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Multiwavelength Pyrometry for Nongray Bodies

Daniel Ng
Lewis Research Center
Cleveland, Ohio

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MULTIWAVELENGTH PYROMETRY FOR NONGRAY BODIES

Daniel Ng
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

A multiwavelength technique has been developed and applied to measure the temperatures of nongray surfaces. The instruments required are a spectral radiometer, a dedicated auxiliary radiation source, and a computer. In general, three radiation spectra are recorded: (1) spectrum S_0 of the auxiliary radiation source, (2) spectrum S_I of the surface-emitted radiation, and (3) spectrum S_{II}, the sum of the radiation of S_I plus the reflected radiation due to the incidence of the auxiliary radiation source on the surface. Subtracting spectrum S_I from spectrum S_{II} yields the reflection spectrum resulting from the incident radiation. From these spectra, a quantity $z(\lambda)$ is derived and is related to the reflectivity $r(\lambda)$ by $r(\lambda) = z(\lambda)/f$, where f is a constant. Spectrum S_I is represented mathematically as the product of a wavelength-dependent emissivity obtained from Kirchhoff's law and a Planck function of temperature T. Application of two-variable (λ and z), nonlinear, least-squares curve-fitting computer software to fit spectrum S_I to this mathematical expression yielded the surface temperature. This technique also measured the spectral reflectivity and emissivity of the surface. Instrumentation necessary to extend measurement to elevated temperatures and in the presence of reflective interference is discussed.

INTRODUCTION

Traditional pyrometry uses either a one-color or a two-color method. In one-color pyrometry, temperature determination requires knowing the emissivity of the surface. In the range of its design operating temperatures (usually in the neighborhood of 1000 K), the fractional error in temperature measurement due to error in emissivity is only about one-tenth of that due to error in pyrometer radiation signals (ref. 1). Nevertheless, accurate temperature measurement would still require more accurate values of emissivity. Accurate temperature measurement without prior knowledge of emissivity is possible if a functional dependence of emissivity with wavelength is assumed (refs. 1 and 2). In two-color pyrometry, more accurate temperature measurement is possible without exact knowledge of emissivity by assuming that the emissivity is the same at the two wavelength bands where measurements are made (ref. 3). However, neither method is capable of correcting for the interference of reflected radiation.

At NASA Lewis, multiwavelength pyrometry has been used to measure surface temperature and to correct for the interference radiation from an extraneous source (refs. 4 and 5). The measured pyrometry radiation spectrum in general covers a broad wavelength region. In these previous studies the surface under consideration was assumed to be gray (emissivity independent of wavelength). In actual application, many bodies such as ceramic materials are nongray. For these materials, the emissivity is known to be wavelength and temperature dependent. It is small at short wavelengths and increases to almost unity at wavelengths around 8 or 10 μm, and then decreases and increases in some manner at longer wavelengths (ref. 6). Thus, conventional pyrometry optimized only for black or gray bodies would produce unavoidable error when applied to nongray bodies (ref. 7). Even for a surface with known emissivity, the value may still vary over time. Accurate temperature measurement requires measuring the emissivity simultaneously.

As described in this report, multiwavelength curve-fitting pyrometry can be extended to measure accurately the surface temperature of a nongray surface by simultaneously measuring the emissivity. It can also accommodate the more general and important case in which extraneous interfering radiation is present. This will be described in another report (ref. 8).

THEORY

The basic components of this pyrometer are a spectral radiometer, an auxiliary radiation source which can be turned on and off (either manually or by mechanical chopping), and a computer for data acquisition, data processing, and numerical calculation.

Three spectra are required:

(1) $S_0(\lambda)$, the spectrum of the auxiliary radiation source (can be accumulated prior to real time measurement)

(2) $S_I(\lambda)$, the spectrum of the surface radiation

(3) $S_{II}(\lambda)$, the spectrum resulting from the superposition of radiation emitted from the surface and radiation from the auxiliary radiation source reflected by the surface

Spectrum $S_0(\lambda)$ is the direct unobstructed spectrum of the auxiliary radiation source in the wavelength region of interest obtained in the geometry shown in figure 1 using the spectral radiometer of a multiwavelength pyrometer.

Spectrum $S_I(\lambda)$ is obtained in a typical pyrometer geometry shown in figure 2 with the auxiliary radiation source turned off. This is the emission spectrum of the nongray surface described by a Planck function of temperature T modified by the wavelength-dependent emissivity of the nongray surface.

