NON-CONTACT TRUE TEMPERATURE MEASUREMENTS IN
THE MICROGRAVITY ENVIRONMENT

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INTRODUCTION

The accurate measurement and control of temperature can be of great importance in most materials manufacturing and processing applications. With present-day technology such measurement almost always requires either physical contact with the subject or an extensive calibration procedure. In many cases contact is either not desirable, because such contact may significantly alter the temperature or other characteristics of the subject, or is not possible because the subject is moving, is too far away, is too hot or is in an otherwise hostile environment. Similarly calibration may not be possible if the characteristics change too much.

Multiwavelength pyrometry can help solve some of these problems by providing a reliable method for emissivity independent noncontact true temperature measurements.

BASIC THEORY

All bodies above absolute zero radiate thermal energy. The most efficient thermal radiator is a black body, which is defined as an object that will absorb all incident radiation. The emitted radiance per unit wavelength or spectral radiance of such a body is given by the Planck radiation law:

$$N'_\lambda = C_1 \lambda^{-5} (\exp(C_2/\lambda T) - 1)^{-1} \tag{1}$$

where λ is the wavelength, T is the absolute temperature and C_1 and C_2 are the Planck constants. Figure 1 is a plot of N'_λ vs. λ at various temperatures. The dotted curve depicts Wiens law (as opposed to Wiens approximation which is discussed later) which relates the peak of the Planck curves to wavelength.

A real body however emits only a fraction of what a black body emits at any given temperature. The spectral radiance of a real body is given by a modified form of the Planck radiation law:

$$N_\lambda = \epsilon_\lambda C_1 \lambda^{-5} (\exp(C_2/\lambda T) - 1)^{-1} \tag{2}$$

The term ϵ_λ is called the emissivity and is defined as the ratio of what a real body emits at a given temperature to what a black body emits at that temperature (i.e. $\epsilon_\lambda = < 1$). In general emissivities of real bodies are functions of wavelength, temperature and surface condition. For fast measurements, though, the emissivity can be considered to be a function only of wavelength. The
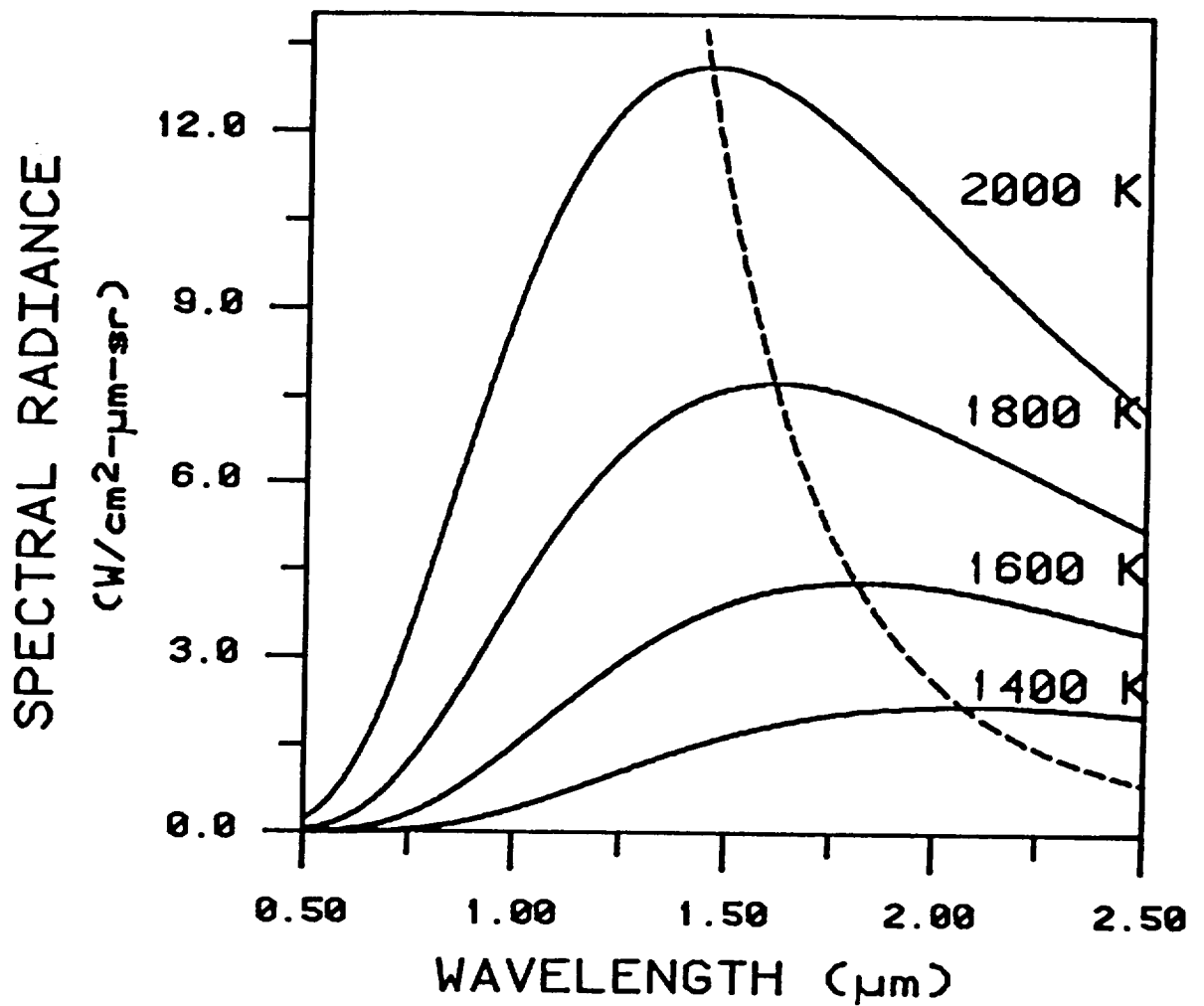
Figure 1 - Spectral radiance curves at different temperatures, as
predicted by the Planck radiation law.

