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September 2001

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# Two-Step Calibration of a Multiwavelength Pyrometer for High Temperature Measurement Using a Quartz Lamp

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## Introduction

There is no theoretical upper temperature limit for pyrometer application in temperature measurements. NASA Glenn's multiwavelength pyrometer can make measurements over wide temperature ranges(1). However, the radiation spectral response of the pyrometer's detector must be calibrated before any temperature measurement is attempted, and it is recommended that calibration be done at temperatures close to those for which measurements will be made. Calibration is a determination of the constants of proportionality at all wavelengths between the detector's output (voltage) and its input signals (usually from a blackbody radiation source) in order to convert detector output into radiation intensity. To measure high temperatures, the detectors are chosen to be sensitive in the spectral range from 0.4 to 2.5 μm. A blackbody furnace equilibrated at around 1000 °C is often used for this calibration. Though the detector may respond sensitively to short wavelengths radiation, a blackbody furnace at 1000 °C emits only feebly at very short wavelengths. As a consequence, the calibration constants that result may not be the most accurate. For pyrometry calibration, a radiation source emitting strongly at the short wavelengths is preferred. We have chosen a quartz halogen lamp for this purpose.

## Method and Results

It would be most desirable to calibrate the pyrometer with a blackbody furnace equilibrated at temperatures near the application temperatures (2000 or 3000 °C). Suitable blackbody furnaces in this temperature range are very inconvenient to use and set up. A great deal of time and preparation is needed to use them, including additionally the provision for an inert gas curtain and other procedures to establish the condition reproducing a known temperature. Commercial quartz halogen lamps are efficient emitters of radiation from approximately 0.4 to 2.5 μm. They are also easier to use. But a quartz lamp is not particularly useful for pyrometry calibration because unlike blackbody furnaces, whose temperatures can be readily determined using thermocouples, the quartz lamp filament temperature cannot be measured so straightforwardly. The spectral emissivity of the tungsten filament in a quartz lamp is complex. Furthermore, the individual spectral transmissivity of the quartz envelope enclosing the filament is also not known. However, if a reliable procedure which will facilitate the quartz lamp to be used as a pyrometer calibration source can be devised in spite of these factors, it would be desirable and beneficial.

The calibration response function K(λ) built into the multiwavelength pyrometer spectrometer by the manufacturer is related to the spectrum of a calibrating blackbody by

$$K(\lambda) = S(\lambda)/[P(\lambda,T) - P(\lambda,T_0)] \quad \textbf{(1)}$$

where S(λ) is the spectrometer output volt signal in response to P(λ,T), the blackbody furnace radiation input signal it receives at wavelength λ and temperature T according to the Planck function given by

$$P(\lambda,T) = \frac{c_1}{\lambda^5}\frac{1}{[\exp(c_2/\lambda T) - 1]} \quad \textbf{(2)}$$

$T_0$ is the temperature of a built-in internal blackbody furnace in the spectrometer, $c_1$ and $c_2$ are the radiation constants. The pyrometer's response function (calibration constant) K(λ) has the unit of volts per energy. Once T and $T_0$ are known, K(λ) is obtained with the same accuracy as S(λ). So if the detectors are very sensitive to short wavelength radiation, but there is hardly any intensity from the blackbody furnace at those wavelengths, then $S(\lambda)$ and hence $K(\lambda)$ will be just due to noise in the detector.

To measure temperature, an experimenter needs only the radiation spectrum $W(\lambda)$ which the pyrometer (spectrometer) hardware and software automatically generate according to Eq. (3) below, after a suitable calibration has been properly accomplished. The intermediate quantities $S(\lambda)$, and the determined once only $K(\lambda)$ are of no concern to the experimenter, and are almost never outputted.

$$W(\lambda) = S(\lambda)/K(\lambda) + P(\lambda, T_0) \tag{3}$$

The explicit relationship between $W(\lambda)$, the emissivity ($\varepsilon_\lambda$) of the emitting surface, the transmissivity ($\tau_\lambda$) of the intervening medium, and the emitter temperature T is given by

$$L_\lambda = \frac{1}{\varepsilon_\lambda \tau_\lambda}\left[S(\lambda)/K(\lambda) + P(\lambda, T_0)\right] = \frac{1}{\varepsilon_\lambda \tau_\lambda} W(\lambda) \tag{4}$$

The multiwavelength pyrometer we used in this investigation has been described elsewhere$^{(1)}$. Eq. (4) connects $P(\lambda,T_0)$ with $L_\lambda$ through $S(\lambda)$ and $K(\lambda)$. It is configured to accept signals (radiation) via a 20-meter long silica optical fiber. By simply positioning the input end of the fiber to receive radiation from a blackbody furnace equilibrated at temperature $T_{BB}$ = 1294 K, a standard calibration will be completed according to Eq. (1). The calibration takes the fiber's transmission, acceptance angle (numerical aperture) and other characteristics into consideration and incorporated them in the spectrometer (calibration) response function $K(\lambda)$.

