High Accuracy Multi-color Pyrometry for High Temperature Surfaces

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An evaluation of previously proposed least-squares multi-color pyrometry methods was carried out to determine their highest achievable accuracy. The study was limited to the visible spectrum and the temperature range of 1700 to 3000 K, typical of electrode surfaces in high-power electric propulsion thrusters. A Monte-Carlo simulation of the various methods showed the effects that the number of colors of the pyrometer, the errors associated with noise and calibration, and the number of measurements have on the uncertainty of the predicted temperature. Some of these methods were found to lead to inaccurate results, an underestimate of the uncertainty of the predicted temperature, or yield larger uncertainties than single-color pyrometry. The two methods that were found to yield the highest accuracy without underestimating the uncertainty are based on fitting the intensity versus wavelength data with three free parameters (temperature and the two coefficients of the emissivity versus wavelength model). Adding complementary measurements, at the price of spatial or temporal resolution, is shown to allow a reduction of the uncertainty in the predicted temperature well below that associated with single-color pyrometry.

I. INTRODUCTION

The intent of least-squares multi-color pyrometry (LSMCP) is to accurately determine the temperature of a heated surface that has an unknown emissivity. Emissivity is a material property that is sensitive to roughness, oxidation, contamination, radiation wavelength, and the angle of observation; factors that are difficult to determine accurately for a given surface *a priori*. The electrodes of high-power electric propulsion thrusters, especially lithium Lorentz force accelerators, are often oxidized or contaminated by propellant, making LSMCP an ideal diagnostic of their surface temperature. The intensity of thermal radiation is measured at discrete, multiple wavelengths to determine the intensity as a function of wavelength. The intensity data are fit to an appropriate radiation intensity model, Planck's law or Wien's approximation, and to an emissivity model to determine the temperature and emissivity. LSMCP reduces the uncertainty in the predicted temperature by measuring the intensity more times than there are free parameters in the intensity and emissivity models.

A. Review of Previous Research

During the past two and a half decades researchers have proposed a variety of methods capable of determining temperature with the use of least-squares multi-color pyrometry, yet there is no consensus on which methods are the most accurate. In 1979 LSMCP was first utilized in a three-color pyrometer that determined the temperature of a flame assumed to have constant emissivity [1]. The first analysis assuming a non-constant emissivity was a computer simulation of a six-color pyrometer [2]. It was developed to compare the temperature determination accuracy of both linear and nonlinear least-squares fitting routines. Two emissivity models were used in the simulation, the first assumes the emissivity has a linear dependence on wavelength (6) while the second assumes the same for the natural logarithm of the emissivity (7). The analysis determined that the predicted temperature was less than 3% from the true temperature when measuring intensity in the infrared spectrum. Using the methods in that analysis, an experimental six-color pyrometer determined the temperature of many metallic surfaces [3]. The metals that gave satisfactory results, less than 3% deviation from the true temperature, had a linear variation of emissivity with wavelength throughout the visible and infrared spectra. These initial papers demonstrated that LSMCP can determine the temperature of many surfaces and proposed the emissivity models and fitting routines evaluated in this paper.

Various methods that fit the intensity data to Wien's approximation were later developed with the goal of reducing the uncertainty of the predicted temperature. Modelling the natural logarithm of the emissivity as a line or polynomial, the relations between intensity measurements, temperature, and emissivity can be algebraically manipulated into many forms [4, 5]. Simulations and experimental pyrometers determined the temperature of many surfaces using those methods.

The most recently developed method assumes the radiance temperature to be a linear function of wavelength [6]. The constant term of the line fit is interpreted as the true temperature.

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In references [7, 8] a Monte-Carlo simulation studied the effects of noise in the intensity data on two different temperature determination methods. One hundred simulations of the intensity measurements, with a 2% uniformly distributed random error added to the intensity, demonstrated that temperatures would be predicted with a reasonably small deviation from the true temperature.

B. Motivation and Structure

Two primary obstacles still exist in developing pyrometers for experimental use. First, since no comparative evaluation of the temperature determination methods has been published, there is no standard method in the field of multi-color pyrometry. Second, the effects of errors associated with noise and calibration on the predicted temperature uncertainty have not been clearly demonstrated to guarantee a required accuracy from a multi-color pyrometer.

After a brief review of pyrometric relations in Section II, we will compare the various proposed temperature determination methods in an effort to determine which methods are redundant or consistently produce a large deviation in predicted the temperature from the true temperature. A disparity in the uncertainties in the temperature determined by each method motivated our investigation of the dependence of the uncertainty on the errors associated with noise and calibration via a Monte-Carlo simulation, discussed in Section IV. The goals are to show that the uncertainty in each predicted temperature agrees with the range of temperatures in the Monte-Carlo simulation, that the true temperature of the surface lies within the predicted error bars, and which methods yield the smallest uncertainty in the predicted temperature. In many cases the resulting uncertainty could be larger than that of single-color pyrometry. A method based on adding complementary measurements to reduce the uncertainty in predicted temperature below that of single-color pyrometry is presented in Section V.