emissivity of these bodies can easily vary by 10% over fairly small wavelength ranges. Therefore, any pyrometer that does not take emissivity changes into account can produce significant errors. Additionally because emissivity is rarely known for a given set of circumstances it must be either measured or calculated separately if an accurate temperature determination is to be made.

STATE OF THE ART

The most sophisticated technique of noncontact temperature measurement available today is Ratio or two-color pyrometry [1]. This method uses an approximation of the Planck relation called the Wien radiation relation:

$$N_\lambda = \epsilon_\lambda C_1 \lambda^{-5} \exp(-C_2/\lambda T) \tag{3}$$

The Wien relation can be solved for temperatures at two different wavelengths to give:

$$T = C_2 \frac{(\lambda_2 - \lambda_1)}{\lambda_1 \lambda_2 \{5\ln(\lambda_2/\lambda_1) - \ln(N_1/N_2) + \ln(\epsilon_1/\epsilon_2)\}} \tag{4}$$

If the wavelengths λ_1 and λ_2 are chosen such that gray body behavior can be assumed (i.e. $\epsilon_1 = \epsilon_2$) then the emissivity term drops out and the temperature measurement is straight-forward. The assumption of gray body behavior becomes more valid as $\Delta\lambda = (\lambda_1 - \lambda_2) \to 0$ but as $\Delta\lambda \to 0$ any errors in the radiance measurements become more significant. Increasing the separation of the wavelengths reduces the effects of radiance measurement errors but the gray body assumption becomes less valid.

References [1-3] provide a thorough analysis of the errors associated with this technique.

MULTIWAVELENGTH THEORY

To increase the accuracy of the temperature measurement farther, the emissivity must be modeled better. This can be achieved by measuring the spectral radiance at a larger (>2) number of wavelengths. The term multiwavelength pyrometry refers to a set of techniques that measure radiance at n different wavelengths and then fit this data to a model that has m undetermined parameters (m<n), to calculate both the temperature and the emissivity simultaneously. The fitting model consists of the modified Planck function (Eq. 2) with a relation containing the m-1 undetermined parameters for the emissivity. The primary strength of multiwavelength pyrometry is that it makes only one assumption about the emissivity, namely, that the spectral emissivity has a smooth first derivative.

There are three solution techniques that fall under the heading of multiwavelength pyrometry, namely, interpolation based, linear least squares (LLS) and nonlinear least squares. Due to the limited nature of this communication we shall limit our discussion to the LLS technique. For a more detailed account of all these techniques see [2,3].

LLS imposes one further limitation on the emissivity model function i.e. that it must be linear in the undetermined parameters. Additionally we are restricted to using Wiens approximation (eq. 3) rather than Plancks law.

The LLS method works by minimizing the error between a model function and the measured data. The model function contains m undetermined parameters which are assumed to have achieved their true value at this minimum. If the model function is linear with respect to the undetermined parameters, the LLS method will yield an analytical solution (it cannot be used if the model function is nonlinear in these parameters). In matrix notation we describe the technique as the problem of minimizing ρ, when

$$\rho = \| A X - B \|. \tag{6}$$

Here B is an n-dimensional vector containing the measured data, X is an m dimensional vector containing the undetermined parameters and A is an n x m coefficient matrix . The symbol $\|C\|$ refers to the square root of the sum of the squares of the terms of C and is called the 2-norm of C.

