4.3.2 Electronics - Auxiliary Equipment

In both configurations, temperature-controlled germanium photodiodes can be used which require the use of the thermoelectric (TE) temperature controllers shown in figures 4.4 and 4.6. The following electronics not previously mentioned are also used routinely: a 4-channel TE temperature controller for the germanium working standards; a TE temperature controller for the germanium monitor; a digital I/O control unit for the optical shutter; and laboratory environmental monitoring system. The environmental monitoring system measures the temperature in each comparator enclosure, the laboratory temperature, relative humidity, barometric pressure, and the electrical power line voltage and frequency.

5. Absolute Spectral Responsivity Scale Realization

This section describes how the NIST absolute spectral responsivity scale and its traceability to the HACR are determined. First, the operation of the HACR and the scale transfer to the trap detectors are briefly reviewed. Then the transfer of the scale from the trap detectors to the visible working standards is described. Finally, the extension of the scale to the UV and near-IR working standards using a pyroelectric detector is explained. The scale realizations are planned annually.

5.1 Transfer from HACR to Traps (405 nm to 920 nm)

The HACR was constructed to improve the accuracy and spectral range of optical power (flux) measurements and is the U.S. primary standard for optical power (fig. 5.1). Cryogenic radiometers are currently used as the primary standard for optical power at other national laboratories [31, 37, 38]. The HACR will be briefly reviewed here. A full description can be found in Ref. [20]. The HACR is an electrical substitution radiometer (ESR) that operates by comparing the temperature rise induced by optical power absorbed in a cavity to the electrical power needed to cause the same temperature rise by resistive (ohmic) heating. Thus the measurement of optical power is determined in terms of the electrical watt in the form of voltage and resistance standards maintained by NIST [39]. Several advantages are realized by operating at cryogenic temperatures (≈5 K) instead of room temperature. The heat capacity of copper is reduced by a factor of 1000, thus allowing the use of a relatively large cavity. Also the thermal radiation emitted by the cavity or absorbed from the surroundings is reduced by a factor of $\approx 10^7$, which eliminates radiative effects on the equilibrium temperature of the cavity. Finally, the cryogenic temperature allows the use of superconducting wires to the heater, thereby removing the non-equivalence of optical and electrical heating resulting from heat dissipated in the wires. The relative combined standard uncertainty of the NIST HACR measurements is 0.021 % [21] at ≈1 mW. The largest components of the uncertainty are those due to the systematic correction for the Brewster angle window transmission and the random error associated with the cavity temperature measurement.

There are drawbacks for making routine measurements of photodetectors with the HACR. Because of its design, the only source that can be used with the HACR is a laser. Equipment setup and measurements with the HACR are very time consuming, typically taking several days for each wavelength. The measurement wavelengths are limited to available laser wavelengths. The power levels used for the highest accuracy measurements with the HACR are ≈0.8 mW which is higher than those desired for typical radiometric applications. Therefore a practical which is higher than those desired for typical radiometric applications. Therefore a practical means of disseminating the optical power scale to customers is to transfer the scale to other NIST facilities specifically designed for transferring the optical power scale to customers (e.g., UV and Vis/NIR SCFs). Trap detectors make excellent transfer standards since they are stable, have uniform responsivity, good linearity, and low noise [21, 15, 31]. Figure 5.2 shows the arrangement of the photodiodes in the trap detectors used for HACR transfer standard detectors. Various detector arrangements acting as "light traps" for the light reflected from the first photodiode have been generically called "trap detectors." The light beam reflection into orthogonal planes reduces effects of polarization on the responsivity.