After completing a blackbody furnace calibration, the multiwavelength pyrometer can easily measure the quartz lamp filament temperature ($T_Q$) if the product $\tau_\lambda\varepsilon_\lambda$ of the lamp filament spectral emissivity ($\varepsilon_\lambda$), and the lamp envelope's quartz spectral transmissivity ($\tau_\lambda$), is constant or nearly constant.

Ninety watts of electrical power is dissipated through the filament of a quartz lamp. The input end of the 20-meter silica fiber is connected to the fiber optics output connector in the quartz lamp's housing. A recorded spectrum of the quartz lamp is shown in Fig. 1. Eq. (5) below, which describes how to transform the spectral data of Fig. 1 into a straight line to determine the lamp filament temperature $T_Q$, is reproduced from Ref. 1.

$$Y = \left( \frac{\mathrm{Ln}\left(\frac{c_1}{\lambda^5}\frac{1}{L_\lambda}\right)}{c_2/\lambda} \right) - \frac{\mathrm{Ln}\left(1 - \exp\left(-\frac{c_2}{\lambda T}\right)\right)}{c_2/\lambda} = \frac{1}{T} - \frac{\lambda}{c_2}\mathrm{Ln}(\varepsilon_\lambda \tau_\lambda) \tag{5}$$

Shown in Fig. 2 are two positive sloped straight lines corresponding to 2 different values of $\tau_\lambda\varepsilon_\lambda$ in Eq. (5) in the appropriate data regions. They fitted the data derived from Fig. 1 very well. These lines intercepted the Y-axis at the same point to give a quartz lamp temperature of 3156 K. A positive slope implies $\tau_\lambda\varepsilon_\lambda < 1$ in Eq. (5). Alternatively this also implies that the quartz lamp radiation source is emitting less than a blackbody and/or some of the emitted radiation has been absorbed (lost) on going through the quartz envelope, and can also include changes in the geometry view factor.

A new (re)-calibration of the multiwavelength pyrometer is now performed using the quartz lamp as the radiation source, again according to Eq. (1) but using $T = T_Q = 3156$ K. The quartz lamp calibrated multiwavelength pyrometer is next used to record a spectrum of the blackbody furnace, shown in Fig. 3. Transformation of the data in Fig. 3 according to Eq. (5) produced a straight line, which is shown in Fig. 4. The intercept of the straight line in Fig. 4 determined the temperature of the blackbody furnace to be $T_{BB}$ = 1294 K again. Observe that the straight line in Fig. 4 exhibited a negative slope, corresponding to $\tau_\lambda\varepsilon_\lambda > 1$, i.e. the blackbody furnace is more emissive than the quartz lamp filament in the second calibration. It therefore reflects the fact that radiation arriving at the spectrometer from the blackbody furnace did not suffer absorption by a quartz envelope. Both factors (conditions) have been incorporated into the quartz lamp response function (calibration constants) but they are now no longer present.

All spectra measured (recorded) by the quartz lamp calibrated multiwavelength pyrometer can be corrected for this apparent enhanced emission. It is simply done by multiplying these spectra by a factor at each of their wavelengths to get back the correct intensity. This multiplication factor is readily obtained by performing a wavelength by wavelength division of two quantities, which are obtained (i) from a Planck function of temperature corresponding to that of the blackbody furnace (T = 1294 K) and (ii) from the experimentally recorded spectrum of the blackbody furnace at this same temperature, i.e. the spectrum in Fig. 3.

Mathematically, the multiplication of a correction factor is a normalization transformation which removes the effects due to the incorporation of the quartz lamp (emissivity and transmissivity) properties into the pyrometer response function during calibration. The spectral dependence of this multiplicative normalization factor is shown Fig. 5. There is no apparent strong spectral dependence through out.

The blackbody furnace (at 1294 K) and quartz lamp (at 3156 K) calibration response functions, $K(\lambda)$, calculated according to Eq. (1) are shown in Figs. 6 and 7. At first examination, apart from their magnitudes, which arose owing to temperature, intensity and geometry differences between the blackbody furnace and the quartz lamp, their spectral appearances are quite similar. However, at the shortest wavelengths, the 1294 K blackbody furnace calibration response function rose very rapidly (Fig. 6) whereas the response function that resulted from a quartz lamp calibration is well behaved and finite (Fig. 7).

The internal blackbody reference temperature $T_0$ is always about 300 K. In Fig. 6, the steep rise at the shortest wavelength is attributed to the fact that at these very short wavelengths, the detector output voltage signal $S(\lambda)$ in the numerator is just constant noise (i.e. poor signal to noise), since a blackbody furnace at 1294 K just does not emit enough radiation to produce any detectable output voltage, whereas the denominator is a very small magnitude non-zero Planck function quantity given by that temperature. The resultant division is the steeply rising (exploding) quantity in the response function curve. On the other hand, the very high intensity radiation emitted by the quartz lamp produced good signal to noise voltage signals in the detector, which when divided by a much larger non-zero Planck function quantity (because of a much higher temperature), resulted in a properly behaved response function curve in Fig. 7. Herein lies the advantage and importance of a calibration using a high temperature radiation source.

