Detector Spectral Response From 350 to 1200 nm Using a Monochromator Based Spectral Comparator

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Antonio Corrons

Instituto de Optica
Madrid, Spain

Edward F. Zalewski

National Measurement Laboratory
National Bureau of Standards
Washington, D.C. 20234

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Antonio Corrons
Instituto de Optica, Madrid, Spain

and

Edward F. Zalewski
National Bureau of Standards
Washington, D. C. 20234

A B S T R A C T

The method of relative spectral detector response measurement based on filters of known transmittance and a spectral irradiance standard lamp was used to measure the responsivity of a thermopile. The thermopile was then used in conjunction with a monochromator based spectral comparator to measure the relative spectral response from 350 to 1200 nm of several other detectors. Several auxiliary experiments to evaluate the accuracy of these techniques are described. The estimated accuracy of relative spectral response measurements using these techniques and this particular instrumentation was found to range from 3 to 7% depending upon the type of detector being measured and the spectral region under study. Finally, the effective transmittance of several filters was measured to evaluate the accuracy of the relative spectral detector response measurements. It was concluded that the effective transmittance test is not a reliable way to judge the accuracy of detector response measurements.

Keywords: Detector; detector radiometry; detector spectral comparator; detector spectral response; filter transmittance test; photodetector; photometer; radiometer; spectral responsivity.

INTRODUCTION

For many radiometric and photometric measurements it is necessary to know the spectral response of the specific detector selected for the experiment. In order to obtain a detector's spectral response one may measure its output relative either to a detector of known spectral response [1-4][1] or to a set of lamp and filter combinations of known spectral irradiance [5-8]. The latter procedure is limited in resolution and accuracy by the size of the obtainable bandwidths. It is also limited by the accuracy of the measurements of the spectral transmittance of the filters and the spectral irradiance of the light source. The first method is by far the most accurate if one uses an amplitude stabilized cw laser as the monochromatic source and an electrically calibrated radiometer as the reference detector [2,3]. However, in most laboratories the detector comparison measurements are usually carried out using a monochromator. Here the bandwidth restrictions are less severe than is the case with the filter method; but the accuracy of this type of measurement is limited by the fidelity of the comparison process (wavelength accuracy, bandwidth and spectral purity of the monochromator's emission and its beam uniformity) and the accuracy of the spectral response of the reference detector.

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[1]Figures in brackets indicate the literature references at the end of this paper.

In this study we have examined both the method of monochromator based spectral comparison measurement and the method of detector spectral response measurement using a spectral irradiance standard lamp and several narrow-band interference filters. This study was undertaken in order to evaluate these techniques which have been used for many years to measure detector response. It is most important to evaluate and understand the limitations of monochromator based spectral response comparators. Even though better monochromatic sources are now available with the advent of amplitude stabilized cw lasers, monochromator based comparators will still continue to be widely used for the transfer of absolute spectral response.

The measurement of relative spectral response using a standard lamp and filters was applied to a thermopile with a blackened receiver surface. Because one would expect the response of such a thermopile to be a nearly constant function of wavelength, it is the ideal detector for this type of response determination. That is, one would expect to achieve the greatest accuracy from the lamp and filter method for a detector whose response did not vary over the bandwidth of each of the various filters. It was found that for the thermopiles available to us and suitable for use with the spectral comparator, the spectral response was not wavelength independent -- variations on the order of 8% were observed. This is quite contrary to what one might reasonably assume from what is known about the reflectivity of a thick gold-black coating [9] and the transmission of the quartz window used in the construction of these thermopiles.

In the second part of this study the performance of a reasonably typical monochromator based detector comparator was evaluated. The evaluation experiments were not elaborate but did serve to uncover some potential problems with beam non-uniformity, image size at the detector aperture, monochromator bandwidth and wavelength uncertainties. The magnitude of the uncertainty in spectral response arising from these effects was estimated. Finally the thermopile, characterized in the first part of this study, and the detector comparator instrument were used to measure the relative spectral response of three detectors: a silicon photodiode, a silicon photodiode with a $V(\lambda)$ [photopic] response, and a silicon photodiode fitted with an infrared cut-off filter.

A common test of the accuracy of a relative spectral response calibration has been to measure the effective transmittance of a set of filters [1]; in a sense the converse of the lamp and filter response determination technique. This test was applied to the three silicon detectors which had been measured relative to the thermopile. Both narrow-band interference filters and broad-band absorbing glass filters were employed. As one might expect, the narrow-band filters provided the more sensitive test while the broad-band filter results gave no indication of some pretty serious errors.

APPARATUS

The thermopile was goldblack coated and mounted in an evacuated housing with a quartz window. The radiation reaching the thermopile was chopped at a low frequency (less than 15 Hz) and the thermopile output was read using a synchronous ac amplifier.

In the measurement of the relative spectral response of the thermopile 17 interference filters covering the wavelength range from 350 to 1500 nm were used with a spectral irradiance standard lamp. The lamp was a 100 watt quartz halogen incandescent lamp that had been calibrated at 26 wavelengths from 250 to 1600 nm. Interpolated values of the spectral irradiance were obtained by fitting either an exponential or a quadratic function to the experimental points depending on the spectral region. The transmittance of each of the interference filters had been measured from 300 to 2300 nm on a double-beam recording spectrometer. In the region of the peak transmittance readings were obtained at 1 nm intervals and in the other regions at 10 nm intervals. The transmittance of four of these filters was also measured at a few check wavelengths using the NBS high accuracy spectrophotometer [10].