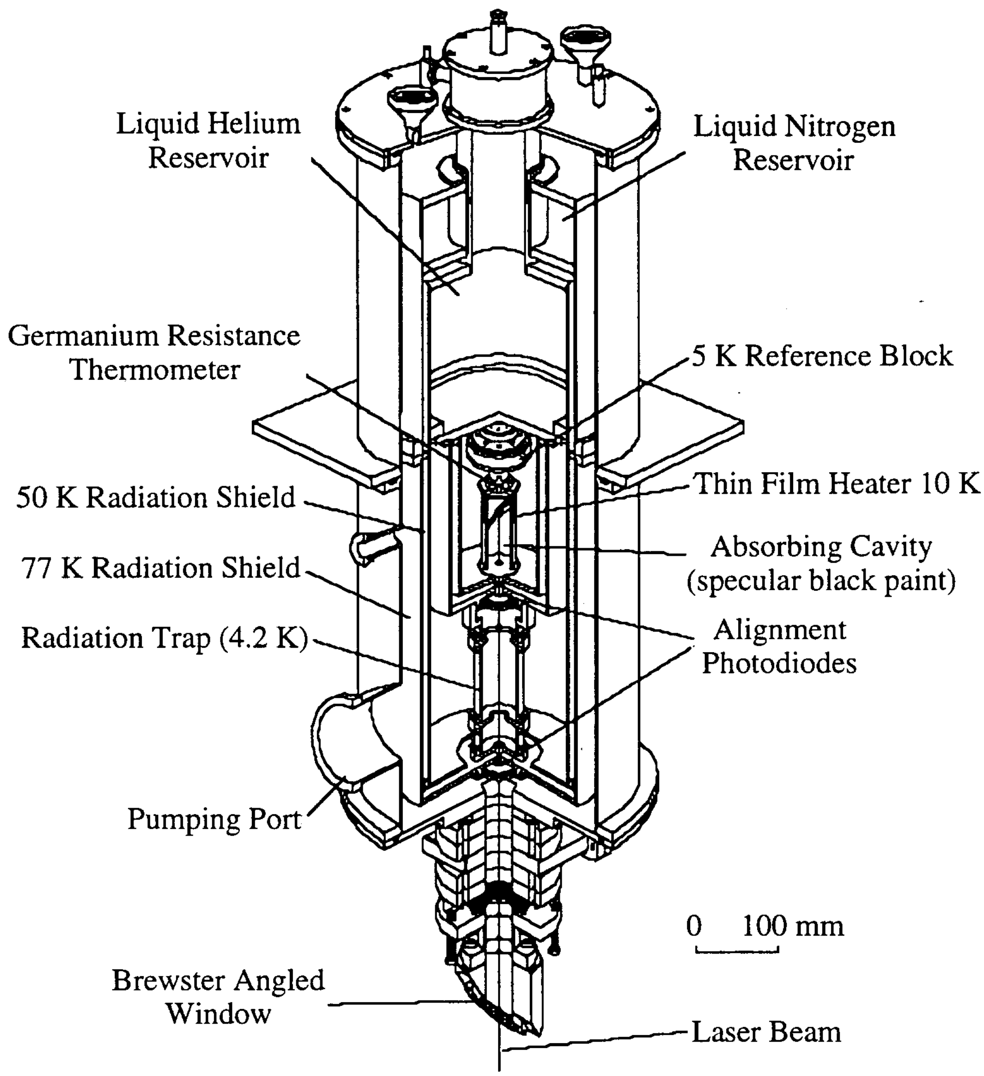

Figure 5.1. NIST High Accuracy Cryogenic Radiometer (HACR).

As a step in transferring the detector spectral power scale, the HACR was used to determine the external quantum efficiency (EQE) of two trap detectors in the visible spectral region (see fig. 5.3a). Figure 5.3b shows a diagram of the setup used to transfer the scale from the HACR to a trap detector using the substitution method. These trap detectors were calibrated at nine laser wavelengths between 406 nm and 920 nm. The reflectance of each trap detector was measured in this spectral range, allowing the internal quantum efficiency (IQE) to be determined. The IQE was modeled and the EQE for the entire spectral range was determined with a relative combined standard uncertainty of 0.03 %. Figure 5.3a shows the measured and modeled EQE of a trap detector. The trap detectors used in the scale transfer showed a maximum relative difference of 0.04 % for orthogonal linear polarizations [21]. Because the output from both of the SCFs is a mixture of polarizations (as with most monochromators) and different from the linear polarization of the lasers used with the HACR, this value is combined by the root-sum-of-squares method (explained in sec. 7.) with the relative combined standard uncertainty. The calibration relative standard uncertainty for the trap detectors when used with the SCFs is 0.05 %.

