Journal of Electrical and Electronic Engineering
2026, Vol. 14, No. 2, pp. 99–109
https://doi.org/10.11648/j.jeee.20261402.14

Research Article

Characteristics of Optimal Wavelengths Selection for High Temperature Quadrispectral Pyrometer in Near-infrared Spectral Range for Metals with Non-linear Emissivity

Ratianarivo Paul Ezekel*

Electronic Department, ESP-Antsirabe, Antsirabe, Madagascar

Abstract

This article examines the behavior of the quadri spectral method in the design of a pyrometer applicable to the heat treatment of metals. The quadri spectral pyrometer incorporates four different optical filters that filter the four spectra to be used and converge them towards the four detectors of the device. The light energy from these spectra will be converted by the detectors into a processable electrical signal. The application of the nonlinear model known as Temperature by Nonlinear Model (TNL) will calculate and select these four wavelengths. This method applies inverse calculus, exploiting Planck's relation for thermal radiation by setting the temperature and then determining the wavelengths using ordinary least squares. With this model, the four wavelengths will be selected sequentially by modeling the emissivity of the metal as a second-degree polynomial. The obtained wavelengths will be subjected to various criteria to choose the best groups for a suitable pyrometer intended for high-temperature metal treatment. Those criteria are flux sensitivity to wavelength and temperature, standard deviation at temperature, and the minimum difference between two successive wavelengths. The various tests against the criteria, given the non-linearity of the emissivity of metals, characterize the model in high temperatures in order to proceed with such a pyrometer design.

Keywords

Multi Spectral Pyrometer, Wavelength, Infrared Radiation, Temperature, Metal

1. Introduction

Temperature measurement remains crucial in industrial life and production across all sectors. One of the most advanced techniques currently available is remote measurement, especially for high temperatures and objects with varying surface shapes. This measurement is based on the radiative properties of the objects whose temperature is being measured and the transformation of this radiation into electronically processable data. Metals are generally known for their nonlinear emissivity. However, several methods offer solutions for designing a pyrometer for remote surface temperature detection. The four-color method with a nonlinear model is the most widely used for pyrometer design, particularly for wavelength selection.

2. Law of Electromagnetic Radiation

2.1. Law of Planck About Thermal Radiation

For a black body at a surface temperature T, the luminance $L_\lambda^0(T)$ is the product of the energy density of the radiation

---

*Correspondence: Ratianarivo Paul Ezekel (rpekekel@gmail.com)

Received: 10 March 2026; **Accepted:** 25 March 2026; **Published:** 13 April 2026

with $\frac{4\pi}{c}$. It is the ratio of the luminous intensity or energy density of the radiation to the emission surface [1].

$$L_\lambda^0(T) = \frac{2hc^2\lambda^{-5}}{e^{\left(\frac{hc}{k\lambda T}\right)}-1} \tag{1}$$

where h =6,6255 x 10^{-34}Js: constant of Planck,

k =1,38 x 10^{-23} JK^{-1}: constant of Boltzmann,

c =2,996 x 10^8 ms^{-1}: Speed of electromagnetic waves in a vacuum.

By posing $C_1 = 2hc^2$ and $C_2 = \frac{hc}{k}$ the so-called Planck constants, The Planck relation becomes [2]:

$$L_\lambda^0(T) = \frac{C_1\lambda_i^{-5}}{e^{\left(\frac{C_2}{\lambda_i T}\right)}-1} \tag{2}$$

2.2. Different Regions of the Infrared Spectrum

The infrared range covers wavelengths from 0.8µm to 1000µm [3]. It is generally divided into three sub-ranges: near, mid, and far.

Table 1. *Different region of the infrared spectrum.*

Near-infrared	Mid Infrared	Far infrared
0.8µm - 2.5µm	2.5µm - 25µm	25µm - 1000µm

2.3. Definition of Spectral Emissivity

Spectral emissivity is defined as the ratio between the monochromatic radiance of the real source and that of a black body at the same wavelengths λ and temperature. It depends primarily on the source, the wavelength, the temperature, and the direction of emission [4-6].

$$\varepsilon_\lambda = \frac{L_\lambda(T)}{L_\lambda^0(T)} \tag{3}$$

With - $L_\lambda(T)$: monochromatic luminance of real source

$L_\lambda^0(T)$: monochromatic radiance a black body

2.4. Spectral Emissivity of Metals

Most surfaces have an emissivity that varies with wavelength and temperature. In the visible and near-infrared spectra, the emissivity of metals can be modeled as a polynomial function of wavelength [7].

$$\varepsilon_\lambda = c_0 + c_1\lambda + c_2\lambda^2 + \ldots + c_n\lambda^n \tag{4}$$

In our case, we use the second-order polynomial model:

$$\varepsilon_\lambda = a + b\lambda + c\lambda^2 \tag{5}$$

For metals with reflective surfaces, they are characterized by a low degree of emission, especially for wavelengths above 4µm, which is non-linear and related to the structure of their surface [8].