II. FUNDAMENTAL RELATIONS

Pyrometry is based on the fact that all surfaces at temperatures above absolute zero emit thermal radiation. Planck's radiation law, modified to include surface emissivity, is the fundamental relation of thermal radiation:

$$u(\lambda,T)=\epsilon_\lambda\frac{C_1}{\lambda^5}\left(\frac{1}{e^{\frac{C_2}{T\lambda}}-1}\right) \tag{1}$$

where u is the intensity, ϵ_λ is the emissivity as a function of wavelength, $C_1 = 1.191\times10^{16}$ W nm^4/cm^2 Sr and $C_2 = 1.4384\times10^7$ nm K are the first and second radiation constants, T is the absolute temperature in Kelvin, and λ is the wavelength of the radiation in nm. With knowledge of the emissivity, the temperature of any surface can be determined by fitting the intensities measured at various wavelengths to the above relation.

Wien's approximation to Planck's law,

$$u(\lambda,T)=\epsilon_\lambda\frac{C_1}{\lambda^5}e^{\frac{-C_2}{T\lambda}}, \tag{2}$$

and the appropriate choice of ϵ_λ allows approximating Planck's law as a linear relation in wavelength. Within the visible spectrum and temperatures less than 3200 K the temperature determined from the approximation will deviate by less than 0.025% from Planck's law. The common form used in pyrometry is

$$\frac{-C_2}{T_r\lambda}=\ln\epsilon_\lambda-\frac{C_2}{T\lambda}, \tag{3}$$

where T_r is called the radiance or brightness temperature and is defined as the temperature determined from the intensity assuming an emissivity of unity

$$\frac{1}{T_r}=\frac{-\lambda}{C_2}\ln\frac{u\lambda^5}{C_1}. \tag{4}$$

The emissivity dependence on wavelength can be expressed in many forms, but we will consider those that fit experimental measurements or simplify the analysis. Most surfaces have an emissivity that varies with wavelength and temperature, but we ignore the temperature dependence based on the assumption that each observed location is at the same temperature. The emissivity of metallic surfaces in the visible and near-infrared wavelengths often exhibit a polynomial dependence on wavelength

$$\epsilon_\lambda=c_1+c_2\lambda+...+c_n\lambda^n. \tag{5}$$

This emissivity dependence can also be interpreted as a Taylor expansion of the emissivity for a narrow range of wavelengths. The number of terms in the expansion is chosen by comparing the increase in uncertainty caused by having more free parameters to the systematic error induced by using a less accurate model. We consider two forms, the linear dependence of emissivity on wavelength,

$$\epsilon_\lambda=a+b\lambda, \tag{6}$$

and the linear dependence of the natural logarithm of emissivity on wavelength,

$$\ln\epsilon_\lambda=a'+b'\lambda. \tag{7}$$

Two factors must be considered when choosing between the two emissivity models, 1) which model best represents the emissivity as a function of wavelength for the heated surface and 2) if the possible reduction in the uncertainty in the predicted temperature yielded by the linear fitting methods, as shown in section IV, is more important than the first factor.

In order to limit the uncertainty in the predicted temperature, the emissivity models are limited to two terms. An analysis in reference [9] determined that emissivity models for six-color pyrometers should not contain more than two free parameters. We have used this guideline for pyrometers of four to ten colors.

III. METHOD COMPARISON

A comparison of the ability of the various methods to accurately determine temperature is shown here with the goal of determining which methods are redundant or produce a large deviation between the true and predicted temperatures. LSMCP methods are differentiated by the relation used in the fitting routine and whether the routine is linear or nonlinear least-squares. The linear least-squares fitting routines lead to analytical solutions while the nonlinear fit require an initial guess and many iterations and is thus more computationally intensive. The results of seven types of pyrometry (ratio pyrometry, single-color pyrometry, and five LSMCP methods) are compared. The LSMCP relations are listed here:

- Linear two-term temperature fitting method [4]:

$$\frac{(1/\lambda_n T_{r_n}) - (1/\lambda_m T_{r_m})}{\lambda_m - \lambda_n} = \frac{1}{T}\frac{1}{\lambda_m \lambda_n} + \frac{b'}{C_2}. \quad (8)$$