Spectrum $S_{II}(\lambda)$ is also obtained in the geometry shown in Figure 2 but with the auxiliary radiation source turned on. Thus $S_{II}(\lambda)$ is the spectrum $S_I(\lambda)$ plus reflected radiation due to the auxiliary radiation source. Subtracting spectrum $S_I(\lambda)$ from $S_{II}(\lambda)$ produces the reflected spectrum $S_{III}(\lambda) = S_{II}(\lambda) - S_I(\lambda)$ due to the incidence of the auxiliary radiation source on the measured surface.

The measured reflectivity at any wavelength is the ratio

$$z(\lambda) = \frac{S_{III}(\lambda)}{S_0(\lambda)} = \frac{S_{II}(\lambda) - S_I(\lambda)}{S_0(\lambda)} \tag{1}$$

Because $S_0(\lambda)$ is measured on a direct path in figure 1, and $S_{III}(\lambda)$ is measured on a reflected path in figure 2, their ratio $z(\lambda)$ includes a constant factor f due to different conditions along the two paths. Two conditions are the geometry of the optical beams and the nonspecular reflecting surface. Thus, the true reflectivity is

$$r(\lambda) = \frac{z(\lambda)}{f} \tag{2}$$

where f will be determined.

Kirchhoff's law is applied to yield

$$e(\lambda, \beta, \theta, T_e) = 1 - r(\lambda, \beta, \theta, T_e)$$

in which emissivity and reflectivity generally possess spectral, angular, and temperature dependencies. The symbols β and θ refer to the polar angular coordinate angles specifying a direction with reference to a suitably chosen coordinate system, and T_e is the temperature of the reflecting surface. In pyrometry application, the angular dependence disappears because the optics of a pyrometer's detector selects signals in a narrowly defined direction. As a result, only the wavelength dependence needs to be considered at a particular temperature. The emissivity of the surface is therefore given by

$$\begin{aligned} e(\lambda) &= 1 - r(\lambda) \\ &= 1 - \frac{z(\lambda)}{f} \end{aligned} \tag{3}$$

In principle, the constant f can be determined from the geometry of the experimental setup. However, it is more conveniently determined by curve fitting.

The mathematical expression for the surface emission radiation spectrum $S_I(\lambda)$ is a Planck function of temperature T modified by the wavelength-dependent emissivity so that

$$S_I(\lambda) = e(\lambda) \frac{C_1}{\lambda^5} \frac{1}{\exp\left(\frac{C_2}{\lambda T}\right) - 1} \tag{4}$$

Substituting equation (3) gives

$$S_I(\lambda) = \left(1 - \frac{z(\lambda)}{f}\right) \frac{c_1}{\lambda^5} \frac{1}{\exp\left(\frac{C_2}{\lambda T}\right) - 1} \tag{5}$$

where c_1 and c_2 are the first and second radiation constants, and f and T are unknown parameters. The quantity z is obtained using the term-by-term spectrum subtraction and division procedures described previously in this section. The adjustable parameters in the expression, f and T, are determined by applying two-variable (λ and z) least-squares curve fitting to fit the spectrum $S_I(\lambda)$ according to equation (5).

RESULTS

Multiwavelength pyrometry was used to measure the surface temperature of a silicon carbide (SiC) ceramic. Silicon carbide is a common ceramic material with well-documented wavelength-dependent emissivity and reflectivity (refs. 6 and 9). The surface of a silicon carbide wafer sample measuring 3 by 25 by 50 mm (0.125 by 1 by 2 in.) was nominally polished to a 10-μm finish. The temperature of the sample was raised above ambient to about 80 °C by placing it in front of a blackbody furnace and allowing to equilibrate. The blackbody furnace temperature was regulated by a temperature controller with ±0.5 °C long-term stability. The emission spectrum was obtained using a spectral radiometer in the wavelength region 2.5 to 14.5 μm.

The spectral radiometer that was used produced a spectrum either in voltages or in radiation energy units. When the spectrum was in volts, the value was a function of wavelength depending on the intensity of the radiation it detected and the detector responsivity. The voltage spectrum was converted into a radiation energy spectrum when internally divided by the spectrometer's response function which was obtained during routine calibrations performed periodically.

