	**1.30**
1300	0.04	0.01	1.28	0.04	0.04	-0.01	0.00	0.00	**1.28**
1350	0.04	0.01	1.73	0.04	0.04	0.00	0.00	0.00	**1.73**
1400	0.01	0.02	2.40	0.04	0.04	-0.01	0.00	0.00	**2.40**
1450	0.02	0.01	2.31	0.04	0.04	-0.01	0.00	0.00	**2.32**
1500	0.03	0.01	2.83	0.04	0.04	0.00	0.00	0.00	**2.83**
1550	0.26	0.02	2.46	0.04	0.04	0.01	0.00	0.00	**2.48**
1600	0.30	0.02	2.14	0.04	0.04	0.02	0.00	0.00	**2.17**
1650	0.35	0.03	2.52	0.04	0.04	0.09	0.00	0.00	**2.54**
1700	0.45	0.05	2.46	0.04	0.04	0.33	0.01	0.01	**2.52**
1750	0.52	0.13	2.61	0.04	0.04	0.30	0.07	0.00	**2.69**
1800	0.54	0.57	2.49	0.04	0.04	0.28	0.54	0.00	**2.68**

7.3.4 Filtered Detector Transfer

Special tests of filtered detectors (such as photometers) can be made. It should be noted that the relative measurement uncertainty (measurement statistical uncertainty) will increase due to the decrease in signal in the "wings" of the response. As mentioned above, when the slope of the responsivity curve is steep, the uncertainties due to stray light, bandwidth, and wavelength calibration can increase by orders of magnitude relative to the uncertainties within the bandpass of the filtered detector.

7.4 Spatial Uniformity Measurement Uncertainty

The repeatability uncertainty components for the responsivity uniformity measurement of a typical photodiode are listed in table 7.8. This is the repeatability of the measured relative responsivity in the central portion of the active area during one measurement scan. The measurement noise is the average standard deviation of the mean of the measurements in the central portion of the active area of the detector. The relative combined standard uncertainty is the RSS of the measurement noise and the one-day DVM uncertainty specification.

The measurement repeatability uncertainty depends on the SNR of the detector and noise due to the amplifier and DVM. The relative measurement noise varies spectrally, primarily due to the

change in monochromator flux magnitude with wavelength. Note that the variation in responsivity over the measured area is much larger than this uncertainty value.

The reported uncertainty is not an indication of the uniformity measurement reproducibility. It does not consider other components which contribute to the reproducibility uncertainty, such as, the ability to reproduce the same irradiance geometry and detector alignment. Uniformity reproducibility results have been reported [49] for a Hamamatsu S1337-1010BQ with a standard deviation of 0.033 % at 500 nm and 0.25 % at 1000 nm.

The intended primary use of the reported uniformity results is qualitative. That is, to indicate if any large discontinuities are present in the responsivity uniformity which can lead to larger than expected uncertainties in absolute responsivity measurements. Quantitative application of the reported uniformity results requires examination of the irradiance geometry and equipment involved. The generalized application of the uniformity measurement results is currently being studied.

Table 7.8. Photodetector Spatial Uniformity Measurement Repeatablity Uncertainty

Source of uncertainty	Relative measurement noise†	DVM uncertainty	**Relative combined standard uncertainty [%]**
Type	A	B	
Relative uncertainty	$u(R)/R$	$u(V)/V$	$\boldsymbol{u_c(S_{Unif})/S_{Unif}}$
	Estimated value [%]		**Root-sum-of-squares**
	0.0009	0.0007	**0.0012**

†Depends on photodetector and signal level.

8. Quality System

The spectroradiometric detector measurements described in this publication are part of the NIST Optical Technology Division calibration services and are in compliance with ANSI/NCSL Z540-1-1994 [57, 58, 59]. Although quality procedures were previously in place, they varied from calibration service to calibration service within the Division. The quality control procedures were typically limited to the technical aspects of the measurements, such as the yearly calibration of voltmeters, the use of multiple working standards, and their routine rotation.

The goal of the Optical Technology Division's ANSI/NCSL Z540-1-1994 compliance project (which began in 1993) was to unify all the calibration services offered by the Division with standard formats and similar procedures. Balancing functionality and bureaucracy was a concern from the start. Efforts were directed toward developing a useful and practical quality system. Excessively sophisticated and complex procedures are avoided, along with redundant documentation. Tools such as checklists, forms, and flowcharts are used where applicable.

8.1 Control Charts

Control charts are a standard statistical tool used for tracking a process over time [60]. Two working s tandard detectors are used for each test (customer) detector measurement. Thus, one