- Linear two-term emissivity fitting method [5]:

$$\frac{1/T_{r_n} - 1/T_{r_m}}{\lambda_m - \lambda_n} = \frac{a'}{C_2} + \frac{b'\left(\lambda_m + \lambda_n\right)}{C_2} \quad (9)$$

- Linear three-term fitting method [5]:

$$-\frac{1}{T_{r_n}} = -\frac{1}{T_0} + \frac{a'\lambda_n}{C_2} + \frac{b'{\lambda_n}^2}{C_2} \quad (10)$$

- Radiance temperature fitting [6]:

$$T_{r_n} = T_0 + g\lambda_n \quad (11)$$

- Non-linear fitting method [3]:

$$u(\lambda, T) = (a + b\lambda)\frac{C_1}{\lambda^5}\left(\frac{1}{e^{\frac{C_2}{T\lambda}} - 1}\right) \quad (12)$$

Ratio pyrometry assumes a constant emissivity, which results in an analytical temperature determination

$$T = \frac{1 - \lambda_1/\lambda_2}{\frac{1}{T_{r_1}} - \frac{\lambda_1/\lambda_2}{T_{r_2}}}. \quad (13)$$

This method is often used with intensity measurements made at wavelengths within a few percent of each other. Ratio pyrometry is included in this study to determine its accuracy when measuring intensity over a wide range of the visible spectrum.

A. Discussion

An appropriate procedure to determine the accuracy of each method would be to measure the thermal radiation of many calibrated surfaces and compare the departure of the temperature predicted by each method from the known temperature. Unfortunately, only refractory metals (tantalum, molybdenum, rhenium, and tungsten) are in the solid state over the range of temperatures used in this study; and of those only tungsten lamps have been calibrated for pyrometric studies. In order to consider various surfaces, we simulated the intensity radiating from refractory metals using Planck's law and emissivity values found in reference [10]. The extent of the existing data limits the possible number of different simulations to 12. In order for the fitting routines to determine an appropriate uncertainty in the predicted temperature there must be an uncertainty associated with the simulated intensity data; we assumed 3%. The resulting deviation of the predicted temperature and its uncertainty (both expressed as percent of the true temperature) are shown in Table I, where each column number corresponds to one of the seven methods discussed below.

1. Single-color pyrometry (Method 1)

Single-color pyrometry, with an assumed emissivity of 0.45, predicted the temperature to within 1% of the actual temperature in eleven of the twelve cases. Published values of emissivity in the visible spectrum for refractory metals lie between 0.3 and 0.7, providing bounds to determine the uncertainty in temperature. The uncertainty was calculated to be between 4% and 7% in all cases. However, any oxidation or surface contamination could effect the emissivity to a greater degree and thus increase the uncertainty.

2. Ratio pyrometry (Method 2)

The temperature predicted by Ratio pyrometry gave a relatively large deviation from the true temperature, yielding the worst results of all methods in ten of the cases. The assumption of constant emissivity across the visible spectrum is thus unjustifiable.

3. Linear fitting methods (Methods 3,4 & 5)

The three linear fitting methods yield temperature predictions to within 0.1% of each other. Because the relations in the two-term fitting methods are reformulations of the relation in linear three-term method, we expected the predictions to be similar. The only difference between the predictions of the methods is the uncertainty they assign to the temperature. Fitting only two of the three terms in the radiation model reduces the uncertainty in the fit because the least-squares routine fits four data points to a two-parameter model, when three parameters exist. The linear two-term temperature fitting method (Method 3) gives the smallest uncertainty because the temperature is directly determined from the two-term fit.

The linear two-term emissivity fitting method (Method 4) has a larger uncertainty because both terms of the emissivity model are fit and the error in the fit is propagated to the temperature. The linear three-term fitting method (Method 5) fits all radiation model parameters directly and thus leads to a higher uncertainty. Each method is equally valid for determining the temperature in cases where the uncertainty is not underestimated by eliminating terms from the fit; however, we will show in section IV that the uncertainty is often under-predicted.

4. *Nonlinear fitting method (Method 6)*

The non-linear fitting method has the least deviation of predicted temperature from the true value for six of the cases and is within 0.1% of the best prediction of temperature in three more cases. This method is well suited to determining the temperature of refractory metal surfaces.

5. *Radiance temperature fitting (Method 7)*

The radiance temperature fitting method produces the largest or second largest deviation in nine of the cases, and in many of those cases the deviations are two to three times larger than the lowest values obtained. Also, the uncertainty is less than the deviation in five cases, implying that the relative accuracy is not satisfactory.

B. Recommendations

We compared the performance of six multi-color pyrometry techniques and found that the one nonlinear method and the three linear ones determine the smallest deviation from the true temperature with a reasonable uncertainty. The radiance temperature fitting method and ratio pyrometry do not accurately predict the temperature. One must be cautious when using the linear two-term fitting routines because the uncertainty could be under-predicted, as discussed in the next section.