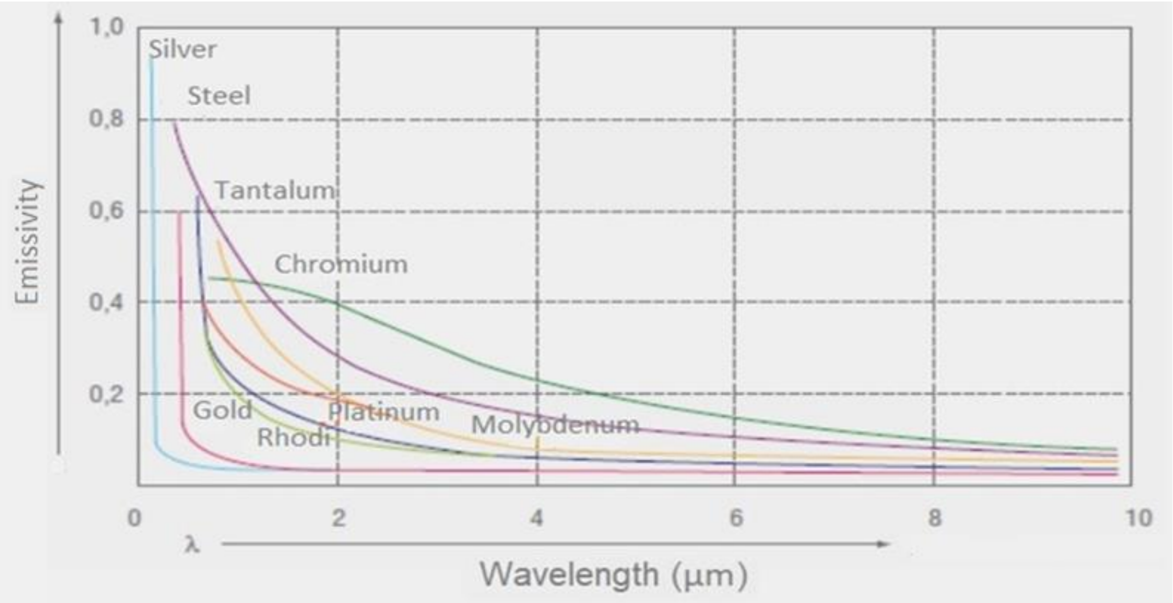

Figure 1. *Spectral emission degree of metals [9].*

3. Multi-spectral Method Based on Planck's Law

3.1. Principle of Quad Spectral Pyrometer

The radiation from the source is filtered by optical systems which allow the four different spectra to pass through and converge them respectively towards the four identical detection systems [10].

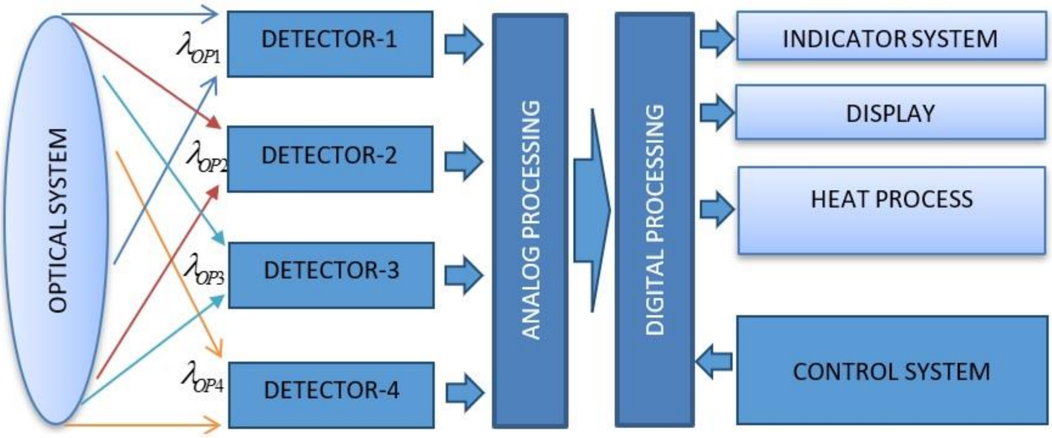

Figure 2. *General principle of quadruspectral pyrometers.*

3.2. Presentation of the TNL.Tabc Model

With this method, temperature and emissivity are calculated simultaneously. The TNL.Tabc model stands for Temperature by Nonlinear Emissivity model, where T, a, b, and c are the parameters to be estimated. This model is based on estimating fluxes expressed using Planck's law of radiance. Emissivity is modeled as a second-degree polynomial.

The flux $L_\lambda(T, a, b, c)$ is a function of wavelength and temperature [11-13].

$$L_{\lambda_i}(T, a, b, c) = (a + b\lambda_i + c\lambda_i^2)\frac{C_1\lambda_i^{-5}}{exp\left(\frac{C_2}{\lambda_i T}\right)-1} \qquad (6)$$

With $\varepsilon_{\lambda_i} = a + b\lambda_i + c\lambda_i^2$ is the spectral emissivity.

The parameter estimation will then be performed by minimizing the function $J(T, a, b, c)$.

$$J(T, a, b, c) = \sum_{i=1}^{4}\left(L_{\lambda_i}^{exp} - L_{\lambda_i}(T, a, b, c)\right)^2 \qquad (7)$$

With - $L_{\lambda_i}^{exp}$: Experimental spectral flux measured at wavelength λ_i,

$L_{\lambda_i}(T, a, b, c)$: Theoretical spectral flux at wavelength λ_i.