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In both the transmittance measurements and the thermopile measurement, the filters were aligned perpendicular to the optic axis of the radiation source. To avoid possible interreflection errors from the thermopile window, it was turned about 5° away from being perpendicular to the optic axis (see Figure 1).
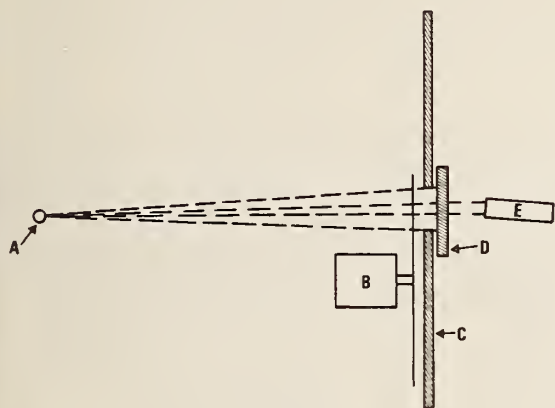

Fig. 1: Measurement of the relative spectral response of a thermopile. (A) Spectral irradiance standard lamp; (B) chopper; (C) baffle; (D) interference filter; and (E) thermopile.
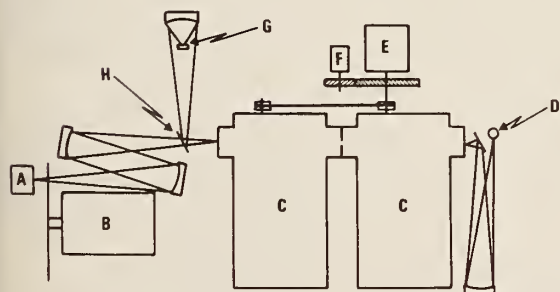

Fig. 2: Spectral Response Comparator: (A) reference or test detector; (B) chopper; (C) grating monochromator, 1/4 meter, Ebert mount; (D) 100 W quartz halogen, coiled-coil tungsten filament lamp; (E) stepping motor wavelength drive; (F) shaft encoder wavelength readout; (G) monitor detector; and (H) beamsplitter (mirror with hole through center).

Detector-amplifier linearity was checked using a multiple aperture technique [11]. Four apertures were employed to check linearity over approximately a factor of four and overlapping measurements (by varying the irradiance by less than four-fold) were used to extend the range of these measurements. Over the dynamic range of our measurements the detector plus amplifier non-linearities were found to be less than 0.4% for both the thermopile and the silicon photodiode systems. This was about the limit of the precision of these measurements.

The comparison of the silicon photo-diode spectral response to that of the thermopile was performed on an instrument that had been built at NBS several years ago [12], see Fig. 2. It differed from the original in one major aspect. For this study both the reference and test detectors were placed in the same beam position and the other beam from the partial mirror (previously used to irradiate the reference detector) was only used to monitor the lamp fluctuations. Briefly the instrument consisted of a 100 watt quartz halogen lamp whose coiled-coil filament was focused onto the entrance slit of the monochromator system. The monochromator system consisted of two 1/4 meter Ebert mount grating instruments operated in tandem to reduced stray (out-of-band) radiation. With the monochromator slit widths that were used, the bandpass (full width at half-height) was measured for each set of gratings and found to be 3.8 nm from 350 to 800 nm and 7.6 nm from 700 to 1800 nm.

Two different sets of gratings were used in order to cover both the visible and infrared spectral regions. A Corning No. 2-63 filter [13] was placed at the entrance port of the monochromator to block the second-order diffraction for the long wavelength measurements.

The output from one of the directions of the beamsplitter was focused onto a fixed silicon photodiode to measure the lamp fluctuations between successive measurements. This monitor detector had an extended ultraviolet

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response in order to facilitate corrections in the blue spectral region down to 350 nm. The infrared cut-off of this detector was approximately the same as that of the other silicon photodiodes which were studied. This meant that the lamp fluctuation corrections became increasingly unreliable at the longest wavelengths. Because the stability of an incandescent lamp is usually better at longer wavelengths than at the shorter ones [14], this was judged to be a negligible error. The output from the other beamsplitter direction was used to irradiate either the thermopile or the test silicon detector. The exit beam of the monochromator was not homogeneous but was an image of the lamp coils cropped by the jaws of the slit. At the focus it measured about 2 mm by 20 mm.

Silicon photodiodes were chosen for these measurements because, besides their increasing commercial importance, they have several physical properties that make them suitable for detector calibration transfer standards. They are typically more uniform in response across the active surface than vacuum photoemissive devices [15]. They do not exhibit the fatigue effects observed in photoemissive [16] and selenium [17] detectors. And they can be made to have a stable and linear response. The silicon detectors were operated in the photovoltaic mode (zero reverse bias) using a very low input impedance amplifier [18].

DETERMINATION OF THE RELATIVE SPECTRAL RESPONSIVITY OF THE THERMOPILE

In the experiment depicted in Fig. 1 the output of the thermopile, V, is a function of its spectral responsivity, $R(\lambda)$, the spectral irradiance of the lamp, $E(\lambda)$, and the spectral transmittance of the filter, $\tau_i(\lambda)$;

$$V_i = \int E(\lambda) \, \tau_i(\lambda) \, R(\lambda) \, d\lambda \qquad (1)$$

If we assume that $R(\lambda)$ is a constant through the principal transmission band of the interference filters (typically 15 nm at the half-maximum transmission points), then the thermopile output is

$$V_i = R(\lambda_i) \int E(\lambda) \, \tau_i(\lambda) \, d\lambda \qquad (2)$$

The integral in the above equation can be evaluated using the lamp and filter calibration values.