IV. EFFECT OF ERRORS ASSOCIATED WITH NOISE AND CALIBRATION

The LSMCP methods that were shown to perform well in the previous section were further analyzed to determine the effect of errors associated with noise and calibration on the predicted temperature uncertainty. We used a Monte-Carlo simulation to determine the range of temperatures and uncertainties to be expected from the LSMCP methods when the intensity measurements are subject to random noise. The deviation in the simulated intensity from the nominal value was limited to the magnitude of the errors associated with noise and

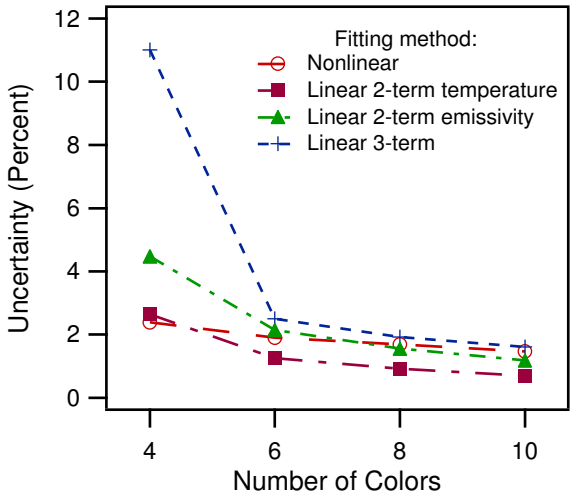


FIG. 1: The predicted temperature uncertainty of four LSMCP methods subject to 1% error associated with noise and calibration.

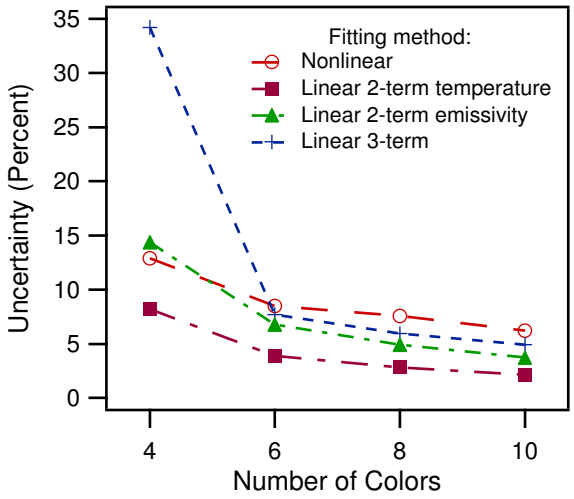


FIG. 2: The predicted temperature uncertainty of four LSMCP methods subject to 3% error associated with noise and calibration.

calibration; chosen to be 1%, 3% or 5%. (The standard deviation was 60% of the error.) We determined that the predicted temperatures and uncertainties of the Monte-Carlo simulation change by less than 2% when more than 1000 cases are included, thus we used 1000 cases throughout the analysis.

A Monte-Carlo analysis was conducted for each combination of 4, 6, 8, and 10 color pyrometers and for noise and calibration errors of 1%, 3%, and 5%. The intensity of the radiation from a 2700 K surface was calculated using Planck's law (1) with the artificial emissivity model

$$\epsilon_\lambda = 0.5 - 0.0001\lambda. \tag{14}$$

The values of the coefficients were chosen to be similar to those determined experimentally for many metal-

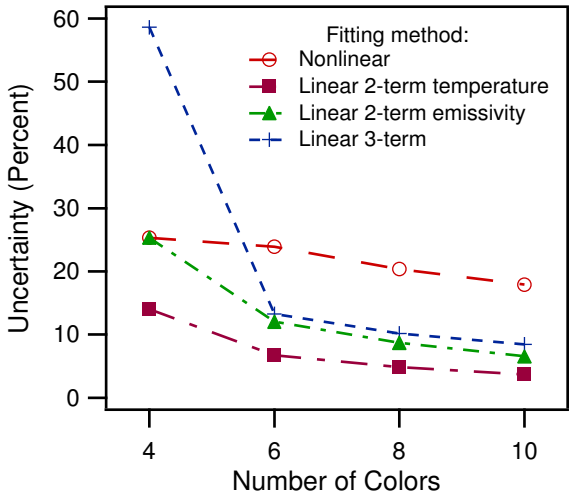


FIG. 3: The predicted temperature uncertainty of four LSMCP methods subject to 5% error associated with noise and calibration.