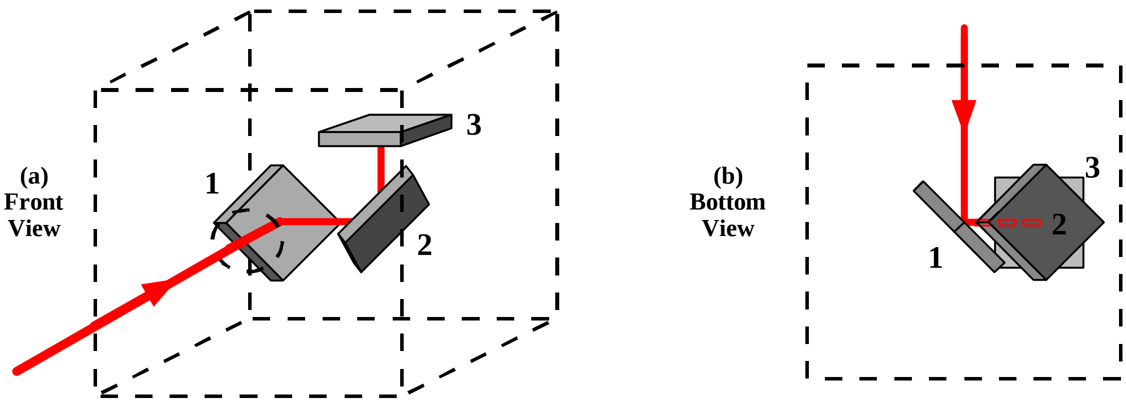

Figure 5.2. Trap detector arrangement of photodiodes minimizes light lost to reflections.

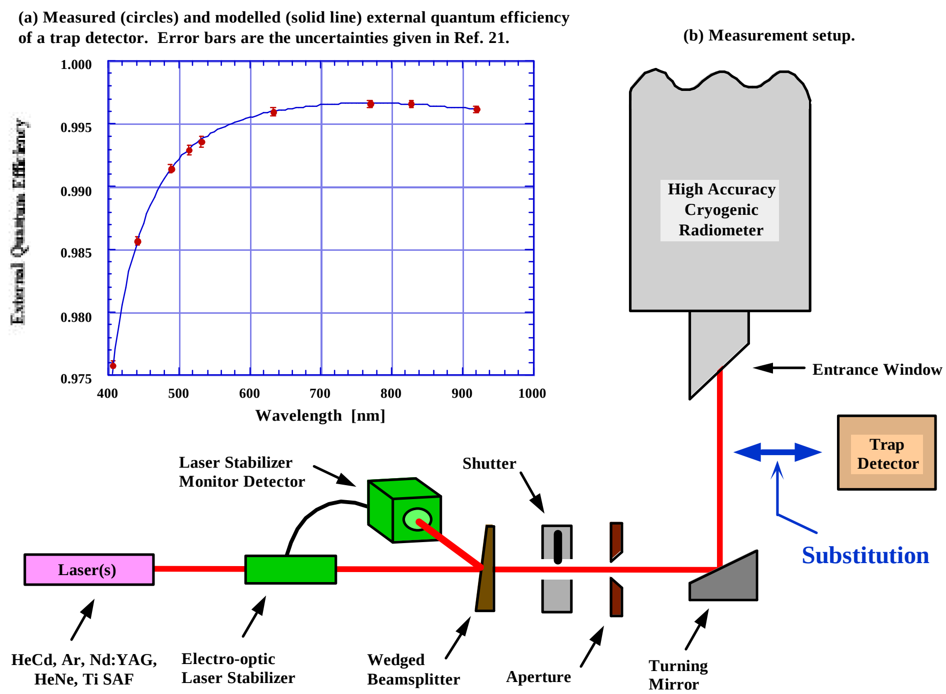

Figure 5.3. Scale transfer by substitution method with the HACR.

Figure 5.4 shows the entire spectral power scale propagation schematically. The HACR is the primary standard for the scale and trap detectors are used as transfer standards as described above. The trap detectors can then be used in a variety of measurements. First, the trap detectors could calibrate a Vis WS. The trap detectors could also calibrate the UV WS or Ge WS over the part of their spectral ranges that overlap. The Vis WS could do this calibration of the UV WS or Ge WS. The pyroelectric detector is used to extend the spectral power scale beyond the trap detectors calibrated spectral range. The calibrated UV WS and Ge WS are used to calibrate the Vis WS in the spectral region beyond the trap detectors. These transfer steps are described below.