The spectral irradiance calibration of the lamp covered the 250 to 1600 nm region and the interference filter calibrations covered the 300 to 2300 nm region. The filters exhibited negligible transmission at wavelengths longer than 1600 nm and the lamp output was negligibly small at wavelengths shorter than 300 nm. The filter transmittance was measured every 1 nm within the principal transmission region and the lamp spectral irradiance, measured at 26 wavelengths, was interpolated at 1 nm intervals. Some of the filters had regions of very low transmittance outside of the principal band. In order to account for this, the limits of integration in eq. 2 were from 300 to 1600 nm in every case. Measurements of the thermopile voltage obtained with each of the interference filters were normalized to the measurement using the filter which peaked at 550 nm. This yields a measure of the relative spectral responsivity of the thermopile at approximately the wavelength of the peak transmittance of each filter.

$$\frac{R_i}{R_{550}} = \frac{V_i}{V_{550}} \frac{\int E(\lambda) \, \tau_{550}(\lambda) \, d\lambda}{\int E(\lambda) \, \tau_i(\lambda) \, d\lambda} \qquad (3)$$

The results are shown in Fig. 3 where the relative response is plotted at the transmission peak of each filter. The line drawn through these data is the approximation of the relative response that was used in subsequent detector measurements. The thermopile has a flat response within a range of ±1% across the visible and falls off in the near infrared. The decrease

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in response is seen to be about 8% at 1200 nm.   There also appears to be a
sharp drop at 450 nm of about 5%.   A second iterative calculation [5] of
eq. 3 using these variations in the relative values of R for the integration
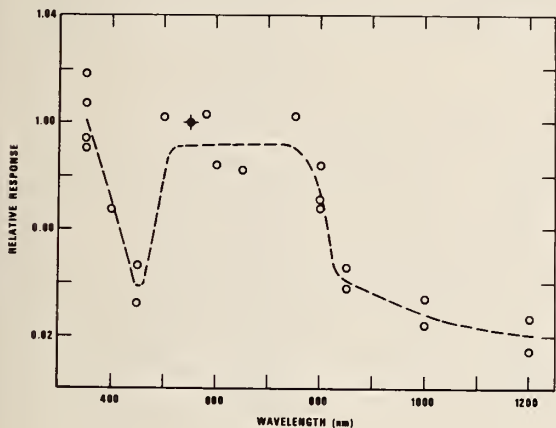outside the principal transmission band yielded essentially the same results.

Fig. 3: Relative spectral response of gold-
black coated, quartz windowed thermopile.
Data normalized to measurement at 555 nm;
dashed line represents the approximate
response function used in subsequent
detector response measurements.

Another thermopile of a similar
design from the same manufacturer was
measured and a nearly identical rela-
tive response function was obtained.
Comparison of these thermopiles with
one having a cavity design and no
window confirmed the variation of
response in the infrared (there was
insufficient signal to check the
ultraviolet response).   Because its
greater sensitivity was needed for
the monochromator comparator measure-
ments the windowed thermopile was
used throughout the rest of the study.

It is our guess that the adhesives
used in the assembly of the windowed
thermopiles may have contaminated the
quartz windows, and that the adhesive
has absorption bands in the regions
where we observe a decrease of the
thermopile response.   The actual cause
of the decreased response is not
important.   It is important, however,
to note that the response of the
reference detector must be measured
and not simply assumed to be flat.

The accuracy of the spectral irradiance calibration is reported as about
±1% over the visible and near IR regions [14].   The transmission measurements
are much more accurate.   However, they were done in collimated light whereas
in the thermopile measurements the light from the lamp subtends an angle of
about 4°.   Rotation of the filters in the spectrophotometer by 4° produced
a 1% variation in transmittance.   The linearity uncertainty (0.4%) and these
two uncertainties added in quadrature equals 1.5%.   Adding to this the
imprecision of the thermopile measurements yields an estimated accuracy of
±2% for the relative response function shown in Fig. 3.

DETERMINATION OF THE RELATIVE SPECTRAL RESPONSIVITY OF OTHER DETECTORS

The relative spectral response function of the thermopile can now be
used to determine the relative spectral response of other detectors using the
spectral comparator instrument.   There are several factors other than the
thermopile response function which also affect the accuracy of the comparison
measurement.   These other major sources of error have been examined in the
following experiments.

The wavelength accuracy of the monochromators can easily be checked by
replacing the spectrally continuous incandescent light source by a line
source such as a mercury or neon discharge lamp.   After adjusting the grating
drive and wavelength readout on an emission line near the center of the
spectral range, measurement of the wavelengths of several lines spanning the
spectrum from 313 to 878 nm were found to be within ±0.2 nm of the published
values.   The error in responsivity, $\Delta R/R$, introduced by this uncertainty, $\Delta \lambda$,
is proportional to the slope, $dR/d\lambda$, of the responsivity versus wavelength
curve.

$$\frac{\Delta R}{R} = \frac{\Delta \lambda}{R} \frac{dR}{d\lambda} \tag{4}$$

Of the three detectors studied, the one with the photopic response has the

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Table 1
Approximate Slope of a Photopic Detector