## Conclusion

Multiwavelength pyrometry calibration can take advantage of the greater radiation emission intensity at short wavelengths afforded by the quartz halogen lamp to obtain a more accurate (calibration) response function at short wavelengths. The temperature of a blackbody furnace was measured with thermocouples. This blackbody furnace temperature was used to calibrate the multiwavelength pyrometer, which was then used to determine the operation temperature of a quartz halogen lamp filament (operated at 90 watts electrical power). The radiation of the quartz lamp filament at this operation temperature was used to calibrate the multiwavelength pyrometer. After this calibration by this quartz lamp, the multiwavelength pyrometer was used to measure the temperature of the original blackbody furnace. The temperature obtained was the same as that measured by thermocouples. Calibration of the multiwavelength pyrometer using a quartz halogen lamp has therefore been shown to be feasible.

## References

1) Gustave Fralick and Daniel Ng, Review of Scientific Instruments, Vol 72, Number 2, 1522-1530, 2001.

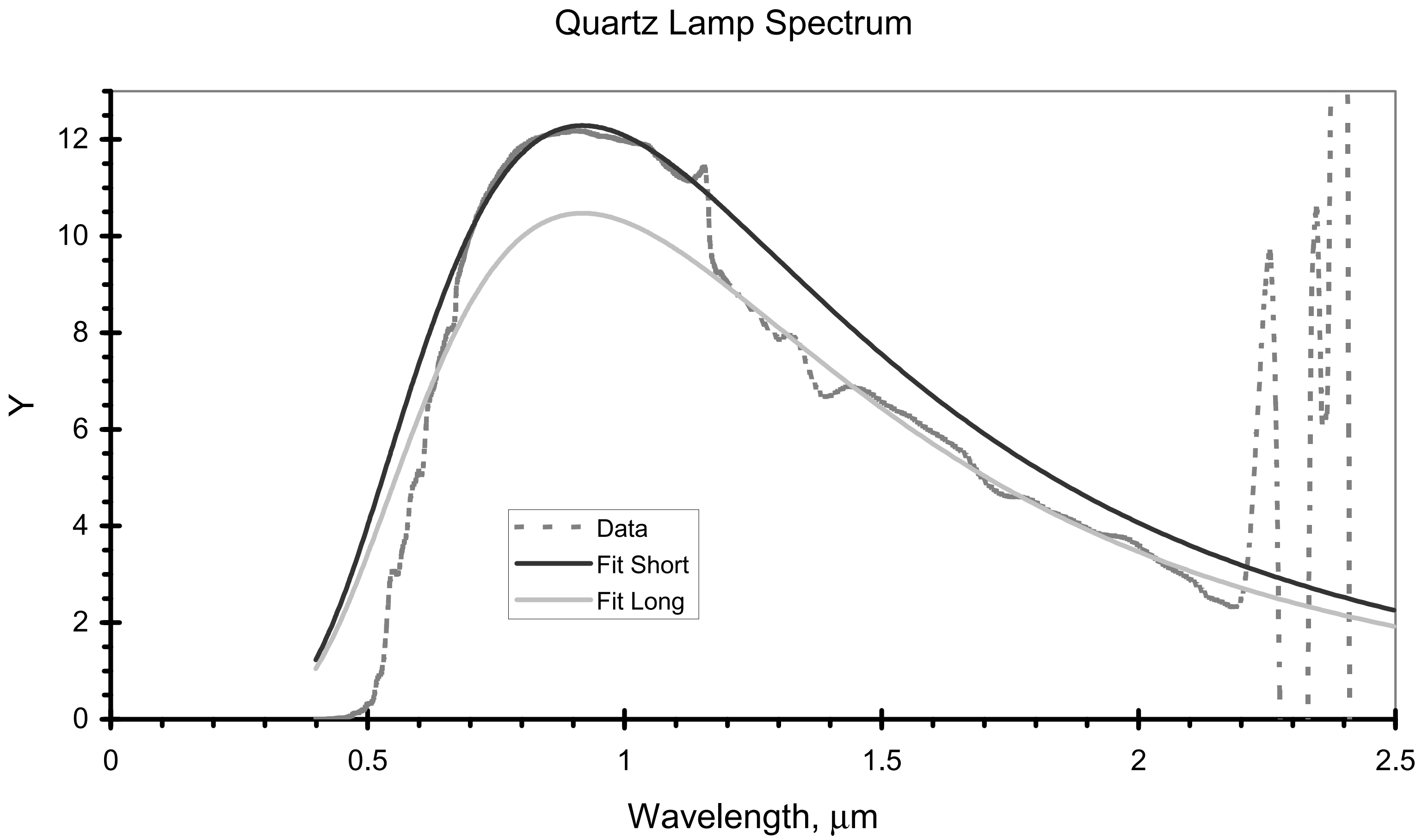

Fig. 1 Radiation Spectrum of Quartz Measured by a Blackbody Furnace Calibrated Spectrometer