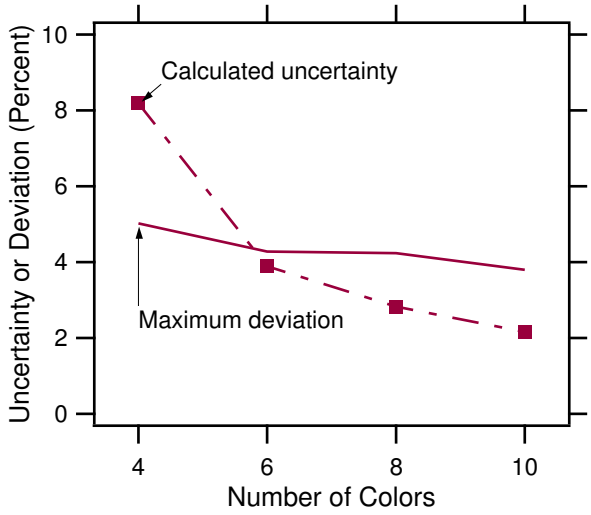


FIG. 4: Demonstration of the under-predicted uncertainty of the linear 2-term temperature fitting method.

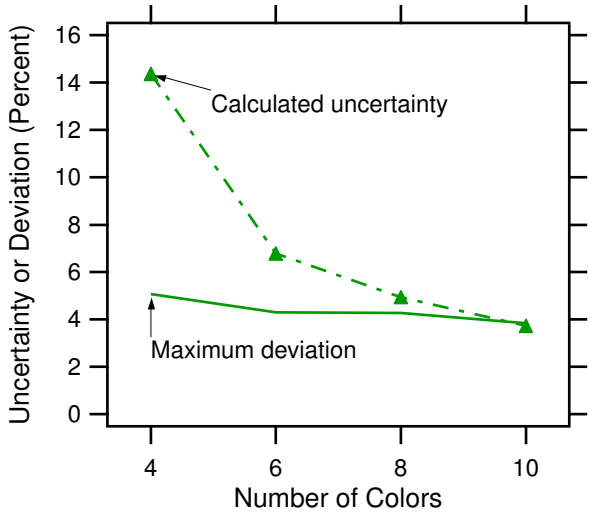


FIG. 5: Demonstration of a under-predicted uncertainty of the linear 2-term emissivity fitting method.

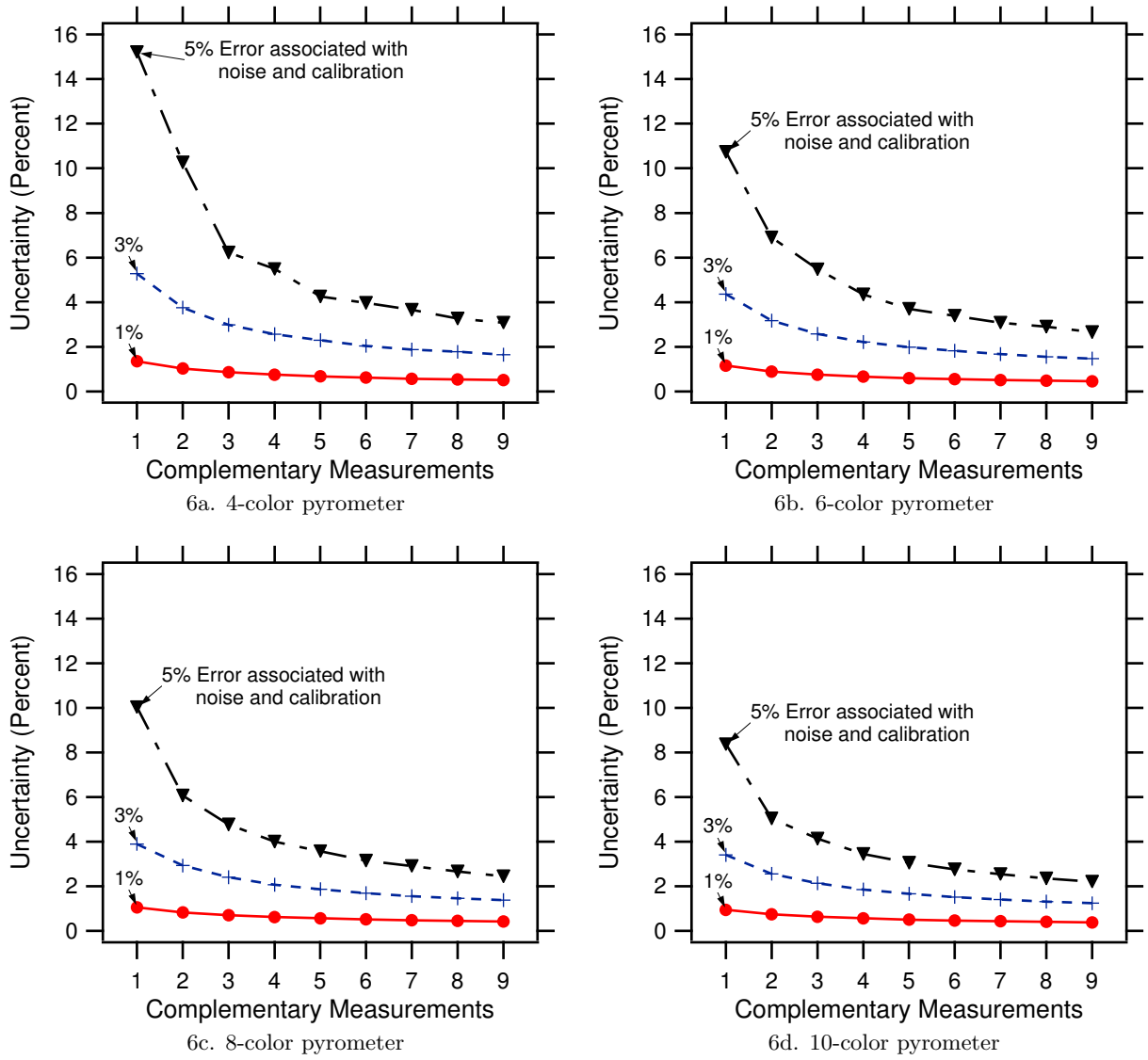
lic surfaces to ensure that the results of the simulations are applicable to the temperature measurement of metal surfaces.