The emission spectrum (in radiation energy units) is shown in figure 3 as a function of wavelength. The deviation of the emission spectrum from a blackbody Planck curve corresponding to the SiC surface temperature is clearly visible. This deviation is due to the wavelength-dependent emissivity. The spikes in the wavelength region 6 to 7 μm are artifacts due to absorption of water and carbon dioxide in the atmosphere. However, the dip at 12 μm is due to a sharp rise (decrease) in reflectivity (emissivity). This increase in reflectivity is explained by the classical dispersion theory of crystals. Since the radiation energy spectrum is a secondary quantity derived from the primary voltage spectrum, the primary voltage data are used in the following analysis which describes how the reflectivity is obtained.

Figure 4 shows the surface emission spectrum S_I of the SiC surface (in volts) obtained by the spectrometer according to the geometry shown in figure 2. Also shown is the spectrum S_{II} (also in volts) obtained when the surface is illuminated by an auxiliary source, a 20-W commercially available infrared lamp. The lamp was regulated by a constant-current power supply such that its typical light output RMS ripple was 0.05 percent. The difference between these two curves gives the reflected spectrum (in volts) due to the auxiliary source incident on the SiC surface (fig. 5). The spectrum S_0 of the unobstructed auxiliary light source acquired with the geometry shown in figure 1 is shown in figure 6. The value z is calculated according to equation (1) and shown in figure 7. This is an experimentally derived quantity related to the emissivity. The quantity $z(\lambda)$ is obtained by using the term-by-term spectrum subtraction and division procedures described previously. The adjustable parameters (f and T) in the expression are determined by the application of two-variable (λ and z), nonlinear, least-squares curve fitting to fit the data of spectrum $S_I(\lambda)$ to equation (5). This curve-fitting software is commercially available.

The temperature determined by curve fitting was 363 K. The good agreement of the fitted curve with the experimental spectrum is shown in figure 8. A 0.125-mm (5-mil) type K (Chromel-Alumel) thermocouple was used such that its junction made as good a contact with the SiC surface as possible. It measured a surface temperature of 360.2 K, in very good agreement with the multiwavelength pyrometer determined value.

The least-squares determined value of f was 0.0248. It was used to calculate the reflectivity according to equation (2) and the emissivity according to equation (3). These results are shown in figures 9 and 10, respectively. The reflectivity's spectral dependence agrees qualitatively with published reflectivity from a polished, optic-axis-oriented crystalline SiC sample using polarized radiations in the 1- to 20-μm wavelength region (ref. 9). The reflectivity $r(\lambda)$ is satisfactorily described by the classical dispersion theory of crystals given by

$$r(\lambda) = \frac{(n - 1)^2 + k^2}{(n + 1)^2 + k^2} \tag{8}$$

with

$$n^2 = (1/2)\left\{\left[\epsilon^2 + 4\left(\frac{\sigma}{\nu}\right)^2\right]^{1/2} + \epsilon\right\} \tag{9}$$

$$k^2 = (1/2)\left\{\left[\epsilon^2 + 4\left(\frac{\sigma}{\nu}\right)^2\right]^{1/2} - \epsilon\right\} \tag{10}$$

$$\epsilon = \epsilon_0 + 4\pi\chi \tag{11}$$

$$\chi = \rho \frac{1 - \nu^2}{\left(1 - \nu^2\right)^2 + \gamma^2\nu^2} \tag{12}$$

$$\frac{\sigma}{\nu} = 2\pi\rho \frac{\gamma\nu}{\left(1 - \nu^2\right)^2 + \gamma^2\nu^2}$$

characterized by ϵ_0, ν_0, ρ, and γ, which are the high-frequency dielectric constant, the resonance frequency, the resonance width, and the strength of the resonance, respectively. These are also related to the susceptibility χ, conductivity σ, index of refraction n, and extinction coefficient k. For ease of calculation, ν is the measured frequency divided by ν_0, and σ is the conductivity divided by ν_0. The reflectivity so calculated using values of $\nu_0 = 2.75\text{x}10^{13}$ Hz, $\rho = 0.029$, $\gamma = 0.15$, and $\epsilon_0 = 2.4$ is shown in figure 9 together with the experimentally measured results. In this way the experimentally determined reflectivity data is fitted to equation (8).