Wavelength	$V(\lambda)$	Slope $(\frac{\Delta V}{\Delta \lambda})$ nm^{-1}	Fractional Change $(\frac{\Delta V}{V \Delta \lambda})$ nm^{-1}
400	.0004	0.4×10^{-4}	0.100
410	.0012	1.6×10^{-4}	0.133
420	.0040	5.1×10^{-4}	0.128
430	.0116	9.5×10^{-4}	8.19×10^{-2}
440	.0230	1.3×10^{-3}	5.65×10^{-2}
450	.0380	1.82×10^{-3}	4.79×10^{-2}
460	.0600	2.59×10^{-3}	4.32×10^{-2}
470	.0910	3.87×10^{-3}	4.25×10^{-2}
480	.1390	5.67×10^{-3}	4.08×10^{-2}
490	.2080	8.93×10^{-3}	4.29×10^{-2}
500	.3230	1.487×10^{-2}	4.60×10^{-2}
510	.5030	2.009×10^{-2}	3.99×10^{-2}
520	.7100	1.85×10^{-2}	2.61×10^{-2}
530	.8620	1.217×10^{-2}	1.41×10^{-2}
540	.9540	6.54×10^{-3}	6.86×10^{-3}
550	.9950	1.99×10^{-3}	2.00×10^{-3}
560	.9950	-2.16×10^{-3}	-2.17×10^{-3}
570	.9520	-6.32×10^{-3}	-6.64×10^{-3}
580	.8700	-9.91×10^{-3}	-1.14×10^{-2}
590	.7570	-1.214×10^{-2}	-1.60×10^{-2}
600	.6310	-1.281×10^{-2}	-2.03×10^{-2}
610	.5030	-1.256×10^{-2}	-2.50×10^{-2}
620	.3810	-1.202×10^{-2}	-3.15×10^{-2}
630	.2650	-1.04×10^{-2}	-3.92×10^{-2}
640	.1750	-7.88×10^{-3}	-4.50×10^{-2}
650	.1070	-5.66×10^{-3}	-5.29×10^{-2}
660	.0610	-3.70×10^{-3}	-6.07×10^{-2}
670	.0320	-2.14×10^{-3}	-6.69×10^{-2}
680	.0170	-1.13×10^{-3}	-6.65×10^{-2}
690	.0082	-6.20×10^{-4}	-7.56×10^{-2}
700	.0041	-2.80×10^{-4}	-6.83×10^{-2}
710	.0021	-1.40×10^{-4}	-6.67×10^{-2}
720	.0010	-8.00×10^{-5}	-8.00×10^{-2}
730	.0005	-3.00×10^{-5}	-6.00×10^{-2}
740	.0003	-2.00×10^{-5}	-6.67×10^{-2}

greatest slope in regions of appreciable response (greater than 10% of peak) (see Table 1). In the region around 500 nm and again around 650 nm the fractional change in response is about 5% per nm. The corresponding uncertainty would be on the order of ±1%. At the extremes this error approaches or exceeds ±2% but then the relative response is on the order of one percent of the maximum value. For a silicon detector the greatest fractional change in response occurs near 1100 nm (about -2% per nm) and again near 400 nm (about 1% per nm). The corresponding uncertainties in response would be ±0.4% and ±0.2% respectively.

The presence of out-of-band radiation can be checked at specific wavelength settings by measuring the instrument output with and without a filter that blocks these wavelengths. Significant out-of-band radiation may be expected at the blue and ultraviolet wavelength settings since an incandescent source is more intense in the other spectral regions. At longer wavelengths, second order diffraction effects are expected unless adequately blocked. The results of measurements made with several blocking filters and a silicon photodiode as the detector are shown in Table 2. The amount of stray radiation is seen to be below 0.04% in each case except in the vicinity of 300 nm. Measurements with the thermopile yielded similar, but noisier, results. For detectors having identical spectral response functions, stray radiation effects cancel out, of course. In other situations an error of ±0.04% would be the worst case expectation. For this instrument it appears that stray light errors will be negligible.

Table 2

Out-of-Band Radiation Test

Wavelength Setting	Blocking Filter[a]	DETECTOR OUTPUT		Percent Stray Radiation[b]
		Without Filter	With Filter	
600 nm blazed gratings				
300nm	0-51	0.0423	0.0001	0.2±0.2
350	0-51	0.6432	0.0002	0.03
400	3-72	3.5918	0.0000	0.00
450	3-66	3.2899	0.0003	0.00
500	3-66	5.6744	0.0000	0.00
600	5-57	8.1494	0.0000	0.00
700	5-57	6.4814	0.0000	0.00
1200 nm blazed gratings plus Corning 2-63 order sorting filter				
800	4-97	10.3122	0.0019	0.02
900	4-97	10.2633	0.0011	0.01
1000	4-97	7.6068	0.0032	0.04

[a] Blocking filters designated by the manufacturer's (Corning) number.

[b] Estimated uncertainty is approximately ±0.01% unless otherwise indicated.

Since the other detectors are not measured simultaneously with the thermopile, drift in the lamp output between measurements may be a potential problem. As stated previously the fixed detector was used to monitor these changes and a correction was made for them. The question remains as to how well the monitor and test detectors track any lamp fluctuations. This was checked by varying the voltage on the lamp. The measurements over as much as a ±25% change in lamp output are shown at four wavelengths in Fig. 4. Perfect tracking would be a straight line of 45° slope. It is seen that the monitor and thermopile track well at 450 and 1100 nm but not at 600 and 900 nm. The non-tracking may be due to several effects. The non-uniformity of the monochromator is probably wavelength dependent, since the spectral output varies over the image of the filament coils and the spectral output is also a function of lamp voltage. This effect coupled with either (1) the non-uniformity of response of the thermopile, (2) the variability of the slit image on the monitor detector (its aperture was overfilled) or (3) the variability of the beamsplitter ratio with slit image (it was a mirror with a hole through the center) could be the cause of the result shown in Fig. 4. We don't believe such a large effect could arise from the detector non-linearities which were very small.
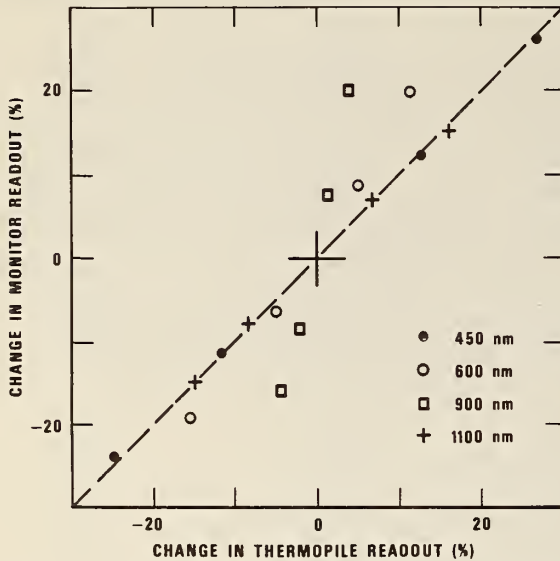

Fig. 4: Tracking of thermopile and monitor detector readings as a function of lamp output and wavelength.