A. Discussion

The dependence of the uncertainty of the predicted temperature on the number of colors of the pyrometer is presented for each fitting method in FIGS. 1, 2, and 3; where the plots show the uncertainty resulting from errors associated with noise and calibration of 1%, 3%, and 5%, respectively. For pyrometers of greater than four colors and errors of 1% or 3%, both the linear three-term and nonlinear methods have similar uncertainties in the predicted temperature. 5% errors associated with noise and calibration cause the nonlinear fitting method to predict large uncertainties in temperature, shown in FIG. 3. The linear two-term fitting methods yield smaller uncertainties than that of the linear three-term method in all cases, with the two-term temperature fitting method being the smallest.

With the exception of the four-color pyrometer, a general comparison of the uncertainty in the predicted temperature of the LSMCP methods and that of single-color pyrometry can be made. FIG. 1 shows that a 1% error associated with noise and calibration generally results in an uncertainty in predicted temperature of less than 2%, while a single-color pyrometer has approximately a 5% uncertainty for all magnitudes of error. The uncertainty in temperature determined by the LSMCP methods when there is a 3% and 5% error (FIGS. 2 and 3) is similar to or larger than that of single-color pyrometry. In order to circumvent the difficulties of lowering the noise of the detector and optics below 3% we developed a method of increasing the accuracy through complementary measurements (Section V).

The Monte-Carlo analysis also determined that the uncertainty is under-estimated for both ten-color pyrometers using the two-term emissivity fitting method and greater than four-color pyrometers using the two-term temperature fit. The curves labelled “calculated uncertainty” in FIGS. 4 and 5 represent the uncertainty in the predicted temperature of the two-term fitting methods; the same as in the previous figures. The “maximum deviation” curves represent the magnitude of the maximum deviation of the predicted temperature from the true temperature. If the “calculated uncertainty” curve has a larger value than the “maximum deviation” curve, the method has determined an appropriate uncertainty; i.e. the true temperature will lie within the error bars. As can be seen in FIGS. 4 and 5, the curves cross in-



6a. 4-color pyrometer

6b. 6-color pyrometer

6c. 8-color pyrometer

6d. 10-color pyrometer

FIG. 6: The uncertainty in the predicted temperature as a function of complementary measurements for the nonlinear fitting method.