At temperatures well above ambient, the difference between the signals of the radiation spectra with and without the auxiliary source is not easy to measure. However, the signal corresponding to that difference can be readily measured by chopping the auxiliary signal and using phase-sensitive detection schemes. Most spectral radiometers have external signal chopping capability. In this way, the spectrum of the reflected signal is readily obtained, and direct two-variable least-squares curve fitting will determine the temperature of the nongray surface.

CONCLUSION

Multiwavelength pyrometry can be used to determine the surface temperature of a nongray (emissivity depending on wavelength) surface by acquiring and analyzing three spectra, two of them from a nongray surface. They are the spectrum of an unobstructed auxiliary radiation source, the surface emission spectrum of the nongray surface, and the spectrum consisting of radiation due to surface emission and reflection due to the incidence of the auxiliary radiation source on the surface. The reflectivity (hence emissivity) of the surface is obtained simultaneously during least-squares curve fitting. The reflectivity is analyzed satisfactorily using the classical dispersion theory of crystals. This pyrometry was demonstrated by measuring the surface temperature of silicon carbide, a material exhibiting wavelength-dependent emissivity. Extension to higher temperatures is possible by a chopping and phase-sensitive detection method.

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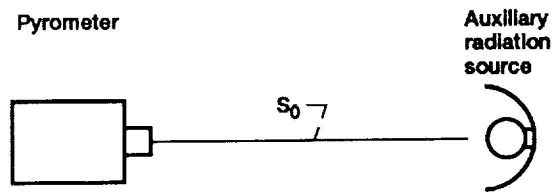

Figure 1.—Experimental arrangement to determine unobstructed spectrum S_0 of auxiliary radiation source.

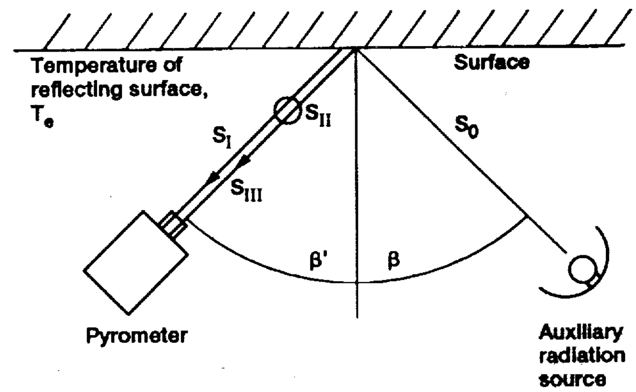

Figure 2.—Experimental arrangement of pyrometry components.

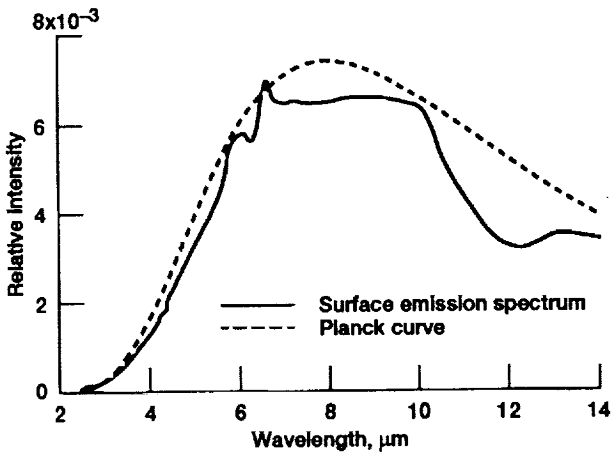

Figure 3.—Surface emission spectrum (in arbitrary energy units) of SiC surface compared with Planck curve for same temperature.

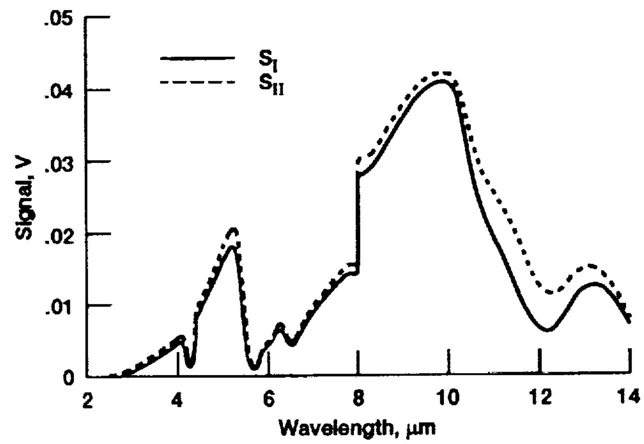

Figure 4.—Surface emission spectra (in volts) of SiC surface (S_I, auxiliary source off; S_{II}, auxiliary source on).