3.3. Model for the Sequential Wavelength Selection Method

To select the four optimal wavelengths, the cost function will be minimized using the least squares method by inverting the calculation. That is, we set the temperature, and from this temperature, the optimal wavelength that minimizes the standard deviation of the target temperature is retrieved. Combining the cost function with the TNL.Tabc model allows us to find the different wavelengths intended for the pyrometer's optical filter [11, 14].

The statistical properties of the parameter estimator associated with the TNL.Tabc model and the parameters provided by the least squares method are given by the variance-covariance matrix. The determination of the standard deviations σ_β of the parameters T, a, b, and c is based on using this matrix. The approximate expression of the ordinary least squares variance-covariance matrix, given for a parameter vector β=(T, a, b, c), considering the independent, identically distributed additive noise (constant variance σ_{noise}^2, and zero mean), is given by the following matrix relation [12].

$$cov(\beta) = \begin{bmatrix} \sigma_T^2 & cov(T,a) & cov(T,b) & cov(T,c) \\ cov(T,a) & \sigma_a^2 & cov(a,b) & cov(a,c) \\ cov(T,b) & cov(a,b) & \sigma_b^2 & cov(b,c) \\ cov(T,c) & cov(a,c) & cov(b,c) & \sigma_c^2 \end{bmatrix}$$

$$cov(\beta) = (X^tX)^{-1}\sigma^2_{noise} \qquad (8)$$

The standard deviation on the temperature σ_T, which is a function of the standard deviation on noise σ_{noise}, is given by the following relationship:

$$\sigma_T = \sqrt{(X^tX)^{-1}}\sigma_{noise} \qquad (9)$$

With X being the sensitivity matrix associated with the variance-covariance matrix. It has the following matrix form:

$$\begin{bmatrix} \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial c} \end{bmatrix}$$

From experience with the infrared camera, the σ_{noise} is about $8{,}97.10^4 Wm^{-2}$ that is to say about $7.43.10^{-3}$% of the maximum of Planck's law [6, 15, 16].

3.4. Pseudo-optimal Method for Wavelength Selection

Wavelengths are selected sequentially. Normally, for a given calculation temperature, there will be one optimal wavelength for the first, two for the second, six for the third, and so on, resulting in 24 optimal wavelengths.

In this case, there are 24 groups of four optimal wavelengths that minimize the standard deviation of the temperature at a given calculation temperature. These 24 groups of wavelengths must then be tested against criteria to determine the best group [1, 13].

In our application, we will try using five calculation temperatures (T_C): 1073.15K, 1173.15K, 1223.15K, 1273.15K, and 1373.15K to find several options and temperature ranges.

Selection of the first optimal wavelength

The first wavelength filter λ_{OP1} minimizes the standard deviation σ_T of the temperature as a monochromatic measurement. Only the temperature is the parameter to be estimated for the cost function $J(\beta)$ [17].

$$J(T) = \left(L_{\lambda_1}^{exp} - L_{\lambda_1}(T,a,b,c)\right)^2 \qquad (10)$$

The sensitivity matrix X consists only of the first row and first column. The temperature will be the only parameter.

$$X = \left[\frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial T}\right]$$

Selection of the second optimal wavelengths

The selection of the second wavelength depends on the first one that has just been selected. We fix a=1, b=1, and $\lambda_1 = \lambda_{OP1}$. The function cost consists of only 02 parameters T and a. The model then becomes TNL.Ta.

$$J(T,a) = \sum_{i=1}^{2}\left(L_{\lambda_i}^{exp} - L_{\lambda_i}(T,a,b,c)\right)^2 \qquad (11)$$

The sensitivity matrix X is composed of 02 rows and 02 columns.

$$X = \begin{bmatrix} \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial a} \\ \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial a} \end{bmatrix}$$

Selection of the third optimal wavelengths

As with the calculation of the second optimal wavelength, the determination of the third depends on the first and second, i.e. $\lambda_1 = \lambda_{OP1}$ and $\lambda_2 = \lambda_{OP2}$. The parameters of the cost function become T, a, and b.

$$J(T,a,b) = \sum_{i=1}^{3}\left(L_{\lambda_i}^{exp} - L_{\lambda_i}(T,a,b,c)\right)^2 \qquad (12)$$

The X sensitivity matrix associated with the TNL.Tab model is formed by a matrix with 3 rows and 3 columns.

$$X = \begin{bmatrix} \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial b} \\ \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial b} \\ \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial b} \end{bmatrix}$$

Selection of the fourth and last optimal wavelengths

The fourth optimal wavelength will be obtained by using the same principle as the second and third optimal wavelengths, by fixing $\lambda_1 = \lambda_{OP1}$, $\lambda_2 = \lambda_{OP2}$ and$\lambda_3 = \lambda_{OP3}$ [6].

The parameters of the cost function become T, a, b, and c.

$$J(T,a,b,c) = \sum_{i=1}^{4}\left(L_{\lambda_i}^{exp} - L_{\lambda_i}(T,a,b,c)\right)^2 \qquad (13)$$

The X sensitivity matrix associated with the TNL.Tabc model is formed by a matrix of 4 rows and 4 columns.

$$\begin{bmatrix} \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial c} \end{bmatrix}$$

4. Results of Criteria for Selecting the Optimal Wavelengths

The groups of optimal wavelengths calculated from the 05 calculation temperatures (T_C): 1073.15K, 1173.15K, 1223.15K, 1273.15K and 1373.15K must respect all the different selection criteria.