It would appear that if lamp stability is a potential problem then the detector and thermopile should be measured simultaneously; one in each separate beam from the beamsplitter.

This is not a practical solution since, as we have seen, the results in Fig. 4 may indicate that the beamsplitter has some spectral selectivity. This spectral selectivity can be more explicitly demonstrated by measuring each beam with the same detector in successive runs. The results of such a measurement (using a silicon detector) are shown in Fig. 5. Here the beamsplitter ratio varies by about 22%. Obviously the two beams are not spectrally identical and any arrangement where the reference detector is in one beam while the test detector is in the other should be avoided.
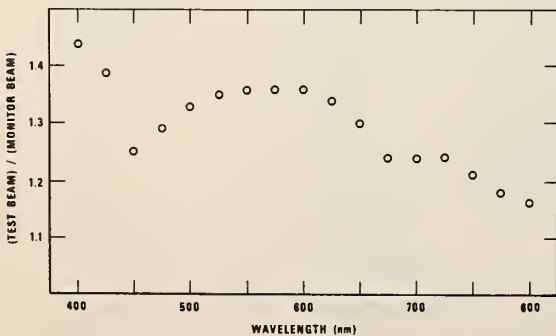

Fig. 5: Comparison of the two reflections of the beamsplitter. "Test beam" refer to readings taken at position A of Fig. 1 and "monitor beam" refers to position G.

The spectral variability of the non-uniformity in the output beam of the monochromator can lead to another error in detector comparison measurements. A non-uniform detector such as the thermopile or an over-filled detector aperture will sample different portions of the beam at different wavelengths. Thus it will appear as if the response of the detector is varying while in reality it is the distribution of the spectral irradiance that is changing. Short of mapping the variations in the monochromator output as a function of wavelength and then correlating these measurements with a map of the detector uniformity, there is no other way of measuring the error introduced by

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this effect. As a qualitative measure of this effect a much simpler experi-
ment was performed. The thermopile was moved in four directions away from
its normal position (rotation by approximately ±20° and ±5mm translation
away from the focal plane) and the change in the relative output of the
monochromator was measured. This is, in effect, a measurement employing
five detectors of different uniformity of response across their surfaces but
having the same relative spectral response. If there were no spectral vari-
ability of the uniformity of the monochromator output, then the output of
"each" detector would read the same spectral variations of the output of the
monochromator. That this is not the case is shown in Fig. 6. Here the
thermopile readouts from each of the five measurements of the spectrum were
area normalized (to adjust the readings to the same scale) and then averaged.
Figure 6 is a plot of the deviations from the average at each wavelength
versus wavelength -- the results for both sets of gratings are presented.
The larger deviations in the blue are not unexpected because the uniformity of
the output of the lamp, and consequently that of the monochromator, would have
greater spectral variability at shorter wavelengths. Although this test is by
no means quantitative, it appears that the non-uniformity effect could add an
uncertainty of at least ±1%, with a much greater uncertainty in the blue
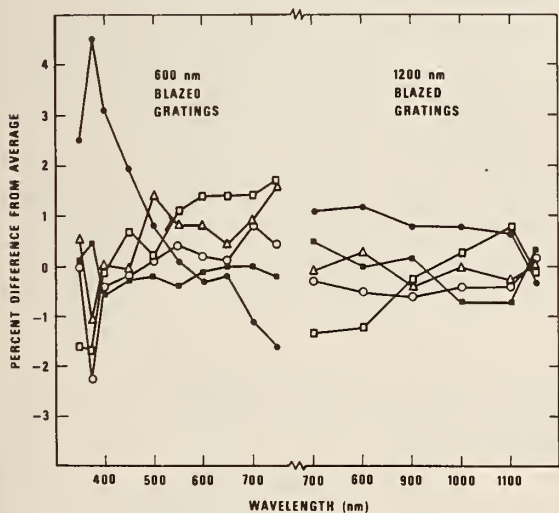spectral region.

Fig. 6: Apparent variations in the relative
spectral output of the monochromator as the
thermopile position is varied. Measurements
with the two different grating sets were made
at different times and precise repositioning
of the thermopile was not possible. Meaning-
ful correlations between the individual
curves in each set is, therefore, not prac-
tical and consequently the various positions
described in the text are not identified in
this figure.

The bandwidth of the monochromator
output also adds an uncertainty when
the test and reference detector
response curves do not have the same
slope. The error can be approximated
as follows. The output of the x
detector, I_X, at the monochromator
wavelength setting λ_0 is given by

$$I_X(\lambda_0) = \int_{\lambda_0-\delta}^{\lambda_0+\delta} R_X(\lambda)\ E(\lambda)\ T(\lambda), \quad (5)$$

where 2δ is the width of the bandpass
(to the zero transmission points), R_X
is the detector spectral response, E
is the spectral irradiance of the lamp
and T is the transmittance of the
monochromator. Within this small
wavelength interval let us approximate
the spectral response of the x detector
as a straight line

$$R_X(\lambda) = R_X(\lambda_0) + (\lambda-\lambda_0)\ \frac{dR_X(\lambda_0)}{d\lambda} \quad (6)$$

Then

$$I_X(\lambda_0) = R_X(\lambda_0) \int_{\lambda_0-\delta}^{\lambda_0+\delta} E(\lambda)\ T(\lambda)\ d\lambda +$$

$$\frac{dR_X(\lambda_0)}{d\lambda} \int_{\lambda_0-\delta}^{\lambda_0+\delta} (\lambda-\lambda_0)\ E(\lambda)\ T(\lambda)\ d\lambda \ . \quad (7)$$

If we approximate the response of the reference detector as a constant over
the bandpass of the monochromator then the corresponding equation for its
output is

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$$I_s(\lambda_0) = R_s(\lambda_0) \int_{\lambda_0 - \delta}^{\lambda_0 + \delta} E(\lambda) \ T(\lambda) \ d\lambda \tag{8}$$