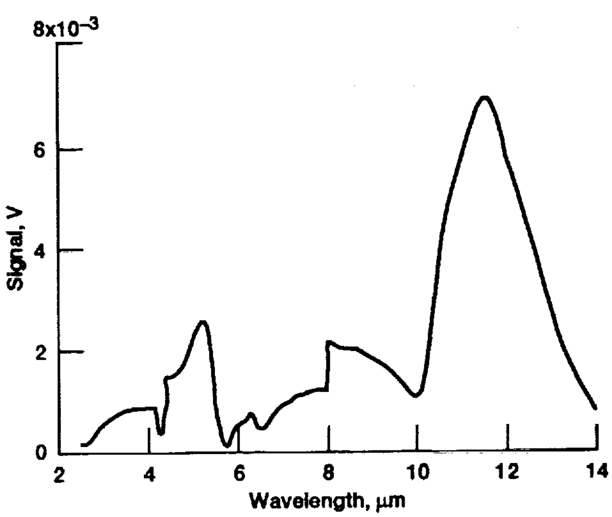

Figure 5.—Reflected spectrum S_{III} from SiC surface obtained by subtracting S_I from S_{II} in figure 4.

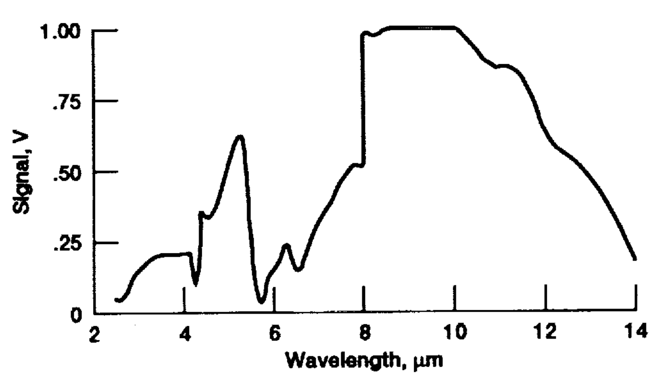

Figure 6.—Unobstructed spectrum S_0 (in volts) of auxiliary radiation source.

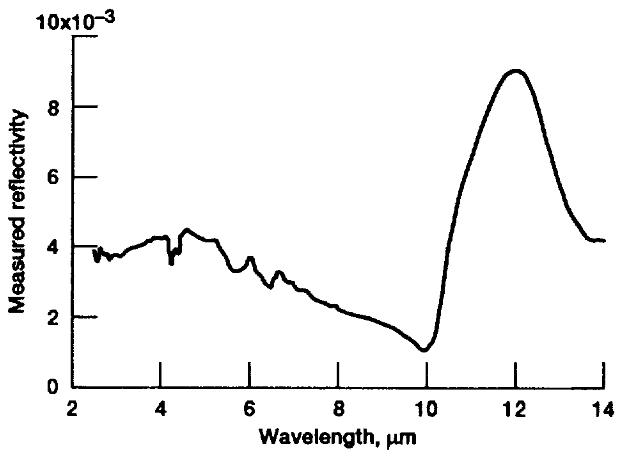

Figure 7.—Measured reflectivity $z(\lambda)$ of SiC surface obtained by dividing spectrum of figure 5 by spectrum of figure 6.

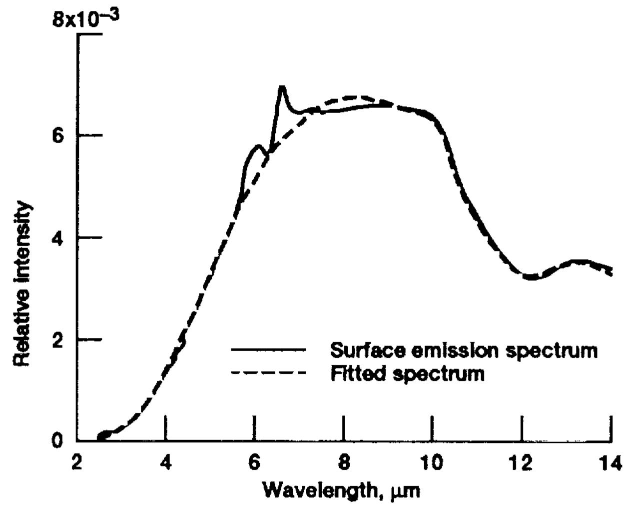

Figure 8.—Surface emission spectrum of SiC surface compared with fitted spectrum according to equation 7.