4.1. Pyrometer Spectral Range Criterion

Our field of study lies in the near-infrared spectral band, between wavelengths of 0.8 µm and 2.5 µm.

For metals, temperature measurement requires the use of short wavelengths, as metals are known for their low emission at wavelengths above 4 µm, in order to avoid unacceptable errors [7, 18].

Table 2. Pre-selected optimal wavelengths in the near-infrared range.

T_C [K]	Channel 1		Channel 2		Channel 3		Channel 4	
	λ_{OP1} [µm]	σ_T [K]	λ_{OP2} [µm]	σ_T [K]	λ_{OP3} [µm]	σ_T [K]	λ_{OP4} [µm]	σ_T [K]
1073.15	2.246	0.000959	1.535	0.005373	1.186	0.043606	0.967	0.461628
							1.392	0.471311
							2.000	0.132117
					1.945	0.038898	1.099	0.128315
							1.719	0.484844
							2.122	0.659303
1173.15	2.054	0.000671	1.403	0.003772	1.085	0.030674	0.884	0.323962
							1.273	0.333100
							1.896	0.090029
					1.778	0.027332	1.005	0.090259
							1.572	0.340205
							1.939	0.465602
1223.15	1.970	0.000568	1.346	0.003185	1.041	0.025831	0.848	0.272897
							1.222	0.279541
							1.821	0.075742
					1.707	0.023056	0.965	0.075973
							1.509	0.287155
							1.857	0.392977
1273.15	1.893	0.000684	1.294	0.002712	1	0.022004	0.815	0.232649
							1.174	0.238138
							1.749	0.064520
					1.640	0.019644	0.900	0.065571
							1.449	0.244430
							1.788	0.334194
1373.15	1.755	0.000357	1.199	0.002005	0.927	0.016302	0.756	0.172321
							1.088	0.176781
							1.622	0.047746
					1.520	0.014494	0.855	0.047922
							1.343	0.180200
							1.658	0.245986

4.2. Criteria for the Minimum Difference Between Two Successive Wavelengths

The minimum difference between two successive wavelengths must be respected. Measurement errors increase with the spectral variation of the emissivity and the increase in the distance between two successive wavelengths [11, 12].

$$\Delta ji\left|\lambda_j - \lambda_i\right|\frac{T\lambda_j^2}{C_2}\Big|_{\lambda_j > \lambda_{i}{}_{Min}} \tag{14}$$

Table 3. Minimum difference between two successive wavelengths [19].

Successive optimal wavelengths	Minimum difference	Maximal value
First and second	$\lambda_{OP1} - \lambda_{OP2} \geq \Delta 1 - 2_{Min}$	$\lambda_{OP2Max} \leq \lambda_{OP1} - \Delta 1 - 2_{Min}$
Second and third	$\lambda_{OP2} - \lambda_{OP3} \geq \Delta 2 - 3_{Min}$	$\lambda_{OP3Max} \leq \lambda_{OP2} - \Delta 2 - 3_{Min}$
Third and forth	$\lambda_{OP3} - \lambda_{OP4} \geq \Delta 3 - 4_{Min}$	$\lambda_{OP4Max} \leq \lambda_{OP3} - \Delta 3 - 4_{Min}$

Table 4. Optimal wavelength selected according to the criterion of the minimum difference between 02 successive spectra.