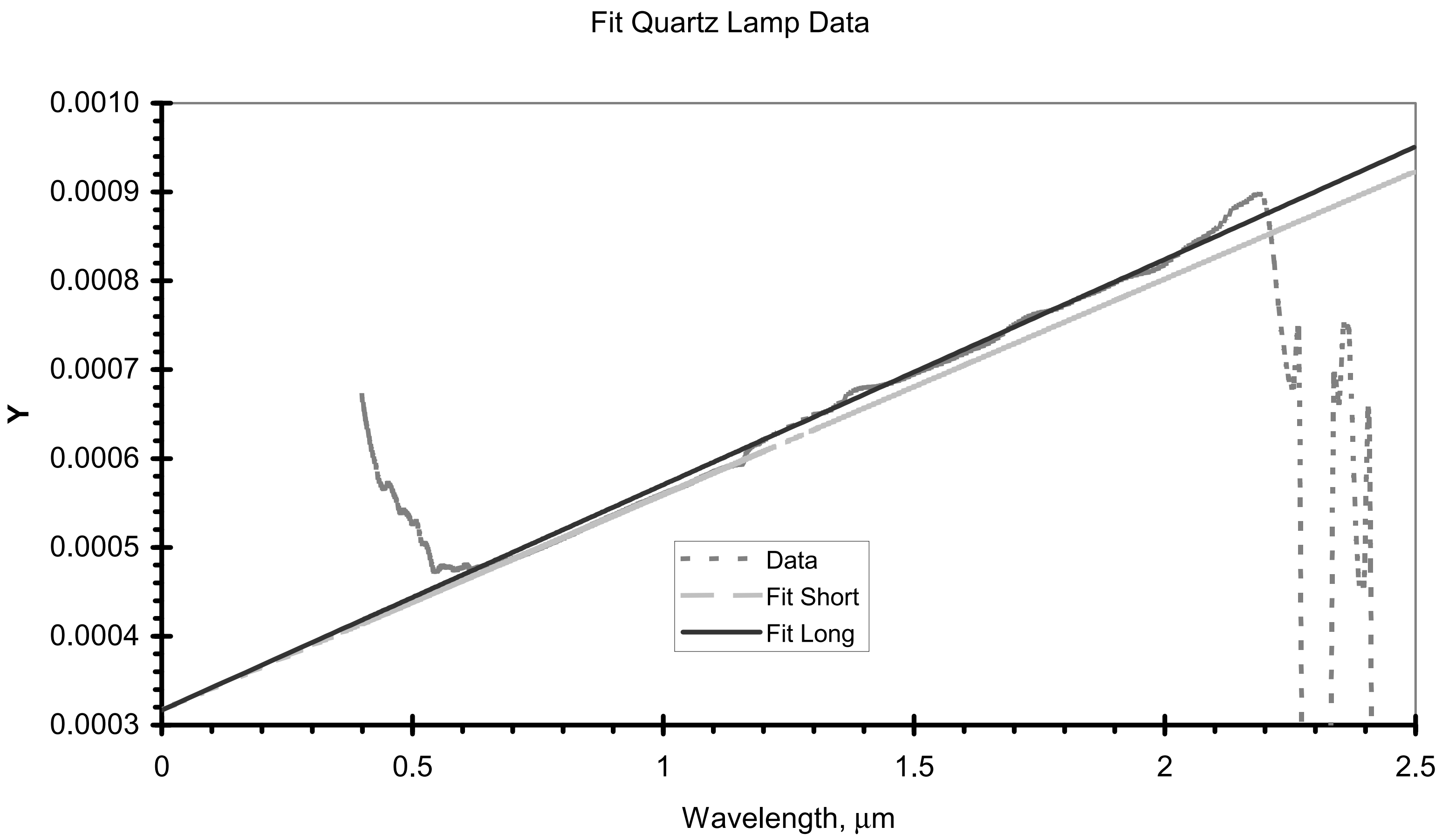

Fig. 2 Quartz Lamp Filament Temperature of 3156 K Determined by Two Fitting Straight Lines' Intercepts. Poor data at the very short and very long wavelength regions are due to poor signal to noise. The short wavelength data region is from about 0.5 to 1.5 µm region, the long wavelength region is from about 1.5 to 2.5 µm region.