Dividing eq. 8 by eq. 7 yields the response of the test detector

$$R_x(\lambda_0) = \frac{I_x(\lambda_0)}{I_s(\lambda_0)} \ R_s(\lambda_0) - \frac{dR_x(\lambda_0)}{d\lambda} \ \frac{\displaystyle\int_{\lambda_0 - \delta}^{\lambda_0 + \delta} (\lambda - \lambda_0) \ E(\lambda) \ T(\lambda) \ d\lambda}{\displaystyle\int_{\lambda_0 - \delta}^{\lambda_0 + \delta} E(\lambda) \ T(\lambda) \ d\lambda} \tag{9}$$

To integrate the term on the right-hand side of the above equation it is convenient to transform the coordinates so that

$$y = \lambda - \lambda_0 \tag{10}$$

Then

$$\int_{\lambda_0 - \delta}^{\lambda_0 + \delta} (\lambda - \lambda_0) \ E(\lambda) \ T(\lambda) \ d\lambda = \int_{-\delta}^{\delta} y \, e(y) \ t(y) \ dy \quad ; \tag{11}$$

with a similar result for the other integral. Let us assume that the irradiance varies linearly over the bandpass, so that

$$e(y) = e_0 (1 + by) \tag{12}$$

and that the bandpass is triangular. For $-\delta \le y \le 0$,

$$t(y) = t_0 (1 + \frac{y}{\delta}) \tag{13}$$

and for $0 \le y \le \delta$

$$t(y) = t_0 (1 - \frac{y}{\delta}) \tag{14}$$

Therefore, eq. 11 is

$$\int_{\lambda_0 - \delta}^{\lambda_0 + \delta} (\lambda - \lambda_0) \ E(\lambda) \ T(\lambda) \ d\lambda = e_0 t_0 \ b\delta^3 / 6 \tag{15}$$

and similarly for the other integral

$$\int_{\lambda_0 - \delta}^{\lambda_0 + \delta} E(\lambda) \ T(\lambda) \ d\lambda = e_0 t_0 \ \delta \tag{16}$$

Equation 9 is then

$$R_x(\lambda_0) = \frac{I_x(\lambda_0)}{I_s(\lambda_0)} \ R_s(\lambda_0) - \frac{b\delta^2}{6} \ \frac{dR_x(\lambda_0)}{d\lambda} \tag{17}$$

For an incandescent source, b is largest in the blue. At 400 nm it is
about 0.02 nm^{-1} for a 3000 K blackbody. A photopic detector has a slope of
10% per nm at this wavelength. Therefore, an instrument with a 3.8 nm band-
pass will be in error by about 0.5%. At 500 nm, b is about 0.01 nm^{-1} and the
detector slope is about 5% per nm, yielding an error of 0.1%. The slope of
the irradiance spectrum at the detector is, of course, not just due to the
spectrum of the lamp. The reflectance and transmittance of the various optical
components will alter the lamp spectrum. Therefore, in order to apply a
correction for the effect of the bandpass one must measure the spectral dis-
tribution at the output of the particular lamp and monochromator combination
employed. Furthermore, as we have seen the response of the reference detector
may not be a constant function of wavelength and will further add to the
uncertainty of the measurement. It is relatively easy to rederive eq. 17 to
include the effect of a reference detector with a spectrally variable response
function. The result is

$$R_x(\lambda_0) = \frac{I_x(\lambda_0)}{I_s(\lambda_0)} \, [R_s(\lambda_0) + \frac{b\delta^2}{6} \frac{dR_s(\lambda_0)}{d\lambda}] - \frac{b\delta^2}{6} \frac{dR_x(\lambda_0)}{d\lambda} \qquad (18)$$

Optimally the effect of the instrument bandpass on the detector spectral
response should not be treated as an uncertainty of the measurement. It is
preferable to apply it as a correction in the manner indicated above. How-
ever, since in our case it appears to be a small correction compared to the
uncertainty due to non-uniformity we will assume it to be a small error in
our measurement: on the order of ±0.5%.

A component of the uncertainty of any measurement is the precision with
which the measurement can be repeated. Table 3 is a list of the estimated
standard deviations for two different silicon detectors being compared to the
same thermopile. Each detector was measured three times during different runs
on different days. The average precision from 450 to 950 nm is 0.6%. Outside
these limits the average precision is 1.7%.

Table 3

Precision (Estimated Standard Deviations for a Single
Measurement) of Silicon Detector to Thermopile Compari-
sons at Several Wavelengths

350 nm	1.9%	750 nm	0.5%
400	1.1	800	0.2
450	0.6	850	0.4
500	0.5	900	0.7
550	0.5	950	0.9
600	1.0	1000	1.6
650	0.6	1050	2.3
700	0.5	1100	1.3

In summary, it is difficult to estimate the overall accuracy of the
detector response transfer measurements made with this spectral comparator
instrument, principally because of the crude estimate we made of the effect
of the non-uniformity of the thermopile response and the spectrally variable
non-uniformity of the monochromator output. Also, since the silicon detectors
are overfilled by the image of the output slit of the monochromator they are
not uniformly sampling the monochromator output thereby contributing a
non-uniformity type of error. If we assume that the non-uniformity contribu-
tion to the uncertainty is on the order of ±1% everywhere except in the blue
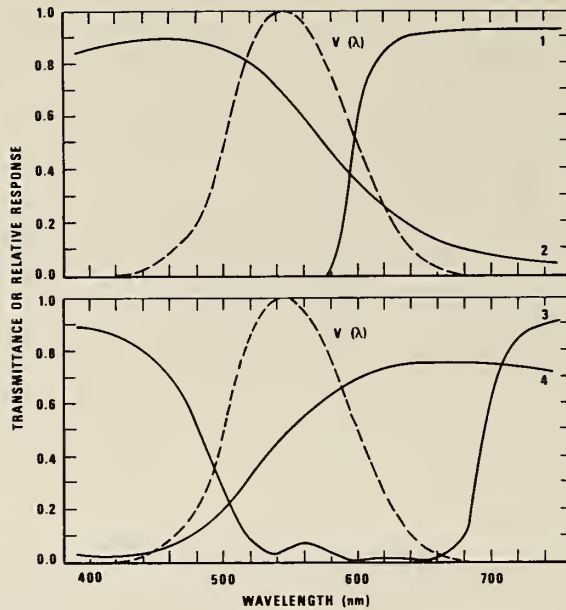where it is about ±4%, then we can combine this in quadrature with the