T_C [K]	λ_{OP} [µm]	σ_T [K]	σ_T [%]	$\Delta\lambda$ [µm]	Δ_{min} [µm]
1073.15	$\lambda_{OP1} = 2.246$	0.000959	0.000089	$\lambda_{OP1} - \lambda_{OP2} = 0.711$ $\lambda_{OP2} - \lambda_{OP3} = 0.349$ $\lambda_{OP3} - \lambda_{OP4} = 0.219$	$\lambda_{OP1} - \lambda_{OP2} = 0.411$ $\lambda_{OP2} - \lambda_{OP3} = 0.192$ $\lambda_{OP3} - \lambda_{OP4} = 0.114$
	$\lambda_{OP2} = 1.535$	0.005373	0.000501		
	$\lambda_{OP3} = 1.186$	0.043606	0.004063		
	$\lambda_{OP4} = 0.967$	0.461628	0.043016		
1173.15	$\lambda_{OP1} = 2.054$	0.000671	0.000057	$\lambda_{OP1} - \lambda_{OP2} = 0.651$ $\lambda_{OP2} - \lambda_{OP3} = 0.318$ $\lambda_{OP3} - \lambda_{OP4} = 0.201$	$\lambda_{OP1} - \lambda_{OP2} = 0.344$ $\lambda_{OP2} - \lambda_{OP3} = 0.160$ $\lambda_{OP3} - \lambda_{OP4} = 0.095$
	$\lambda_{OP2} = 1.403$	0.003772	0.000321		
	$\lambda_{OP3} = 1.085$	0.030674	0.002614		
	$\lambda_{OP4} = 0.884$	0.323962	0.027614		
1223.15	$\lambda_{OP1} = 1.970$	0.000568	0.000046	$\lambda_{OP1} - \lambda_{OP2} = 0.624$ $\lambda_{OP2} - \lambda_{OP3} = 0.305$ $\lambda_{OP3} - \lambda_{OP4} = 0.193$	$\lambda_{OP1} - \lambda_{OP2} = 0.329$ $\lambda_{OP2} - \lambda_{OP3} = 0.154$ $\lambda_{OP3} - \lambda_{OP4} = 0.092$
	$\lambda_{OP2} = 1.346$	0.003185	0.000260		
	$\lambda_{OP3} = 1.041$	0.025831	0.002112		
	$\lambda_{OP4} = 0.848$	0.272897	0.022311		
1273.15	$\lambda_{OP1} = 1.893$	0.000684	0.000054	$\lambda_{OP1} - \lambda_{OP2} = 0.599$ $\lambda_{OP2} - \lambda_{OP3} = 0.294$ $\lambda_{OP3} - \lambda_{OP4} = 0.185$	$\lambda_{OP1} - \lambda_{OP2} = 0.317$ $\lambda_{OP2} - \lambda_{OP3} = 0.148$ $\lambda_{OP3} - \lambda_{OP4} = 0.088$
	$\lambda_{OP2} = 1.294$	0.002712	0.000213		
	$\lambda_{OP3} = 1.000$	0.022004	0.001728		
	$\lambda_{OP4} = 0.815$	0.232649	0.018273		
1373.15	$\lambda_{OP1} = 1.755$	0.000357	0.000026	$\lambda_{OP1} - \lambda_{OP2} = 0.556$ $\lambda_{OP2} - \lambda_{OP3} = 0.272$ $\lambda_{OP3} - \lambda_{OP4} = 0.171$	$\lambda_{OP1} - \lambda_{OP2} = 0.293$ $\lambda_{OP2} - \lambda_{OP3} = 0.119$ $\lambda_{OP3} - \lambda_{OP4} = 0.082$
	$\lambda_{OP2} = 1.199$	0.002005	0.000146		
	$\lambda_{OP3} = 0.927$	0.016302	0.001187		
	$\lambda_{OP4} = 0.756$	0.172321	0.012549		

4.3. Standard Deviation on the Temperature of the Fluxes Obtained from the Optimal Wavelengths

The standard deviation of the optimal wavelengths must be checked in order to determine the errors at different temperatures.

Table 5. Standard deviation on temperature according to the calculated optimal wavelengths.

T_C [K]	λ_{OP} [µm]	Temperature for checking the standard deviation of the temperature						
		975.15K	1073.15K	1173.15K	1223.15K	1273.15K	1373.15K	1473.15K
1073.15	$\lambda_{OP1} = 2.246$	0.001459	0.000959	0.000686	0.000595	0.000524	0.000420	0.000349
	$\lambda_{OP2} = 1.535$	0.003146	0.001559	0.000884	0.000693	0.000555	0.000378	0.000273
	$\lambda_{OP3} = 1.186$	0.011394	0.004336	0.001977	0.001408	0.001033	0.000600	0.000379
	$\lambda_{OP4} = 0.967$	0.056348	0.016485	0.006042	0.003911	0.002627	0.001305	0.000719
1173.15	$\lambda_{OP1} = 2.054$	0.001582	0.000982	0.000671	0.000571	0.000493	0.000382	0.000310
	$\lambda_{OP2} = 1.403$	0.004541	0.002068	0.001094	0.000832	0.000648	0.000419	0.000290
	$\lambda_{OP3} = 1.085$	0.021317	0.007281	0.003035	0.002078	0.001471	0.000801	0.000478
	$\lambda_{OP4} = 0.884$	0.138194	0.035367	0.011602	0.007152	0.004595	0.002106	0.001084
1223.15	$\lambda_{OP1} = 1.970$	0.001674	0.001011	0.000675	0.000568	0.000486	0.000371	0.000296
	$\lambda_{OP2} = 1.346$	0.005532	0.002417	0.001235	0.000925	0.000711	0.000448	0.000304
	$\lambda_{OP3} = 1.041$	0.029580	0.009576	0.003817	0.002564	0.001782	0.000940	0.000546
	$\lambda_{OP4} = 0.848$	0.219035	0.052467	0.016292	0.009805	0.006161	0.002715	0.001351
1273.15	$\lambda_{OP1} = 1.893$	0.001789	0.001050	0.000685	0.000571	0.000484	0.000343	0.000286
	$\lambda_{OP2} = 1.294$	0.006791	0.002847	0.001406	0.001038	0.000786	0.000484	0.000321
	$\lambda_{OP3} = 1.000$	0.041610	0.012759	0.004862	0.003202	0.002185	0.001116	0.000631
	$\lambda_{OP4} = 0.815$	0.349686	0.078430	0.023061	0.013551	0.008329	0.003529	0.001697
1373.15	$\lambda_{OP1} = 1.755$	0.002101	0.001164	0.000725	0.000592	0.000492	0.000357	0.000274
	$\lambda_{OP2} = 1.199$	0.010626	0.004095	0.001886	0.001350	0.000995	0.000582	0.000370
	$\lambda_{OP3} = 0.927$	0.084590	0.023272	0.008105	0.005130	0.003377	0.001616	0.000863
	$\lambda_{OP4} = 0.756$	0.917752	0.180401	0.047544	0.026628	0.015659	0.006132	0.002754