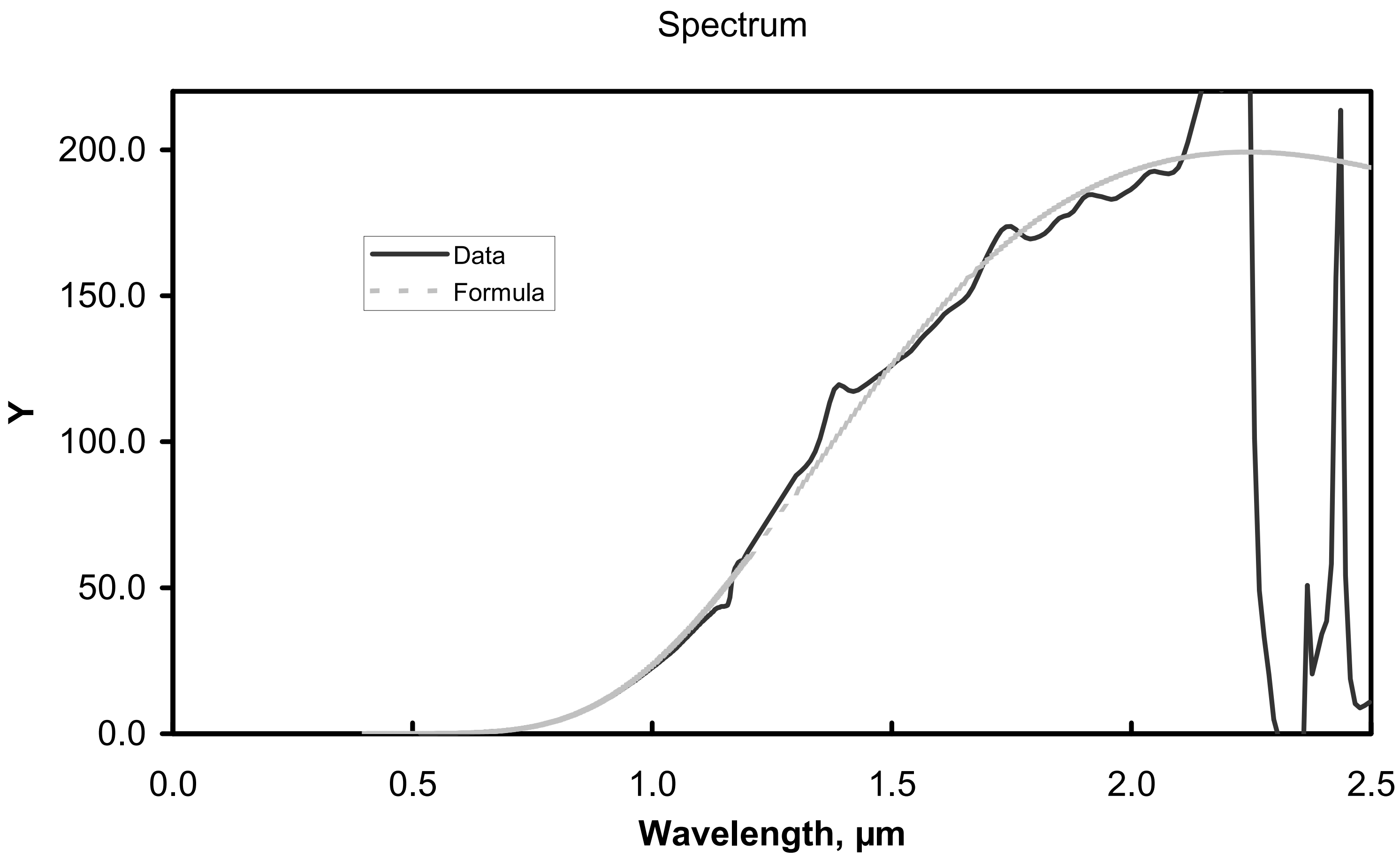

Fig 3. Blackbody Spectrum Recorded by the Quartz Lamp Calibrated Multiwavelength Pyrometer.