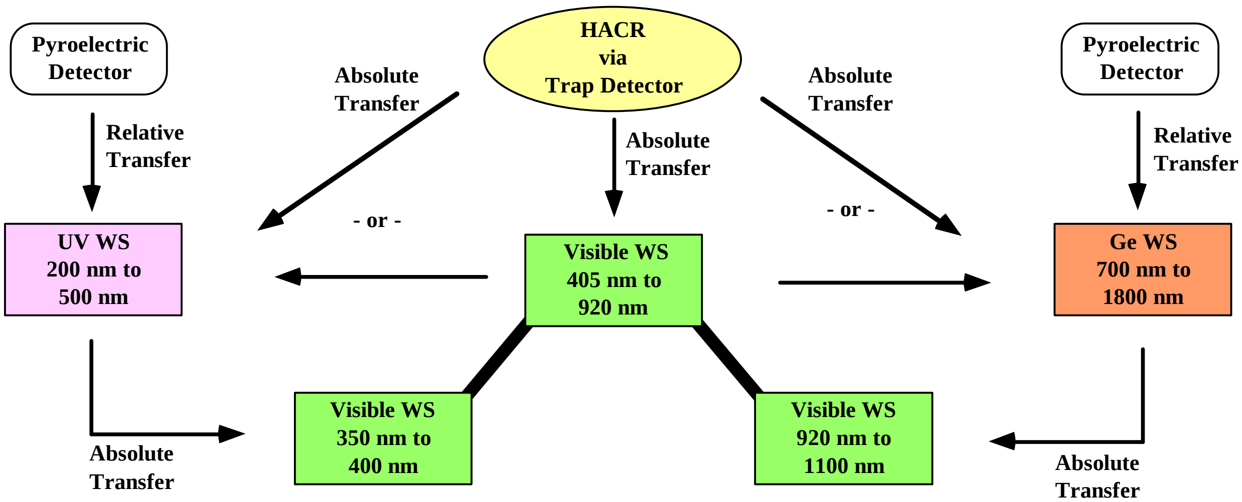

Figure 5.4. NIST spectral power scale propagation chain.

5.2 Traps to Visible Silicon Working Standards

Trap detectors are not used for routine spectral power (responsivity) measurements in the SCFs because the positioning of the trap detectors is time consuming and requires critical alignment to ensure the beam from the Vis/NIR SCF *f*/9 optical system does not overfill any of the trap detector's photodiodes. Also trap detectors have not been available for the UV and near-IR spectral regions, requiring that the spectral power scale be transferred to other detectors. The Vis WS (Hamamatsu S1337-1010BQ) are used for routine measurements since they are easier than the trap detectors to align in the focal plane. Trap detectors can be used to provide higher accuracy measurements when required (over the modeled EQE spectral region).

The four Vis WS are measured against two trap detectors, using the typical measurement setup and routine described later. An automated computer routine is used to determine the center of the active area for each detector. The measurements are then taken at that position. The Vis WS and traps are operated unbiased (the photovoltaic or short-circuit mode) and the signals are measured with calibrated transimpedance amplifiers and DVMs. The amplifier gain for both the working standards and trap detectors is 10^6.

The spectral responsivity is found using eq (3.27) where S_S = S_T, the modeled EQE from the HACR. The spectral responsivity of each Vis WS is the weighted mean of the measurement with both trap detectors [40] (see fig. 5.5a.). Figure 4.2 shows that the optical power used for these measurements is typically less than 1 μW.

5.3 Extension to Ultraviolet (200 nm) and Near-Infrared (1800 nm)

Expanding responsivity measurements beyond the modeled EQE spectral region of the trap detectors requires different calibrated detectors. Detectors are required that cover the spectral regions of measurement interest and also overlap with the trap modeled EQE spectral region. If the relative responsivity of the detector were known, comparisons with the trap detectors would then transfer the spectral responsivity scale to the detector. This detector could then be used as a working standard.

One method to extend the spectral range of the responsivity measurements is to use a spectrally flat detector. The spectrally flat detector could be calibrated by comparison with the trap detectors and used as a working standard. A second method is to use a spectrally flat detector to measure the relative responsivity of another detector. This detector could then be calibrated by comparison with the trap detectors and used as a working standard. The latter method was used to extend the spectral range of the responsivity measurements. The transfer method described here uses one broadband, spectrally flat, windowed, pyroelectric detector. The "flatness" of the responsivity is determined by measuring the reflectance from the pyroelectric's surface (absorber) and the window transmission.

The method chosen not only depends on the transfer uncertainty, but also upon the operation of the detectors. Depending on the situation, some detectors, especially spectrally flat detectors, have drawbacks to their use. Cryogenically cooled detectors are often large and heavy, making automated movement of the detectors difficult. And, there is the added complexity of using cryogens. Pyroelectric detectors require a chopped beam (thus additional equipment) and some models have a poor signal-to-noise ratio (SNR) at the power levels typically found with monochromator-based systems. These characteristics may make a detector cumbersome and impractical to use routinely as a working standard.