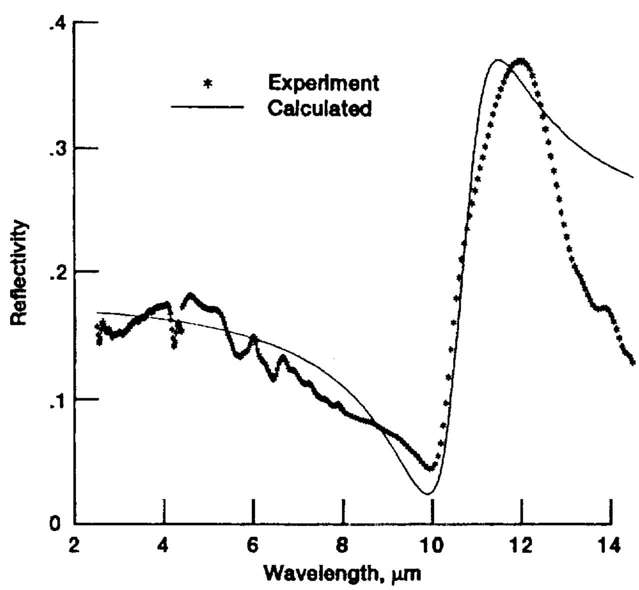

Figure 9.—Experimentally determined reflectivity compared with calculated reflectivity using classical dispersion theory with $\nu_0 = 2.75 \times 10^{13}$ Hz, $\rho = 0.029$, $\gamma = 0.15$, and $\epsilon_0 = 2.4$.

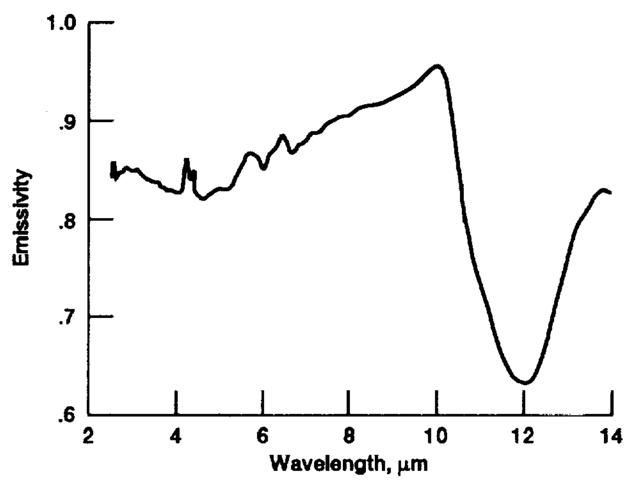

Figure 10.—Spectral emissivity of SiC surface.

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13. ABSTRACT ***(Maximum 200 words)***

A multiwavelength technique has been developed and applied to measure the temperatures of nongray surfaces. The instruments required are a spectral radiometer, a dedicated auxiliary radiation source, and a computer. In general, three radiation spectra are recorded: (1) spectrum S_0 of the auxiliary radiation source, (2) spectrum S_I of the surface-emitted radiation, and (3) spectrum S_{II}, the sum of the radiation of S_I plus the reflected radiation due to the incidence of the auxiliary radiation source on the surface. Subtracting spectrum S_I from spectrum S_{II} yields the reflection spectrum resulting from the incident radiation. From these spectra, a quantity $z(\lambda)$ is derived and is related to the reflectivity $r(\lambda)$ by $r(\lambda) = z(\lambda)/f$, where f is a constant. Spectrum S_I is represented mathematically as the product of a wavelength-dependent emissivity obtained from Kirchhoff's law and a Planck function of temperature T. Application of two-variable (λ and z), nonlinear, least-squares curve-fitting computer software to fit spectrum S_I to this mathematical expression yielded the surface temperature. This technique also measured the spectral reflectivity and emissivity of the surface. Instrumentation necessary to extend measurement to elevated temperatures and in the presence of reflective interference is discussed.

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