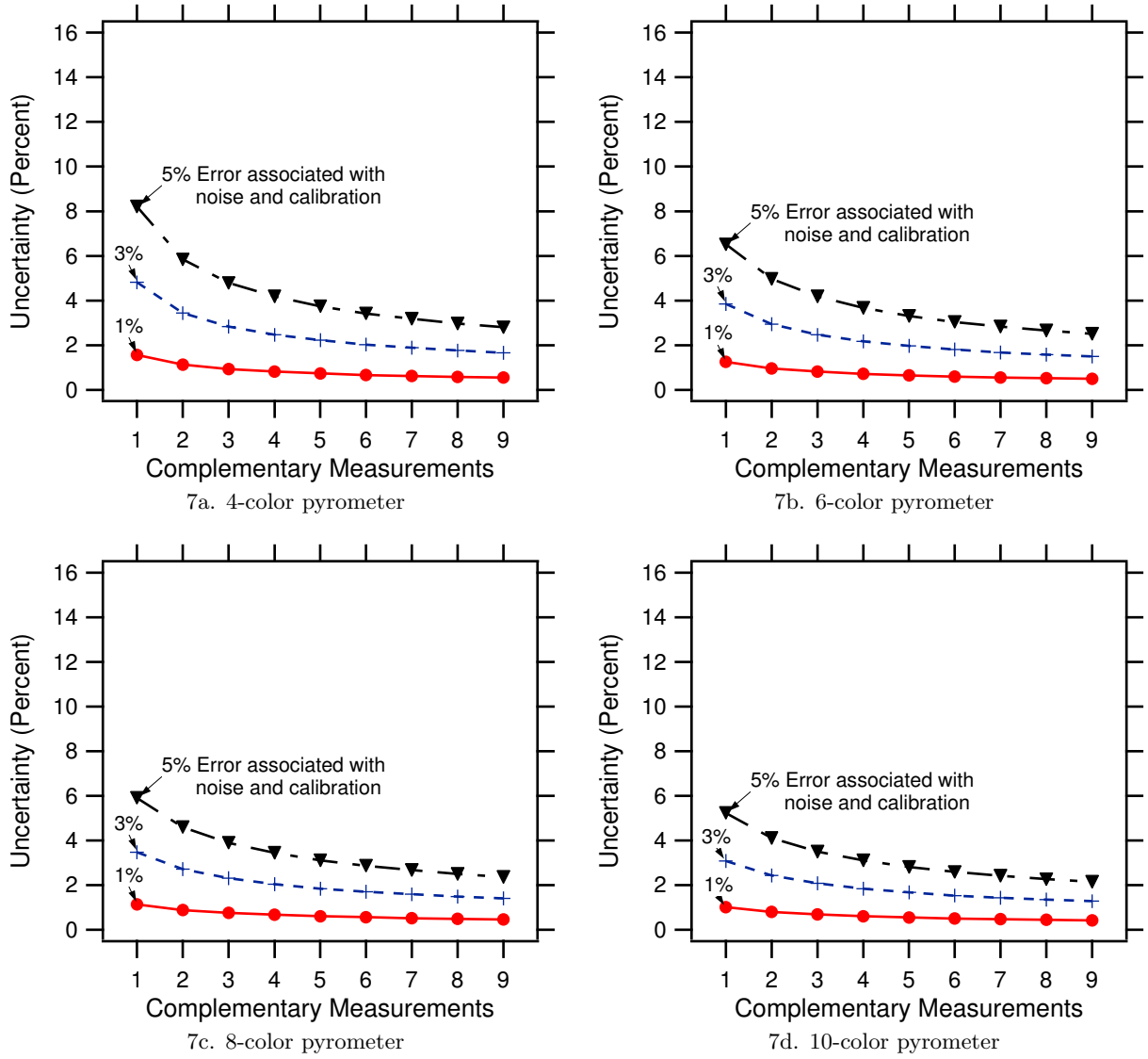
dicating that the methods under-predict the uncertainty. Although only the cases of 3% error associated with noise and calibration are shown, the trends are identical in the other cases.

B. Recommendations

The results of the Monte-Carlo analysis demonstrate that fitting the intensity data using either the linear three-term or nonlinear fitting methods will always predict the appropriate uncertainty in the temperature, but the uncertainty may not be the smallest when compared to that of the linear two-term fits. When the error associated with noise and calibration is less than 5%, the linear three-term and nonlinear fits yield approximately the same uncertainty in the predicted temperature. This allows a method to be selected based solely on the emissivity model that best represents the surface being measured. The two-term temperature fitting method should only be used with 4-color pyrometers, while the linear two-term temperature emissivity fitting method is can be used with 4, 6, and 8-color pyrometers.

V. COMPLEMENTARY MEASUREMENTS

The uncertainties in the predicted temperature found for the linear three-term and nonlinear fitting methods are larger than those of single-color pyrometry when the errors associated with noise and calibration are greater than 1%, making single-color pyrometry more accurate in many cases. A new method for LSMCP, designated complementary measurements, was developed to reduce



7a. 4-color pyrometer

7b. 6-color pyrometer

7c. 8-color pyrometer

7d. 10-color pyrometer

FIG. 7: The uncertainty in the predicted temperature as a function of complementary measurements for the linear three-term fitting method.

the uncertainty below that of single-color pyrometry. We define complementary measurements as additional intensity data measured at each wavelength of the pyrometer. For a pyrometer with a fixed number of colors this implies using adjacent pixels on a CCD array or including measurements taken at successive times.