Fig. 7: Comparison of the visible transmittance
of the four calibrated absorbing glass filters
and a photopic detector. The curves are:
(1) selenium red glass; (2) copper green glass;
(3) cobalt blue glass; (4) carbon yellow glass;
and V(λ) is the relative response curve for an
ideal photopic detector.

Table 4

Difference Between Observed and Calculated Transmittance
of Absorbing Glass Filters -- Responsivity Determined
with the Corrected Thermopile Response Function

Filter Type	Silicon Photodiode	Photopic Detector	Photodiode with Silicon - IR Cut-off
Blue	-0.5%	-0.7%	-1.4%
Green	0.2	-0.3	-0.5
Yellow	0.3	0.3	0.5
Red	0.03	1.0	1.2

Table 5

Difference Between Observed and Calculated Transmittance
of Absorbing Glass Filters -- Responsivity Determined
with an Uncorrected (Flat) Thermopile Response Function

Filter Type	Silicon Photodiode	Photopic Detector	Photodiode with Silicon - IR Cut-off
Blue	0.1%	-0.2%	0.0%
Green	-0.4	-0.4	-0.4
Yellow	0.05	0.4	0.3
Red	0.1	1.1	0.9

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uncertainties due to the relative thermopile response (±2%), the non-linearity (±0.4%), the bandpass (±0.5%), and the wavelength error (±0.1 to ±2%) to obtain an overall uncertainty. Adding this result to a 3σ estimate of the precision yields accuracy limits of ±3% to ±4% in the mid-spectral range (500-1000 nm) and ±6 to ±7% in the blue and near infrared for the determination of relative spectral response.

EVALUATION OF THE RELATIVE SPECTRAL RESPONSE MEASUREMENTS

A commonly used technique to check the accuracy of the relative spectral response of a detector is to measure the effective transmittance of a filter [1]. That is, the transmission of a specific irradiance function, $E(\lambda)$, by a filter whose spectrophotometrically measured transmittance is $\tau(\lambda)$. For a detector of relative spectral response, $r(\lambda)$, the effective transmittance, T, is computed as follows:

$$T = \frac{\int E(\lambda)\ \tau(\lambda)\ r(\lambda)\ d\lambda}{\int E(\lambda)\ r(\lambda)\ d\lambda} \tag{19}$$

The comparison of the calculated and measured values of T is then taken to be a measure of the accuracy of the $r(\lambda)$ function.

We obtained from the NBS Spectrophotometry Group four calibrated absorbing glass filters [19]. The visible transmittance for each of these filters plus the relative response of a photopic detector is depicted in Fig. 7. Table 4 lists the differences between the calculated and measured effective transmittances of each of these filters using the three silicon detectors measured above. The agreement is remarkable. The effective transmittance errors are everywhere less than 1.5%; typically they are about 0.5%. Whereas the estimated uncertainty of the relative response ranged from 3 to 7%.

If the relative responsivities of the three silicon detectors are recomputed using a wavelength independent response function for the thermopile, a different set of results is obtained from the computation in eq. 19. The effective transmittance errors obtained using a flat thermopile response as the reference detector are shown in Table 5. Although we have changed the relative spectral responsivities by 5% in the blue and 8% in the near infrared, the changes in the effective transmittance measurements, especially those of the (bare) silicon photodiode, do not indicate this. The reason that they do not becomes clear if we examine eq. 19 in a little detail.

Suppose that $r(\lambda)$ is the true detector response function while our measurements are in error by a wavelength dependent function $\delta(\lambda)$. The calculated effective transmittance is then

$$T_{calc} = \frac{\int e(\lambda)\ \tau(\lambda)\ [r(\lambda) + \delta(\lambda)]\ d\lambda}{\int E(\lambda)\ [r(\lambda) + \delta(\lambda)]\ d\lambda} \tag{20}$$

and T_{expt} is given by eq. 19. If we make the following assumption

$$\int E(\lambda)\ r(\lambda)\ d\lambda \gg \int E(\lambda)\ \delta(\lambda)\ d\lambda \quad,$$

then eq. 20 can be approximated as

$$T_{calc} = [\frac{\int E\ \tau r\ d\lambda}{\int E\ r\ d\lambda} + \frac{\int E\ \tau\delta\ d\lambda}{\int E\ r\ d\lambda}]\ [1 - \frac{\int E\delta\ d\lambda}{\int Er\ d\lambda}]$$

The indication of dependence on λ has been omitted to simplify the form of the equation. The difference between the calculated and observed effective transmittance would be

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$$\frac{T_{calc} - T_{expt}}{T_{expt}} = [1 + \frac{\int E\tau\delta d\lambda}{\int E\tau r d\lambda}] \; [1 - \frac{\int E\delta d\lambda}{\int E r d\lambda}] - 1 \qquad (23)$$

The ratio of integrals in the first bracket is an estimate of the error within the filter transmission band, and the ratio in the second bracket is the estimate over the entire response range of the detector. If these two ratios are of the same order of magnitude, that is, if the errors within the filter transmission band are approximately the same as those throughout the detector response band, then the product of the two brackets in eq. 23 is approximately equal to one. Actually

$$\frac{T_{calc} - T_{expt}}{T_{expt}} = \frac{\int E\tau\delta d\lambda}{\int E\tau r d\lambda} - \frac{\int E\delta d\lambda}{\int E r d\lambda} - \frac{\int E\tau\delta d\lambda}{\int E\tau r d\lambda} \cdot \frac{\int E\delta d\lambda}{\int E r d\lambda} \qquad (24)$$

The estimate of the spectral response error, the first term on the right, will be increased or diminished depending on the errors throughout the rest of the response range. The effective transmittance test can be a qualitative indication of relative spectral response errors if two conditions are met. First the transmission band of the filter must be small with respect to the response range of the detector. And second, the relative response errors within the transmission band must be large with respect to the errors throughout the rest of the response range. The correct magnitude of the error cannot be determined by this test.