4.4. Sensitivity of the Flux to Temperature and Wavelength

The model called TNL.Tabc involves taking temperature measurements without fully controlling all influencing factors. However, certain precautions must be taken to minimize temperature measurement error. Our working range lies on the increasing portion of the Planck curve because the reduced sensitivities of the flux to temperature χ_T and wavelength χ_λ are all the better when working at shorter wavelengths. The wavelengths obtained should provide better sensitivity to both temperature and wavelength.

$$\chi_T = \frac{1}{L_\lambda(T)} \frac{dL_\lambda(T)}{dT} \tag{15}$$

$$\chi_\lambda = \frac{1}{L_\lambda(T)} \frac{dL_\lambda(T)}{d\lambda} \tag{16}$$

Table 6. Sensitivity of the flux from the optimal wavelengths.

T_C [K]	λ_{OP} [µm]	Temperature for verifying of sensitivity of the flux						
		975.15K	1073.15K	1173.15K	1223.15K	1273.15K	1373.15K	1473.15K
1073.15	$\lambda_{OP1} = 2.246$	0.006773	0.005576	0.004674	0.004304	0.003978	0.003429	0.002990

T_C [K]	λ_{OP} [μm]	Temperature for verifying of sensitivity of the flux						
		975.15K	1073.15K	1173.15K	1223.15K	1273.15K	1373.15K	1473.15K
	$\lambda_{OP2} = 1.535$	0.009898	0.008140	0.006813	0.006268	0.005786	0.004976	0.004326
	$\lambda_{OP3} = 1.186$	0.012810	0.010534	0.008815	0.008109	0.007485	0.006435	0.005591
	$\lambda_{OP4} = 0.967$	0.015711	0.012919	0.010811	0.009945	0.009179	0.007891	0.006856
1173.15	$\lambda_{OP1} = 2.054$	0.007402	0.006091	0.005102	0.004697	0.004339	0.003737	0.003255
	$\lambda_{OP2} = 1.403$	0.010829	0.008905	0.007452	0.006856	0.006328	0.005442	0.004729
	$\lambda_{OP3} = 1.085$	0.014002	0.115147	0.009635	0.008863	0.008181	0.007033	0.006111
	$\lambda_{OP4} = 0.884$	0.017186	0.014132	0.011826	0.010879	0.010041	0.008632	0.007500
1223.15	$\lambda_{OP1} = 1.970$	0.007716	0.006348	0.005317	0.004894	0.004520	0.003892	0.003389
	$\lambda_{OP2} = 1.346$	0.011287	0.009282	0.007767	0.007146	0.006596	0.005671	0.004929
	$\lambda_{OP3} = 1.041$	0.014594	0.012001	0.010042	0.009238	0.008527	0.007330	0.006369
	$\lambda_{OP4} = 0.848$	0.017916	0.014732	0.012328	0.011341	0.010467	0.008998	0.007818
1273.15	$\lambda_{OP1} = 1.893$	0.008029	0.006605	0.005531	0.005090	0.004701	0.004047	0.003522
	$\lambda_{OP2} = 1.294$	0.011741	0.009655	0.008079	0.007432	0.006861	0.005898	0.005126
	$\lambda_{OP3} = 1.000$	0.015193	0.012493	0.010454	0.009617	0.008876	0.007631	0.006630
	$\lambda_{OP4} = 0.815$	0.018641	0.015329	0.012827	0.011800	0.010891	0.009363	0.008135
1373.15	$\lambda_{OP1} = 1.755$	0.008658	0.007122	0.005962	0.005486	0.005066	0.004359	0.003792
	$\lambda_{OP2} = 1.199$	0.012671	0.010420	0.008719	0.008021	0.007403	0.006365	0.005531
	$\lambda_{OP3} = 0.927$	0.016389	0.013477	0.011277	0.010374	0.009575	0.008231	0.007152
	$\lambda_{OP4} = 0.756$	0.020096	0.016525	0.013828	0.012721	0.011741	0.010093	0.008769

Table 7. Sensitivity of flux to wavelength on verification temperatures.

T_C [K]	λ_{OP} [μm]	Temperature for verifying flux of sensitivity to wavelength						
		975.15K	1073.15K	1173.15K	1223.15K	1273.15K	1373.15K	1473.15K
1073.15	$\lambda_{OP1} = 2.246$	708783	438419	215437	118132	28815.5	-129307	-264699
	$\lambda_{OP2} = 1.535$	3017940	2433730	1949550	1737360	1541990	1194490	894948
	$\lambda_{OP3} = 1.186$	6295360	5315970	4503650	4147350	3819100	3234490	2729580
	$\lambda_{OP4} = 0.967$	10640700	9167330	7945180	7409060	6915060	6035040	5274610
1173.15	$\lambda_{OP1} = 2.054$	1072800	748273	480169	363010	255370	64539.6	-99164.8
	$\lambda_{OP2} = 1.403$	3947540	3247910	2667830	2413500	2179270	1762380	1402700
	$\lambda_{OP3} = 1.085$	7950900	6780620	5809910	5384100	4991770	4292950	3689210
	$\lambda_{OP4} = 0.884$	13263700	11500700	10038200	9396680	8805530	7752420	6842330
1223.15	$\lambda_{OP1} = 1.970$	1273700	920437	628392	500698	383333	175134	-3618.14
	$\lambda_{OP2} = 1.346$	4446190	3685950	3055540	2779110	2524490	2071220	1680020
	$\lambda_{OP3} = 1.041$	8840230	7568920	6514380	6051800	5624470	4866320	4210320
	$\lambda_{OP4} = 0.848$	14664100	12748200	11158900	10461700	9819330	8674880	7685850