A Monte-Carlo analysis, similar to that used in section IV, of the linear three-term and nonlinear fitting routines determined the predicted temperature and its uncertainty when complementary measurements are included. The linear two-term fitting methods under-estimate the uncertainty of the predicted temperature in the majority of the cases and thus are ignored. The analysis included one to nine complementary measurements, 1%, 3%, and 5% error associated with noise and uncertainty, and 4, 6, 8, and 10-color pyrometers.

It can be seen in FIGS. 6 and 7 that the uncertainty in the predicted temperature is always less than the 5% associated with single-color pyrometry when the number of complementary measurements is greater than three or four. For example, a four-color pyrometer with a 3% error requires two complementary measurements with the nonlinear fitting method and one complementary measurement with the linear fit. The figures also show that the uncertainty in the predicted temperature asymptotes to the same value for each fitting method and error. This yields the minimum uncertainty attainable by that method given an error associated with noise and calibration.

VI. CONCLUSIONS

We have addressed the obstacles that exist for developing multi-color pyrometers for experimental use by comparing the ability of five LSMCP methods to determine temperature and the uncertainty of that prediction. We showed that:

1. The radiance temperature fitting method does not accurately predict the temperature.
2. The linear two-term temperature fitting method accurately predicts the temperature only with four-color pyrometers.
3. The linear two-term emissivity fitting method accurately predicts the temperature with 4, 6, and 8-color pyrometers.
4. The linear three-term and nonlinear methods accurately predict the temperature with pyrometers of any number of colors.

These conclusions indicate that the linear three-term and nonlinear fitting methods could be considered the standards in LSMCP, with the linear 2-term fitting methods being used only in certain circumstances.

Except when the errors associated with noise and calibration are at or below 1%, single-color pyrometers, with a modest assumption of the range of the emissivity, offer a higher accuracy than LSMCP. The method of complementary measurements was introduced to reduce the uncertainty in the results of LSMCP. This method can be used with linear three-term and nonlinear fitting methods to reduce the uncertainty in the predicted temperature well below that of single-color pyrometers, with the price of reduced temporal or spatial resolution.

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Material & Temperature	Method 1	2	3	4	5	6	7
Tantalum 1700 K	0.7 ±12.6	3.9 ±2.5	-0.6 ±4.1	-0.5 ±6.9	-0.6 ±17.3	0.3 ±2.5	3.0 ±0.9
Tantalum 2200 K	-0.1 ±17.0	4.4 ±3.3	0.5 ±5.4	0.5 ±9.1	0.5 ±22.6	1.0 ±3.6	3.2 ±1.1
Tantalum 2400 K	-0.1 ±18.7	3.7 ±3.4	4.1 ±6.1	4.0 ±10.7	4.1 ±25.6	4.2 ±5.9	2.7 ±1.2
Tantalum 2800 K	-0.2 ±22.2	3.8 ±4.1	1.8 ±7.0	1.8 ±11.9	1.8 ±29.2	1.9 ±5.5	2.4 ±1.4
Molybdenum 2000 K	-0.8 ±14.8	2.1 ±2.9	0.1 ±5.6	-0.0 ±9.5	0.1 ±23.5	0.3 ±4.2	1.4 ±1.0
Molybdenum 2800 K	-2.3 ±22.0	2.3 ±4.2	-2.0 ±6.9	-2.2 ±11.4	-2.0 ±29.0	-1.5 ±4.7	0.7 ±1.3
Rhenium 1810 K	-0.5 ±12.7	0.8 ±2.6	-2.2 ±4.3	-2.1 ±7.1	-2.2 ±18.1	-1.7 ±2.9	0.2 ±0.9
Tungsten 1800 K	-0.0 ±12.8	1.0 ±2.5	0.5 ±4.4	0.5 ±7.4	0.5 ±18.5	0.5 ±3.8	0.6 ±0.9
Tungsten 2000 K	-0.1 ±14.4	1.3 ±2.8	0.4 ±4.9	0.4 ±8.3	0.4 ±20.6	0.4 ±4.1	0.7 ±1.0
Tungsten 2200 K	-0.2 ±16.2	1.5 ±3.1	0.4 ±5.4	0.4 ±9.1	0.4 ±22.6	0.5 ±4.4	0.9 ±1.1
Tungsten 2400 K	-0.2 ±17.9	1.8 ±3.4	0.1 ±5.9	0.1 ±9.9	0.1 ±24.6	0.3 ±4.6	1.0 ±1.2
Tungsten 2900 K	-0.6 ±22.8	3.1 ±4.3	-0.8 ±7.0	-0.9 ±11.7	-0.8 ±29.4	-0.4 ±5.0	1.6 ±1.4

TABLE I: Deviation of predicted temperature from the true temperature and the uncertainty in the predicted temperature for the seven pyrometric methods. (Percent of true temperature)