Khan [3] has shown that the relative error in the parameter estimation is limited by the following relation

Relative Error < K * (relative random noise in the data) (7)

This equation says that *the error or the uncertainty in the calculation of the undetermined parameters is always less than some multiple of the perturbation of the radiance data due to the measuring instrument.* The perturbations of the radiance data can be either systematic or random in nature. The systematic variations can be caused by systematic nonlinearities in the measuring radiometer and/or by an incorrect calibration of the radiometer. These variations are not too troublesome if they are not too large, as would be the case for any reasonably designed radiometer. The random variations introduced into the radiance data due to random variations or electrical noise in the radiometer, however, are more troublesome. These appear as an uncertainty in the estimated values of the parameters after being amplified by some factor 'K', i.e. a 1% random variation in the radiance data would appear as a K% uncertainty (error) in the parameter solution.

K is a function of the wavelength range and the specific function chosen to model the emissivity. For example K is approximately equal to 7 for a constant emissivity and about 130 for a linear exponential emissivity.

COMPUTER SIMULATIONS

A computer model was developed to test the ability of the aforementioned techniques to predict temperatures, emissivities and the associated errors. The following flow chart describes the simulation procedure.
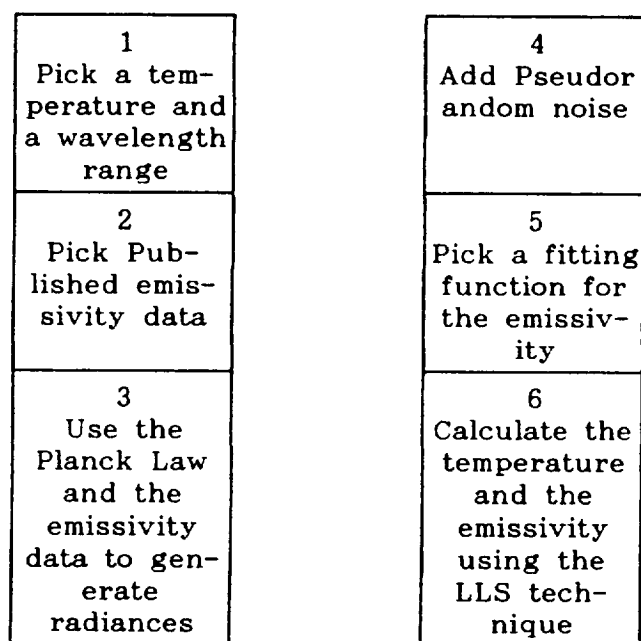
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1 Pick a tem- perature and a wavelength range	4 Add Pseudor andom noise
2 Pick Pub- lished emis- sivity data	5 Pick a fitting function for the emissiv- ity
3 Use the Planck Law and the emissivity data to gen- erate radiances	6 Calculate the temperature and the emissivity using the LLS tech- nique

Figure 2 - Flowchart describing the simulation procedure

Figure 3 depicts some of the emissivity data (curve fit to cubic polynomials) used for these simulations. The data were extracted from the literature [4,5]. Figure 4 presents the results of some of the simulations for Iron, Platinum and Molybdenum at 1600 K and for two noise levels. The figure shows that the theory is indeed capable of predicting the error in the parameter estimation. Although at the higher noise levels the theoretical predictions are very conservative.

A large number of these simulations were performed for different materials and at various temperatures and noise levels.

EXPERIMENTAL VERIFICATION

The instrument constructed to test the theory presented here, (known as the MITTMA) consists of a personal computer and a commercial spectrograph that is portable and is about the size and weight of a video camera. This system was configured to measure radiances at 135 wavelengths simultaneously. These radiance data were calibrated for detector and optics variations using a Black Body Radiance source and then passed to the temperature calculation routines.

The minimum temperature accurately (within 1%) measurable using the MITTMA in its present configuration is around 1200 K. This lower limit is imposed by the detector sensitivity. At present the system uses silicon photodiodes which are useful in the .5 to 1.1 micron wavelength range. The low temperature limit could be easily extended by going to a detector which is sensitive further out into the infrared spectrum, such as InSb.