5.3.1 Pyroelectric Detector

A pyroelectric detector only responds to a change in radiant flux. The operation of pyroelectric detectors thus requires modulated or chopped (ac) optical radiation and lock-in detection. The pyroelectric material is coated with an optically black (flat) material, in this case a gold black. Details of the characteristics and operation of pyroelectric detectors can be found in the literature [41].

The operation of a pyroelectric detector depends upon the spectral absorptance of the gold black material. Using the law of conservation of energy the absorptance $a_{\mathrm{p}}(l)$ is given as

$$a_{\mathrm{p}}(l) = 1 - r_{\mathrm{p}}(l) \text{ [unitless]}, \tag{5.1}$$

where $r_{\mathrm{p}}(l)$ is the reflectance and the transmittance $t_{\mathrm{p}}(l)$ is assumed to be equal to zero. The predicted spectral responsivity $S_{\mathrm{p}}(l)$ of the pyroelectric detector is

$$S_{\mathrm{p}}(l) = t_{\mathrm{w}}(l) \cdot a_{\mathrm{p}}(l) \cdot CF_{\mathrm{p}} = t_{\mathrm{w}}(l) \cdot \left(1 - r_{\mathrm{p}}(l)\right) \cdot CF_{\mathrm{p}} \text{ [U}\cdot\text{W}^{-1}\text{]}, \tag{5.2}$$

where $t_w(l)$ is the pyroelectric detector window transmittance and CF_p is a calibration factor which scales the output signal (in U units) to the optical power received by the pyroelectric detector. The calibration factor could be determined by measurements with the HACR or comparison to the trap detectors. If the calibration factor is set to an arbitrary value, then the relative responsivity $s_p(l)$ is determined. Note that the lower case "s" is used to designate relative responsivity [2].

The reflectance of the pyroelectric detector $r_p(l)$ is measured with a modified Perkin-Elmer Lambda-19 spectrophotometer [42]. The window transmittance $t_w(l)$ is measured using the NIST transmittance measurement service facility [43]. The window transmittance can also be found by determining the ratio of the signals from two measurements using the SCF, one with and the second without the window in front of a detector.

5.3.2 Responsivity Measurements

From eq (3.27), it can be shown that the relative responsivity $s_x(l)$ of a test detector x can be written

$$s_x(l) = \frac{R_x(l)}{R_p(l)} \cdot s_p(l) \text{ [arbitrary U·W}^{-1}\text{]}, \tag{5.3}$$

where $s_p(l)$ is the relative responsivity of the pyroelectric detector. Equation (5.3) can now be used to determine the relative responsivity of a test detector using the pyroelectric detector as a standard by the same substitution method (measurement equation) described earlier. It should be noted that the pyroelectric detector described here had a poor SNR adding significantly to the measurement uncertainties.

The test detector is then calibrated using the trap or Vis WS detectors over the part of their spectral ranges that overlap. This data is used to scale the relative responsivity of the test detector. Only one point is needed in principal; but, in practice, about 50 different spectral points are used to obtain an average scaling factor to apply to the entire relative responsivity curve.

5.4 Germanium (NIR) Working Standards

The Ge WS relative spectral responsivities are determined using the Vis/NIR SCF and the pyroelectric detector. The weighted average of several measurements are taken, due to the SNR of the pyroelectric detector. The Ge WS responsivity is then measured using the trap detectors over the spectral region from 700 nm to 920 nm. The trap comparison data is the average of three scans during one measurement. This data is used to scale the relative responsivity. Two additional Ge WS, identical to the first two, were measured using the first two Ge WS (comparison using the pyroelectric was not done because of time constraints). See fig. 5.5b and c.

5.5 UV Silicon Working Standards

The relative spectral responsivity of the four UV WS is measured using the UV SCF and the pyroelectric detector. Measurements have been taken with and without the pyroelectric's window. The data without the window is noisier and is not used in determining the UV WS relative spectral responsivity. Even with the window, getting a good SNR requires that many measurements be taken and averaged.

The responsivity of all four UV WS is also measured using all four Vis WS in the Vis/NIR SCF over the spectral region of 405 nm to 500 nm. The average of three scans with each Vis WS was used as the responsivity for each UV WS. This data was used to scale the relative responsivity of the UV WS. See fig. 5.5d and e. The trap detectors were not available, so the Vis WS were used for the scale transfer increasing the relative standard uncertainties from 405 nm to 500 nm by 0.02 %.