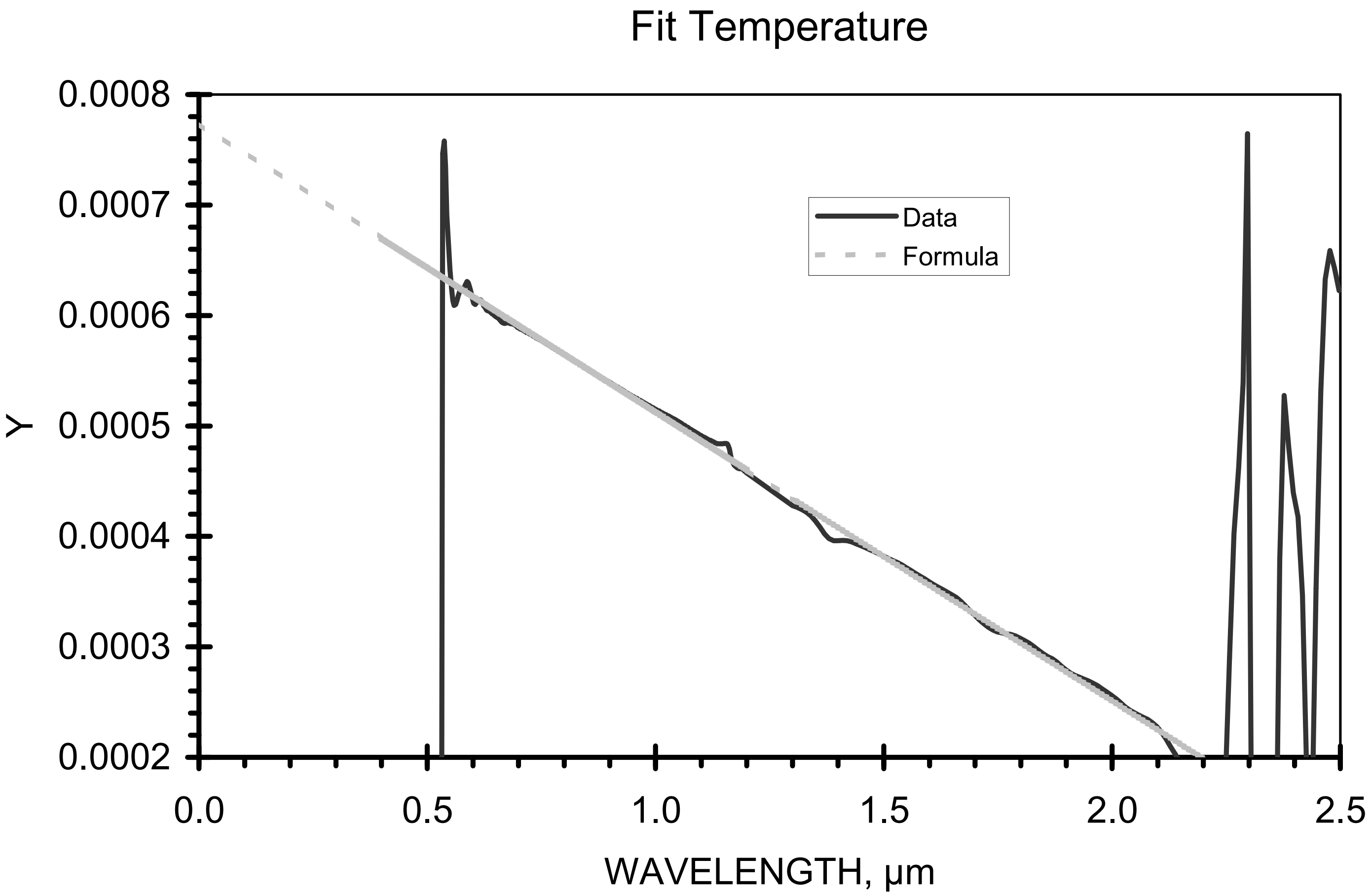

Fig. 4 Blackbody Furnace Temperature = 1294 K Determined From Fitted Line Intercept.