Table 1 lists the results of some of the experiments performed using the MITTMA. As can be seen from the data in table 1, these techniques can measure temperatures with an accuracy similar to that of thermocouples if a sufficiently noise free signal is available.
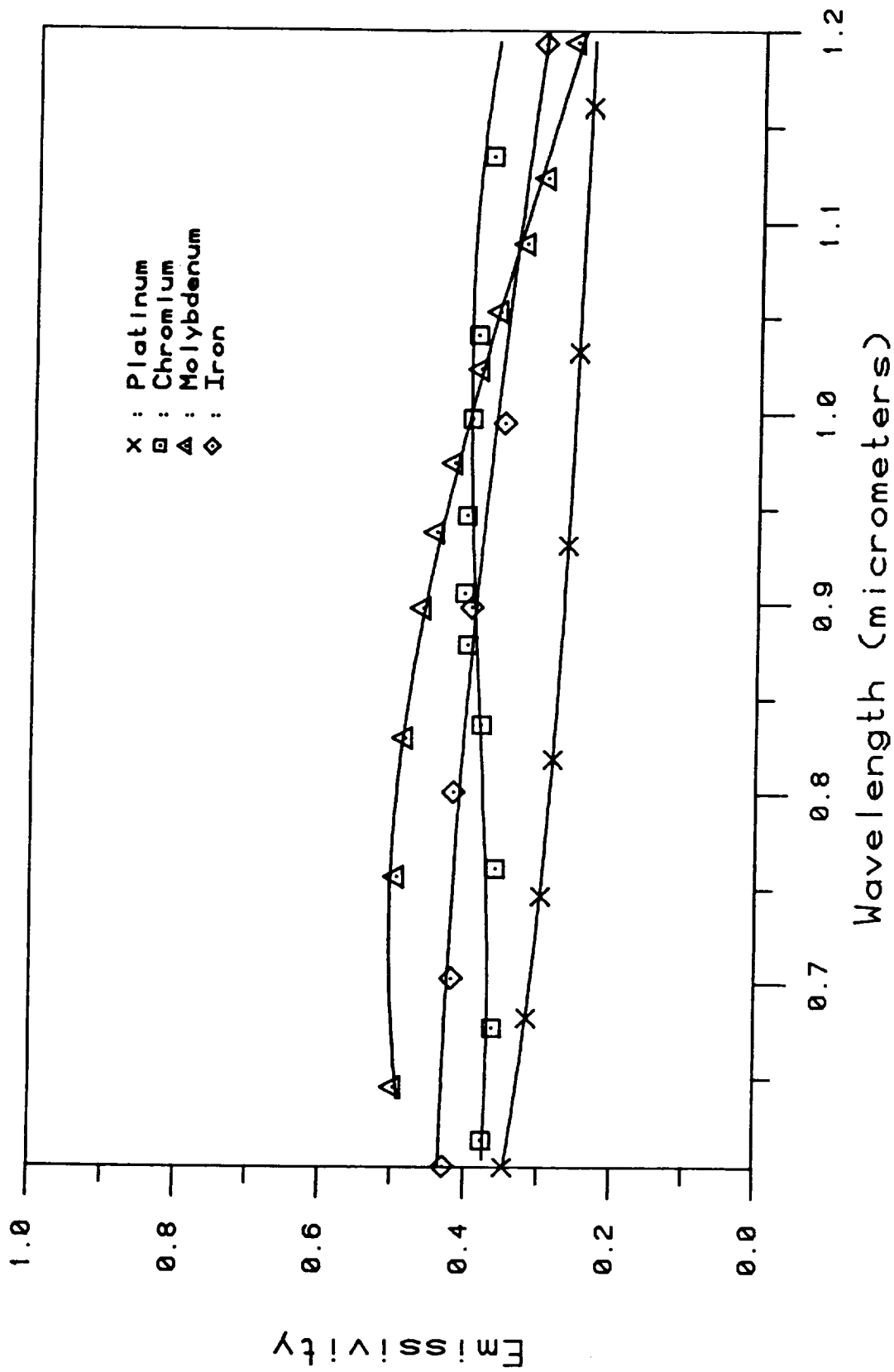
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Figure 3 — Emissivity data from the literature and the approximat-
ing polynomials.