T_C [K]	λ_{OP} [μm]	**Temperature for verifying flux of sensitivity to wavelength**						
		975.15K	**1073.15K**	**1173.15K**	**1223.15K**	**1273.15K**	**1373.15K**	**1473.15K**
1273.15	$\lambda_{OP1} = 1.893$	1486270	1103270	786471	647884	520461	294298	99976.3
	$\lambda_{OP2} = 1.294$	4965930	4143300	3461080	3161900	2886300	2395610	1971990
	$\lambda_{OP3} = 1.000$	9784980	8407280	7264470	6763160	6301240	5478390	4767390
	$\lambda_{OP4} = 0.815$	16124000	14049800	12329300	11574500	10879000	9639990	8569220
1373.15	$\lambda_{OP1} = 1.755$	1952330	1506060	1136600	974840	826027	561657	334207
	$\lambda_{OP2} = 1.199$	6114380	5156120	4361330	4012740	3691580	3119630	2625670
	$\lambda_{OP3} = 0.927$	11811500	10208300	8878370	8294970	7757400	6799760	5972200
	$\lambda_{OP4} = 0.756$	19255100	16844500	14844900	13967800	13159500	11719500	10475000

5. Discussions About the Calculation Results

5.1. Pyrometer Spectral Range Criterion

Multispectral measurement minimizes error, so choosing short wavelengths provides better temperature accuracy.

We have five calculation temperatures here, and since we are working in the near-infrared spectrum, after applying this criterion, only 15 optimal wavelength groups remain, compared to 24 initially without this criterion [1, 7].

5.2. Criteria for the Minimum Difference Between Two Successive Wavelengths

A selected optimal wavelength group meets the criterion of minimum distance between two successive optimal wavelengths. Furthermore, the minimum required separation between two wavelengths is proportional to the longer of the two successive wavelengths. It is also observed that all the first optimal wavelengths in each group with the lowest standard deviations do not meet the criterion of minimum separation between two successive wavelengths.

5.3. Standard Deviation on the Temperature from the Temperature Range of the Fluxes Obtained from the Optimal Wavelengths

As the calculation temperature increases up to 1373.15 K, the optimal wavelengths decrease to at least 0.140 μm.

It is also observed that the standard deviation of the temperature improves as the measurement temperature increases. Therefore, temperature errors decrease for measurements at high temperatures.

The standard deviation degrades inversely with wavelength. And this degradation almost doubles if the wavelength exceeds the lower limit of the near-infrared range, especially for the fourth wavelength.

Between 975.15 K and 1473.15 K, the optimal wavelengths selected at T_C=1073.15 K have a better standard deviation than those at T_C=1373.15 K.

5.4. Sensitivity of the Flux to Temperature and Wavelength

The temperature sensitivity of the flux increases as the wavelength decreases. In the spectral band of our pyrometer, the temperature sensitivity of the flux applied at a given wavelength decreases as the temperature increases.

In the spectral band between 0.8 μm and 2.5 μm, the temperature sensitivity of the flux is significantly better at 975.15 K than at 1473.15 K. Therefore, the lower the temperature being measured, the better the temperature sensitivity of the flux.

The sensitivity of the flux to wavelength increases as the wavelength decreases. Therefore, measurements using wavelength spectra in the near-infrared region are highly recommended. The flux sensitivity to wavelength obtained from higher temperatures is increasingly better than that calculated at the lower limit within the temperature range to be measured. Wavelengths calculated from temperatures below 1273.15 K present a negative value for the flux sensitivity to wavelength at high temperatures.

6. Conclusions

Only the optimal wavelengths calculated from a temperature of 1273.15 K meet all the selection criteria for the four optimal wavelengths for a multispectral pyrometer. Therefore, using the sequential least-squares method for selecting optimal wavelengths in the TNL.Tabc model, it is better to use a temperature above 1273.15 K.

Considering the permeability of the area and criteria such as flux sensitivity to wavelength and temperature, standard deviation at temperature, and the minimum difference between two successive wavelengths, selecting wavelengths from the near-infrared spectrum gives better results for reducing errors, i.e., a low standard deviation. Temperature measurement of metals requires the use of short wavelengths, and the flux sensitivity to temperature is high for measurements at low temperatures.

Abbreviations

TNL	Temperature Nonlinear

Acknowledgments

I express sincere gratitude to the electronic engineering department teams at the Polytechnical High School of Antsirabe at the University of Vakinankaratra, Madagascar. I give thanks to my family and my colleagues for their support during the realization of this article.