5.6 Extension of Visible Silicon Working Standards

The spectral responsivities of the four Vis WS is measured in the Vis/NIR SCF from 925 nm to 1100 nm with the first two Ge WS. The average of three scans with each Ge WS is assigned as the responsivity for each Vis WS in the 925 nm to 1100 nm spectral region. The Vis WS are also measured from 350 nm to 405 nm with the UV WS in the Vis/NIR SCF. The average responsivity of three scans with all four UV WS is assigned to each Vis WS. Figure 5.5f shows the Vis WS scale extension measurements. The uncertainties are significantly higher in these regions, compared to the trap spectral region, due to the pyroelectric detector SNR and the additional transfer measurements.

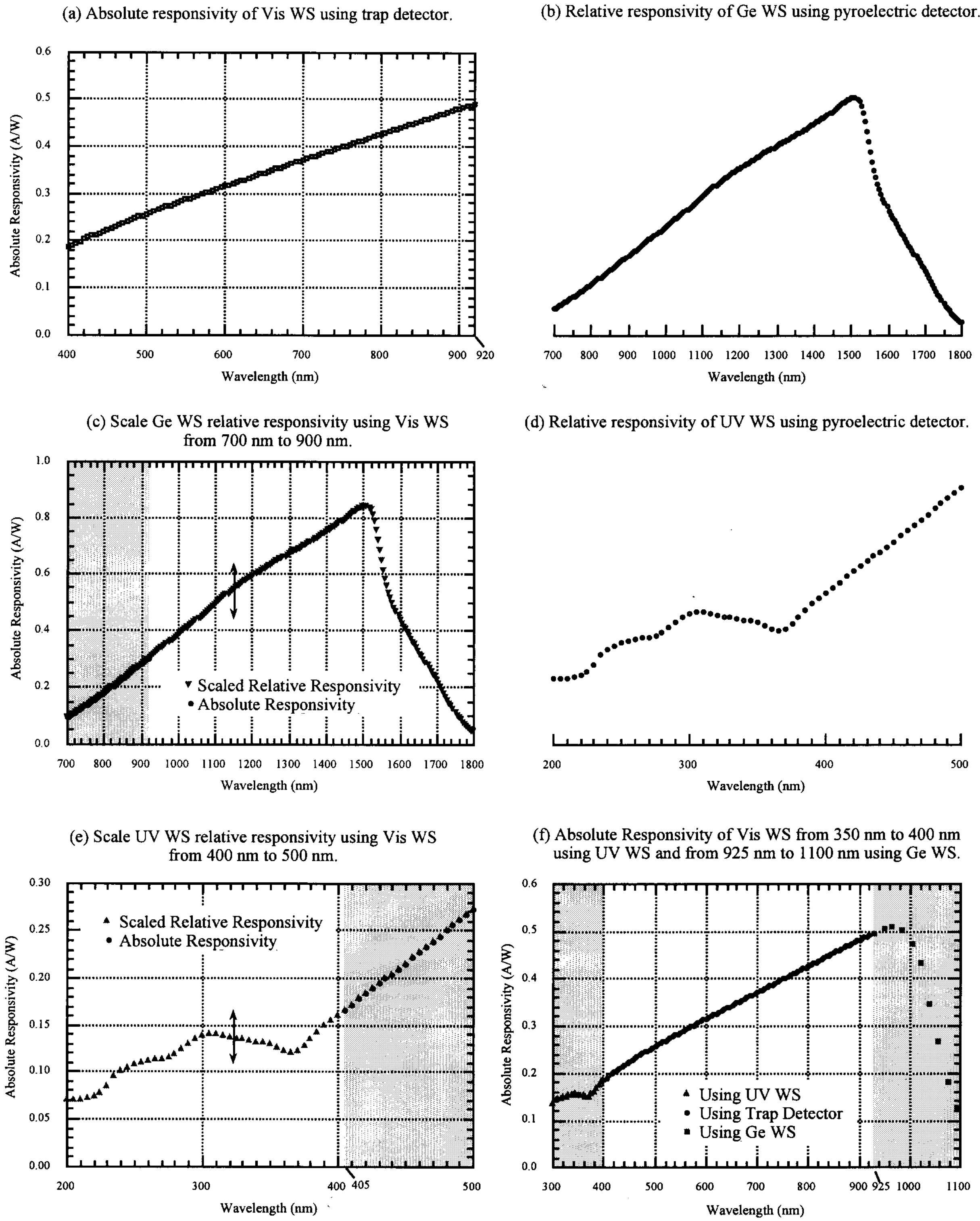

Figure 5.5. NIST detector spectral responsivity scale realization. Shaded areas indicate regions of spectral overlap for calibration transfer.