X : Platinum
□ : Chromium
△ : Molybdenum
◇ : Iron
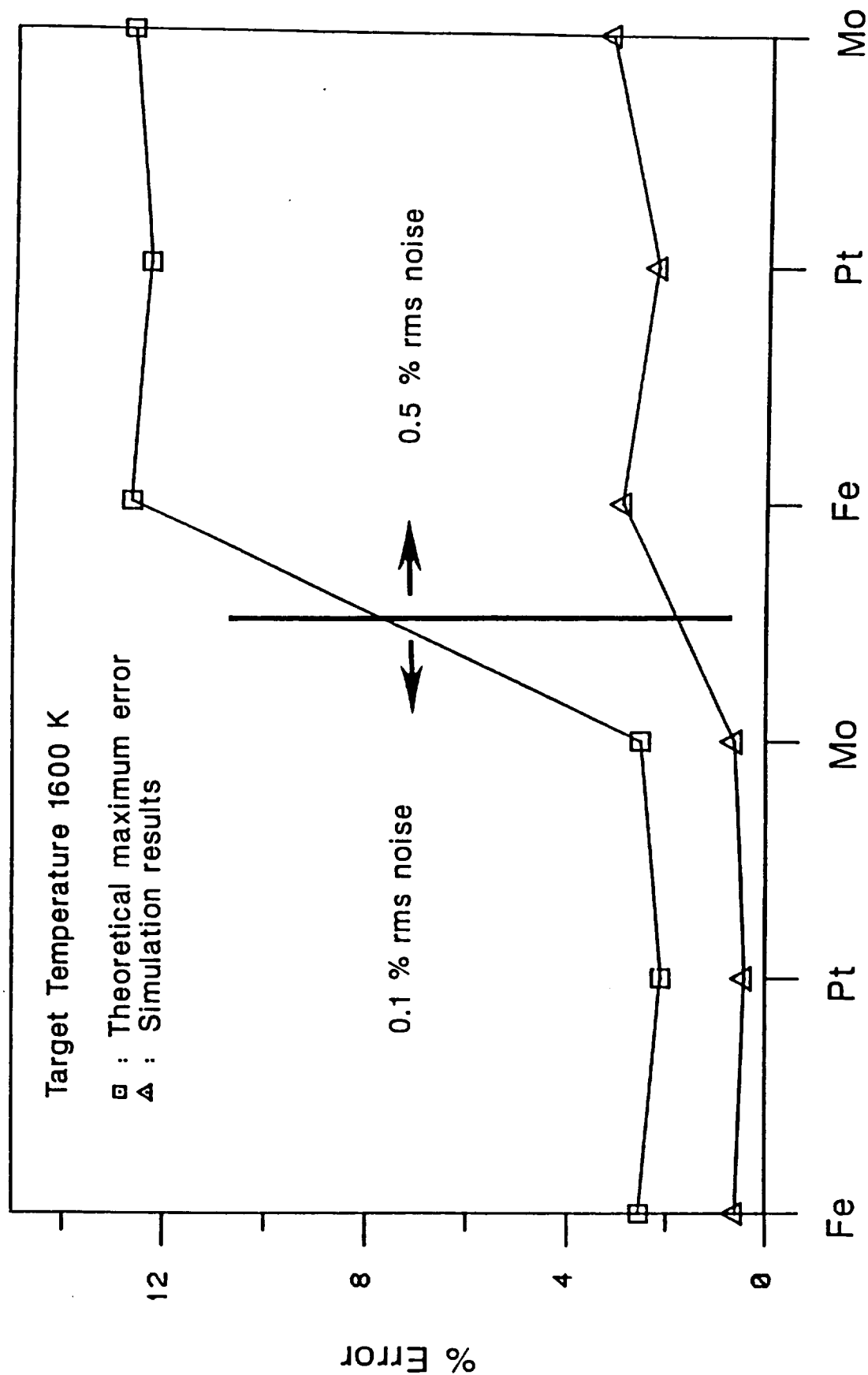
Wavelength (micrometers)

Emissivity

Figure 4 – Simulation results for Iron, Platinum and Molybdenum at 1600 K. This figure shows the effect of an increase in the measurement noise (from 0.1% to 0.5% rms) on the uncertainty in the parameter estimation.

Source	Thermocouple Temperature (K)	MITTMA Temperature (K)	% Difference
Tungsten Strip	2625	2617	0.3
Black Body with Filter A	1234	1241	0.6
Black Body with Filter B	1233	1251	1.5
Platinum Strip	1255	1251	0.32
Platinum Strip	1121	1155	3.0
Platinum Strip	913	970	6.24

Table 1. Results of the experiments on different sources.

In order to simulate the effects of a changing emissivity at a constant temperature the temperature of a black body, viewed through different filters, was measured. The results of two of these experiments are presented in table 1.The two filters used are identified here as A and B and their transmissivities are shown in figure 5. This filter combination can be thought of as simulating the effects of oxidation of a surface, where the material goes from having a shiny, low emissivity surface (filter B) to a dark high emissivity surface (filter A). It should be pointed out here that filter B gives worse results because the shape of its transmissivity curve somewhat resembles that of the Planck curve thereby causing the curve fitting techniques to become confused between the effects of temperature and emissivity. This phenomenon is referred to as 'correlation' and is discussed in detail by Khan [3]. Nonetheless it can be seen from these results that accuracies of better than one percent are achievable using these techniques.