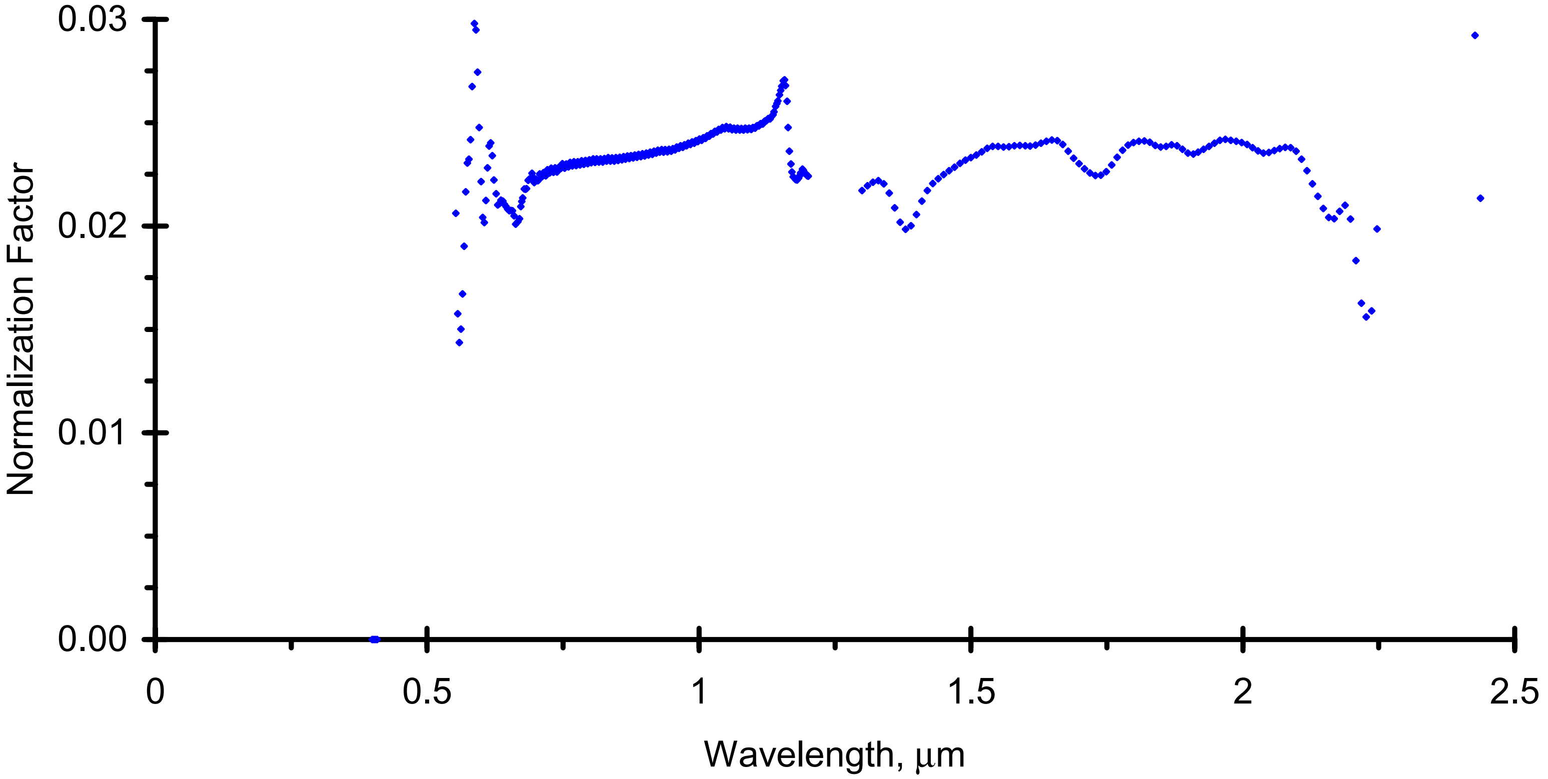

Fig. 5 Multiplication Factor Which Removes The Quartz Lamp Effect From a Spectrum.