Author Contributions

Ratianarivo Paul Ezekel: Conceptualization, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing

Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflicts of interest.

References

[1] PhilippeHerve, JulieCedelle, IonutNegreanu, Infrared technique for simultaneous determination of temperature and emissivity, https://www.sciencedirect.com/science/article/pii/S1350449510000721

[2] Th. Duvaut, Comparison between multiwavelength infrared and visible pyrometry: Application to metals, https://www.sciencedirect.com/science/article/pii/S1350449507001375

[3] TairanFu, MinghaoDuan, JiaqiTang, ConglingShi, Measurements of the directional spectral emissivity based on a radiation heating source with alternating spectral distributions, https://www.sciencedirect.com/science/article/pii/S001793101500784X

[4] G. R. Gathers, Analysis of multiwavelength pyrometry using nonlinear chi-square fits and Monte Carlo methods, https://link.springer.com/article/10.1007%2FBF00503888

[5] Helcio R. B. Orlande, Olivier Fudym, Denis Maillet, Renato M. Cotta, Thermal Measurements and Inverse Techniques, https://www.crcpress.com/Thermal-Measurements-and-Inverse-Techniques/Orlande-Fudym-Maillet-Cotta/p/book/9781138113862

[6] Thomas Pierre, Benjamin Rémy, Alain Degiovanni, Microscale temperature measurement by the multispectral and statistic method in the ultraviolet-visible wavelengths, https://aip.scitation.org/doi/10.1063/1.2826945

[7] M. Boivineau, G. Pottlacher, Thermophysical properties of metals at very high temperatures obtained by dynamic heating techniques: recent advances, https://www.inderscience-online.com/doi/pdf/10.1504/IJMPT.2006.009468

[8] A Barlier-Salsi, Stray light correction on array spectroradiometers for optical radiation risk assessment in the workplace, http://iopscience.iop.org/article/10.1088/0952-4746/34/4/915/meta

[9] Simone MATTEÏ, Thermal radiation from opaque materials https://www.techniques-ingenieur.fr/base-documentaire/energies-th4/transferts-thermiques-42214210/rayonnement-thermique-des-materiaux-opaques-be8210

[10] Tairan Fu, Jiangfan Liu, Minghao Duan, Anzhou Zong, Temperature measurements using multicolor pyrometry in thermal radiation heating environments, https://doi.org/10.1063/1.4870252

[11] Christophe Rodiet, Benjamin Rémy, Alain Degiovanni, Franck Demeurie, – Optimisation of wavelengths selection used for the multi-spectral temperature measurement by ordinary least squares method of surfaces exhibiting non-uniform emissivity, https://www.tandfonline.com/doi/abs/10.1080/17686733.2013.812816

[12] Jian Xing, Shuang Long Cui, Yuan Dong Shi, A Iteration Processing Algorithm for Multi-Wavelength Pyrometer, https://doi.org/10.4028/www.scientific.net/AMM.568-570.401

[13] V. TankH. Dietl, Multispectral infrared pyrometer for temperature measurement with automatic correction of the influence of emissivity, https://www.sciencedirect.com/science/article/pii/0020089190900492

[14] George Zonios, Noise and stray light characterization of a compact CCD spectrophotometer used in biomedical applications, https://www.osapublishing.org/ao/abstract.cfm?URI=ao-49-2-163

[15] AntónioAraújo, Dual-band pyrometry for emissivity and temperature measurements of gray surfaces at ambient temperature: The effect of pyrometer and background temperature uncertainties, https://www.sciencedirect.com/science/article/pii/S0263224116304687

[16] Th. Duvaut, D. Georgeault, J. L. Beaudoin, Multiwavelength infrared pyrometry: optimization and computer simulations, https://www.sciencedirect.com/science/article/pii/1350449595000402

[17] Christophe Rodiet, Benjamin Remy, Alain Degiovanni, Optimal wavelengths obtained from laws analogous to the Wien's law for monospectral and bispectral methods, and general methodology for multispectral temperature measurements taking into account global transfer function including non-uniform emissivity of surfaces, https://www.sciencedirect.com/science/article/pii/S1350449516300147

[18] C. RODIET, T. PIERRE, B. REMY et A. DEGIOVANNI, Temperature measurement by multispectral method in the infrared and ultraviolet https://www.researchgate.net/publication/265047799

[19] Christophe rodiet, Benjamin Remy, Thomas Pierre and Alain Degiovanni, Influence of measurement noise and number of wavelengths on the temperature measurement of opaque surface with variable emissivity by a multi-spectral method based on the flux ratio in the infrared-ultraviolet range, https://www.researchgate.net/publication/275030564

Biography

Ratianarivo Paul Ezekel is a Teacher at Polytechnical High School of Antsirabe, Vakinankaratra University, Electronic Engineering Department. He completed his PhD in Electronic Divices et Systems Engineering from Antananarivo University in 2018, and his Master of Engineering in Automatic Electronic Systems from Polytechnical High School of Antananarivo in 20010. Recognized for his exceptional contributions, Dr. RATIANARIVO Paul Ezekel has been known as the chef department of electronic engineering.

Research Field

Ratianarivo Paul Ezekel: Electronic system, Instrumentation, Embedded systems, programmable system