Figure 6 presents a comparison between the theoretical and experimental error in the temperature estimation for the platinum strip source. This figure plots the *percent* difference between the MITTMA predicted temperature and the thermocouple temperature for a number of measurements of this source at a constant temperature versus the measurement number. This figure also plots the theoretically predicted error (eq. 7) versus the measurement number. Again
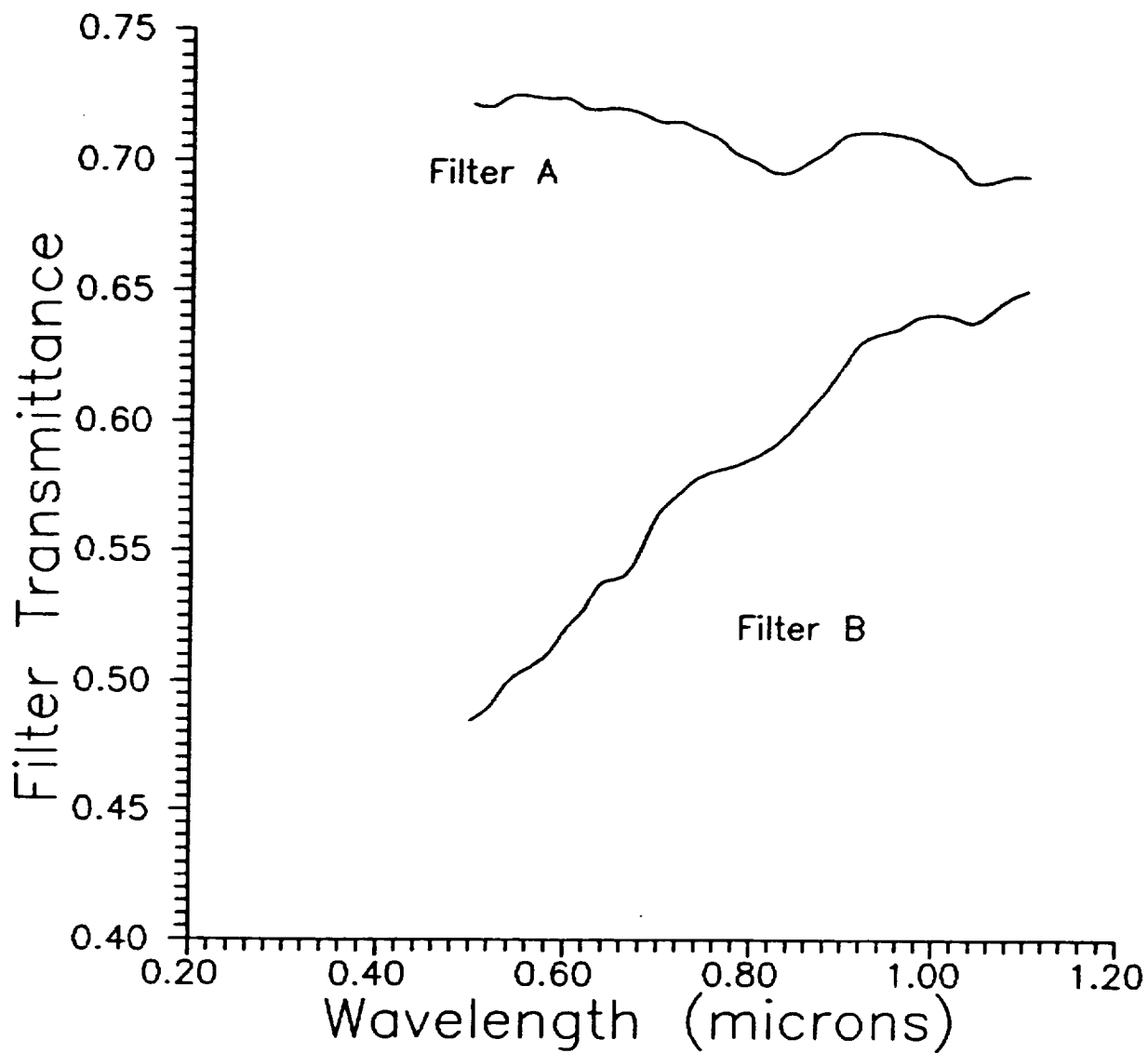
Figure 5 – Transmissivities of the filters used to simulate the effects of oxidation of a surface.
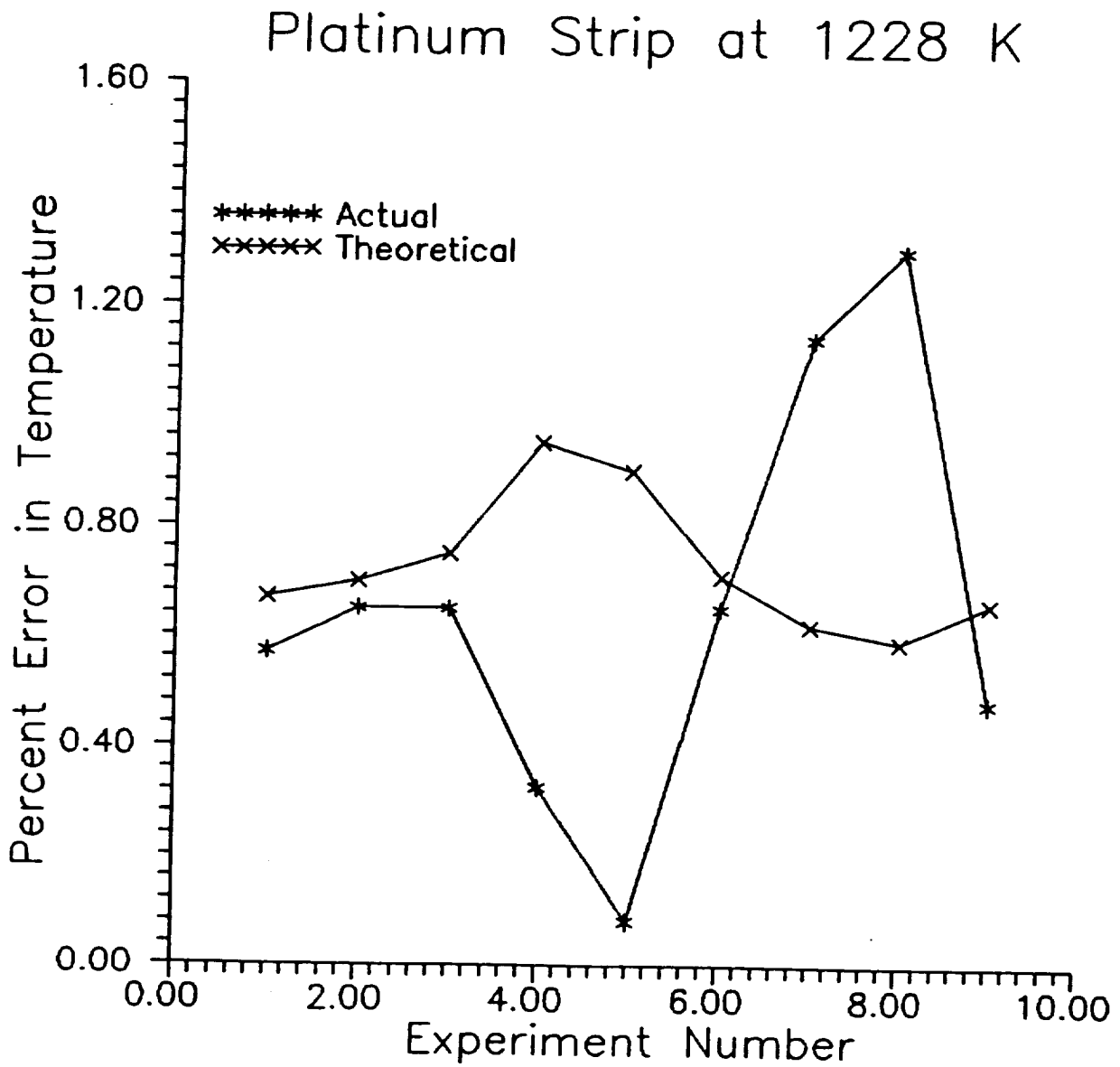
Figure 6 – Comparison of the experimental and theoretically predicted errors in the estimation of temperatures for the platinum strip source.

