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 standard detectors are used for each test (customer) detector measurement. Thus, one working standard can be used to calculate the spectral responsivity of the second working standard. Since the working standards are randomly chosen each week, this allows all of the working standards to be compared to each other over time. The responsivity of a given working standard detector can then be tracked over time using control charts. In practice, only a few wavelengths (e.g., every 100 nm) need to be plotted on a control chart for each working standard. An example control chart for a visible working standard at 600 nm is shown in figure 8.1. The center line is the mean responsivity during a period when the measurement process is stable (i.e., "in control"). The upper control limit (UCL) and lower control limit (LCL) are respectively plus and minus three times the average standard deviation of the mean of the responsivity measurements. This should include almost all of the expected random measurement fluctuations. Figure 8.1 shows a trend in the responsivity measurements that does not appear to be due to random fluctuations but is still within the control limits. This demonstrates the value of control charts.

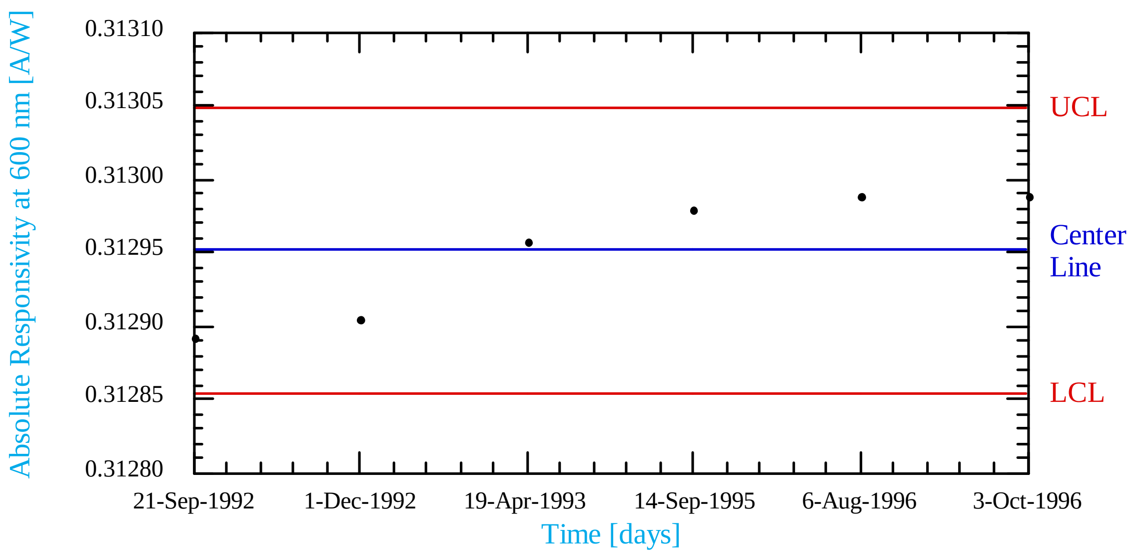

Figure 8.1. Control chart example for a NIST Visible Working Standard (Vis WS).

8.2 Comparison to Other Laboratories

Comparisons have been made between the UV responsivity scales of the UV SCF and the NIST Synchrotron Ultraviolet Radiation Facility (SURF) II [61, 62]. The SURF II responsivity scale is derived from a different physical basis (synchrotron radiation) than the UV SCF's scale (derived from the HACR). The comparisons have agreed within the stated uncertainties of both scales. Future UV intercomparisons are planned with SURF III [63] and a second absolute cryogenic radiometer being installed at SURF III.

There have been few international spectral responsivity intercomparisons. The latest carried out by the Bureau International des Poids et Measures (BIPM) was in 1992 [32, 64]. NIST agreed with the BIPM responsivity scale to better than 0.01 % from 500 nm to 900 nm. The relative difference increased to ≈ 0.4 % at 950 nm and 1000 nm and steadily increased from 0.03 % at 450 nm to 3 % at 248 nm. The larger deviations below 400 nm were reported by several labs (including NIST) but were typically within the stated measurement uncertainties.

Currently there is a spectral responsivity comparison underway between NIST and Centro Nacional De Metrología (CENAM) in Mexico. It is hoped that with the establishment of the North American Calibration Cooperation (NACC) this will be an ongoing intercomparison and will eventually include National Research Council (NRC) in Canada as well. It is also expected that there will be additional intercomparisons among regional groups of Europe, Asia, North America, and South America.

9. Characteristics of Photodiodes Available from NIST

This section describes the characteristics of the silicon photodiodes provided by NIST under Service ID numbers 39071S and 39073S. The physical and electrical characteristics of the photodiodes are discussed and the results of linearity measurements are given. The precision apertures are described and the photodiode fixture mechanical diagrams are shown.

9.1 Hamamatsu S1337-1010BQ

Hamamatsu S1337-1010BQ silicon photodiodes have been supplied by NIST as spectral (power) responsivity standards. NIST currently supplies the Hamamatsu S2281 for this purpose (NIST Service ID number 39073S). As mentioned previously, the Hamamatsu S1337 series diode is a popular diode for radiometric standards and it has been extensively characterized [31, 32]. Hamamatsu describes [65] the S1337-1010BQ as a p-n diode with a 1 cm x 1 cm active area, a fused quartz window, and a ceramic case. The spectral response range is 190 nm to 1100 nm with a peak at 960 nm. The S1337-1010BQ also has a high shunt resistance (dynamic impedance), with a typical value of 200 MΩ and a minimum value of 50 MΩ.

The typical measured spectral responsivity and quantum efficiency are shown in figures 6.2 and 6.3, respectively. The typical spatial uniformities measured at 500 nm and 1000 nm are shown in figure 6.4a and b, respectively. The temperature coefficient of several and S1337 series photodiodes were measured using a temperature-controlled fixture. All of the measurements were made following the typical spectral responsivity procedures at temperatures around 25 °C. Figure 9.1 shows the average temperature coefficient of the Hamamatsu S1337 series photodiode. A second common silicon photodiode series, the S1226, is shown for comparison in figure 9.1 along with the wavelength of peak responsivity for each photodiode.

The linearity of the S1337-1010BQ at 633 nm is shown in figure 9.2 spanning irradiance levels from 0.5 mW/cm^2 to 6.6 mW/cm^2. Each data point represents the ratio of the photodiode responsivity at the indicated irradiance to the responsivity at low power. The linearity was measured by using a beamsplitter to irradiate two photodiodes at approximately a 10:1 intensity ratio, with the diode aperture filled and uniformly irradiated [66]. The linearity is dependent on the irradiation geometry and will differ for spot sizes significantly smaller than the aperture size.