The first condition is met by the interference filters that were used in the first part of this study to measure the relative spectral response of the thermopile. The result of an effective transmittance test using some of these filters is given in Table 6. Two things are immediately obvious. First the variations of relative spectral response for the silicon photodiode and the silicon photodiode plus ir cut-off filter are on the order of the estimated uncertainties of the previous section. Second, the variations of the photopic response indicate substantially greater errors than expected. This may be due simply to the failure of the effective transmittance test as noted in eq. 24. That is, the estimate of the spectral response error has been substantially increased in the blue and decreased in the red spectral regions. On the other hand, the bandpass errors and wavelength errors may have been greater than expected since our detector did not have the same slopes as the ideal photopic detector, nor was the monochromator output spectrum the same as a 3000 K blackbody. In any event, it is obvious that the broadband effective transmittance test failed completely to indicate the presence of some pretty large errors in all three detectors.

CONCLUSIONS

Small improvements beyond the ±2% uncertainty level can possibly be made in the lamp and filter method of measuring the relative spectral response of a thermopile. But these are hardly worth the effort considering the accuracy that can be obtained with a characterized electrical substitution radiometer [2,3] (ESR). Pyroelectric ESR's are now commercially available that have uncertainties of about one percent in absolute response throughout the wavelength range from the near uv to the near ir. Furthermore, their sensitivity and uniformity surpasses that of thermopiles. Use of the lamp and filter method to measure other detector response functions will almost certainly have uncertainties exceeding ±3%. Spectral comparison to a reference detector of an accurately known response provides a more accurate method of detector measurement.

Several conclusions can be drawn regarding the improvement of the mono-chromator based spectral comparator used in this study. The largest source

Table 6

Difference Between Observed and Calculated
Transmittance of Interference Filters

Filter Transmittance Peak	Silicon Photodiode	Photopic Detector	Silicon Photodiode with IR Cut-off
350 nm	-0.8%	---[a]	---[a]
400	-3.4	---[a]	0.4%
450	-3.8	93.2%	4.2
500	1.1	19.6	0.5
550	0.4	1.2	-0.7
580	0.8	-1.1	-0.4
600	-0.4	-8.2	-1.6
650	0.6	---[a]	-0.4
750	3.5	---[a]	-2.0
800	-1.7	---[a]	---[a]
850	-2.1	---[a]	---[a]
1000	0.8	---[a]	---[a]
1200	0.9	---[a]	---[a]

[a]Nearly zero detector output.

of uncertainty was due to the lack of spatial uniformity in the monochromator output and the detector response. The monochromator output can be made more uniform by using a more uniform light source such as a strip lamp or an entrance diffuser on the monochromator itself. Thermopiles can not be made more uniform without a loss in sensitivity. Hence another type of reference detector is called for, such as, a pyroelectric detector or a silicon photodiode. Also, if it is at all possible one should underfill the detector apertures rather than overfill them.

The uncertainty due to the monochromator bandpass can be reduced by using eq. 18. One needs to know the relative spectral distribution of the monochromator output and the relative spectral response of the reference and test detectors. Since the response of the test detector is an unknown, obtaining a bandpass correction is an ex post-facto calculation. The error due to such an iteration should be smaller than the magnitude of the bandpass correction itself.

The use of a monitor detector is a reasonable way to improve measurement precision. However, use of a partially reflecting mirror is preferable to the pierced mirror used in this study. This would insure that the monitor detector views the same portion of the monochromator output as the reference and test detectors.

The major source of imprecision in these measurements was the thermopile. It has already been recommended that it be replaced by either a pyroelectric on a silicon detector. From the standpoint of repeatability and sensitivity a silicon photodiode would be the preferred reference detector. However, if wide spectral range is required then a black-coated pyroelectric is the detector of choice.

Given the increased sensitivity of the silicon photodiode one can substantially reduce the instrument bandpass. This will, of course, reduce the bandpass correction (and its corresponding uncertainty) and decrease the wavelength error somewhat. Further reduction of the wavelength error requires mechanical improvements of the wavelength drive and readout.

Finally we do not recommend the effective transmittance measurement of a filter as a reliable test of the accuracy of a spectral response measurement. The cancellation of errors as shown in eq. 24 clearly indicates an erroneous estimation of the error within the filter transmission band.

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The method of relative spectral detector response measurement based on filters of known transmittance and a spectral irradiance standard lamp was used to measure the responsivity of a thermopile. The thermopile was then used in conjunction with a monochromator based spectral comparator to measure the relative spectral response from 350 to 1200 nm of several other detectors. Several auxiliary experiments to evaluate the accuracy of these techniques are described. The estimated accuracy of relative spectral response measurements using these techniques and this particular instrumentation was found to range from 3 to 7% depending upon the type of detector being measured and the spectral region under study. Finally, the effective transmittance of several filters was measured to evaluate the accuracy of the relative spectral detector response measurements. It was concluded that the effective transmittance test is not a reliable way to judge the accuracy of detector response measurements.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Detector; detector radiometry; detector spectral comparator; detector spectral response; filter transmittance test; photodetector; photometer; radiometer; spectral responsivity.

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