we find that the MITTMA temperature has an average difference of only .8 percent from the thermocouple temperature and, just as importantly, the error predicted by equation 7 is also about .7 percent. We therefore have reliable a method of estimating the accuracy of our temperature calculations.

The multiwavelength techniques presented here and in [3] have the additional advantage that they can be used to calculate the emissivity of the surface as well as the temperature from the same set of measurements. Figure 7 presents the results of four of these calculations for the platinum data of figure 6. Specifically these emissivity vs. wavelength curves correspond to measurements number 4, 5, 6 and 8 with errors of +4, -1, -8 and -16 K respectively. Due to the nature of these techniques it can be shown [3] that the relative error in the emissivity estimation is much greater than the relative error in temperature estimation for a given set of data. Figure 8 bears out this observation in that the variation from measurement to measurement is high as fifty percent and it is extremely unlikely that the emissivity actually changed by fifty percent during these measurements. Nonetheless if the techniques really are performing as well as is claimed here then one would expect that the real emissivity of platinum would lie somewhere between the two emissivity curves corresponding to the -1 and +4 K errors. An examination of the published emissivity data [5] for clean platinum strip shows that this is indeed true to within the accuracy of that data.

CONCLUSIONS

The theory developed here has been shown to be capable of calculating true temperatures of any material from radiance measurements at a number of different wavelengths. This theory has also been shown to be capable of predicting the uncertainty in these calculated temperatures.

An additional advantage of these techniques is that they can estimate the emissivity of the target simultaneously with the temperature. This aspect can prove to be very important when a fast method of generating reflectivity vs. wavelength or emissivity vs. wavelength data is required. It is presently both difficult and time consuming to generate such data.

Experiments performed on various materials over a range of temperatures and experimental conditions have been used to verify the accuracy of this theory.

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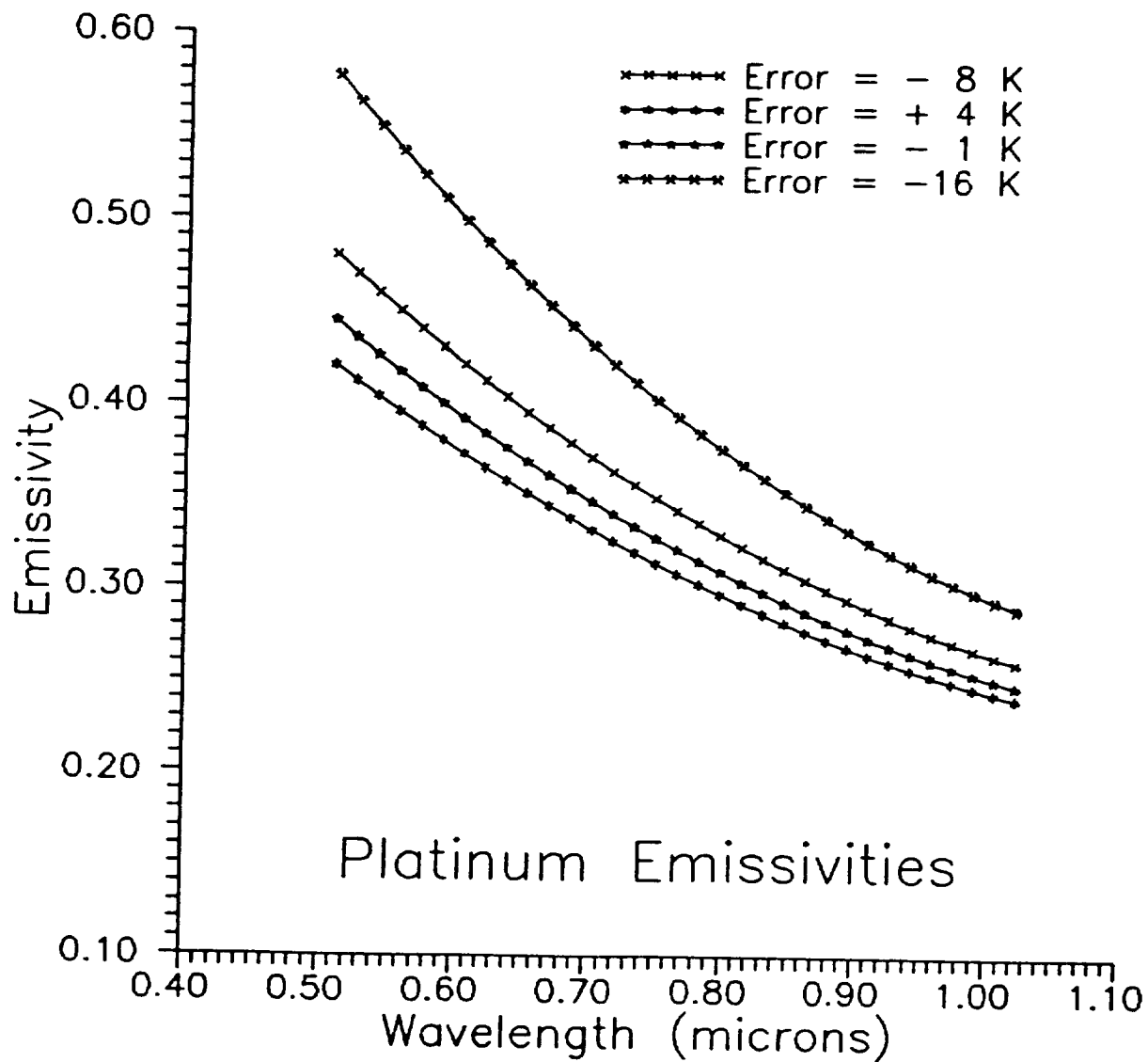
Figure 7 - Calculated spectral emissivities for platinum. The four curves correspond to four separate measurements and therefore to four distinct temperature errors. The true emissivity of platinum would lie between the curves corresponding to the -1 and +4 K errors.