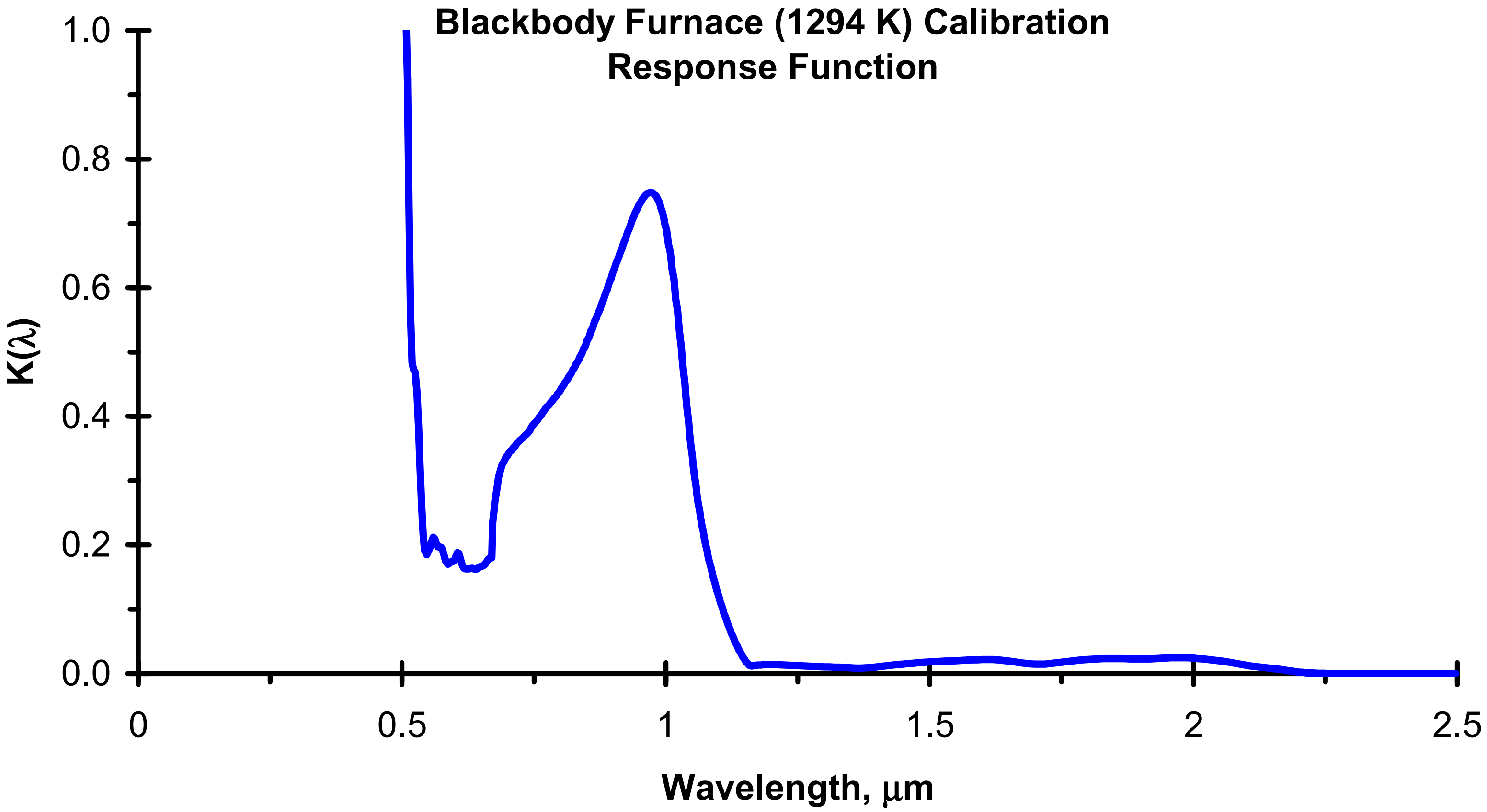

Fig. 6 Response Function determined at 1294 K Using a Blackbody Furnace.

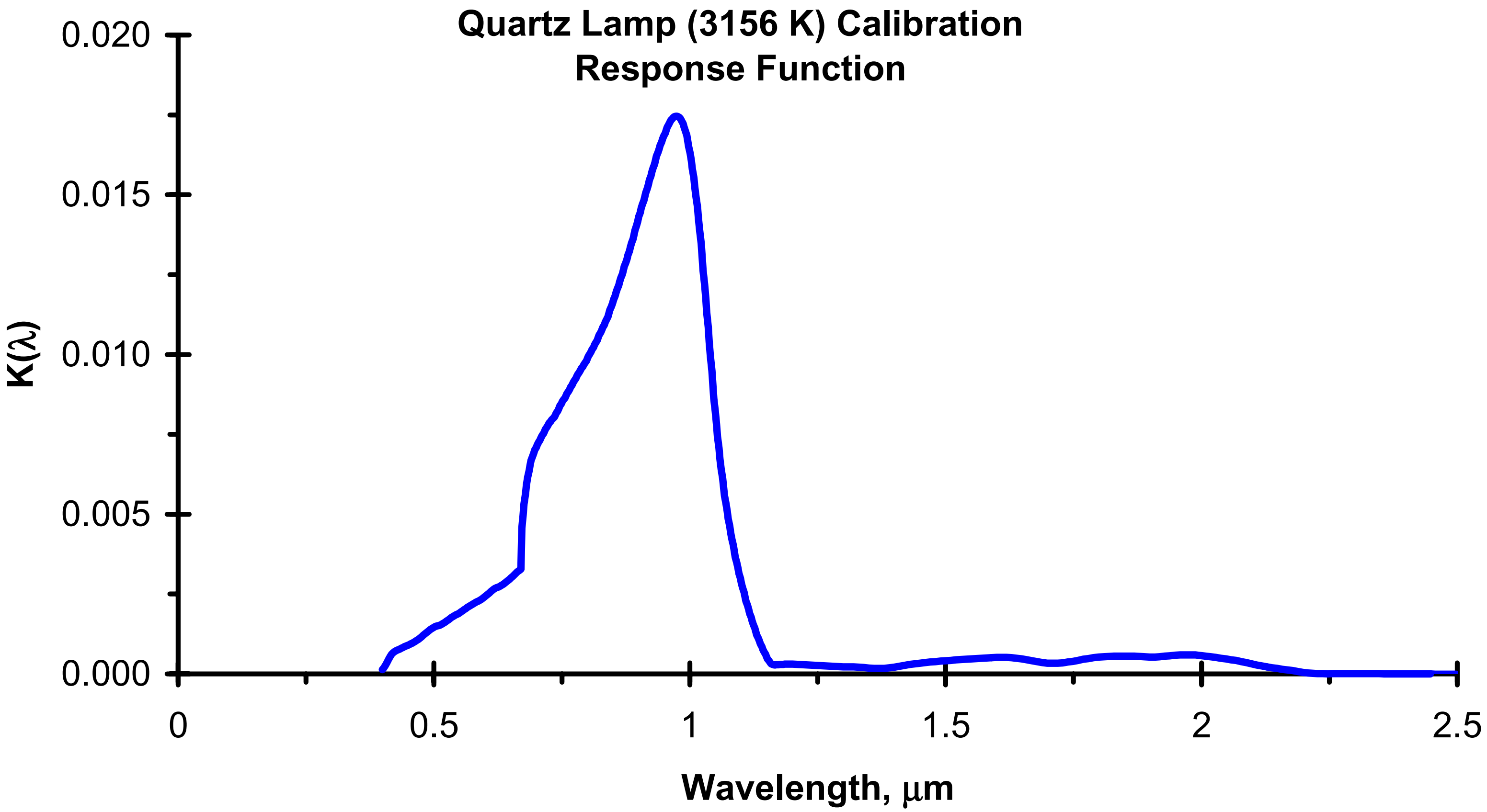

Fig. 7 Response Function determined at 3156 K Using a Quartz Halogen Lamp.

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