

EXPLORATION OF ALTERNATIVE METHODS FOR FITTING RADIATION THERMOMETER SIGNAL TO BLACKBODY TEMPERATURE

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Abstract - In the science of radiation temperature measurement, the measurement of temperature from calibration blackbodies has used the Sakuma-Hattori Equation in the Planckian Form to relate temperature and emitted radiance. This is very useful as it makes calculations and a curve fit relationships between temperature and radiance much simpler than using Planck's Law. While this approach is standard, it may not always account for the non-linear and real effects acting upon the measurement outcome which detract from the results' accuracy. This may be especially true if the relationship between radiance and the radiation thermometer's signal output is not linear.

This paper discusses an occasion where such a problem has manifested itself. Several parameterized equations based on the Sakuma-Hattori Equation are introduced as an attempt to improve the curve fit. Measurement results are used to determine the quality of each equation with respect to the curve fit.

INTRODUCTION

The Heitronics KT19.82 has been used as a transfer standard for radiometric calibrations at the Fluke Corporation facility in American Fork, Utah for the past three years. (This facility was formally known as Hart Scientific and will be referred to as Fluke – American Fork in this paper.) A method of curve-fitting radiometric signal to blackbody temperature data was developed to provide a good curve fit. However, it could be that better solutions exist based on standard radiometric transfer functions.

BACKGROUND INFORMATION

The current method used for curve fitting radiometric data at Fluke – American Fork has worked very well. However, this method cannot be tied back to a scientific formula based on physical phenomena. Since the current method used was implemented, several new guidelines have been published stressing the use of the Sakuma-Hattori Equation in the Planckian form as part of the measurement equation for radiation thermometry. [1][2][3]

Current Method of Curve Fitting

At Fluke – American Fork, a polyfunction (1) has been used to curve-fit Heitronics KT19 signal data to blackbody temperature. The polyfunction used was found to provide the best curve fit for this instrument over a wide range of temperatures. [4] It has been shown not only to fit calibration points well, but points between the calibration points have been found to have minimal error. There are two undesirable attributes to using this method. First, the polyfunction is not related back to any physical phenomena. It is purely a continuous equation that provides a good fit for Fluke – American Fork's KT19 radiometric data. Second, the polyfunction used has five parameters. The KT19 calibration performed at Fluke – American Fork has seven points, which results in only two degrees of freedom. It would be more desirable to have an equation that has four parameters.

$$T = AS^{\frac{1}{2}} + BS^{\frac{3}{2}} + CS^2 + D\ln(S) + T_0 \quad (1)$$

where:

- A, B, C, D, T_0 : curve-fitting parameters
- S: KT19 radiometric signal ('RAD' output)
- T: blackbody temperature

Sakuma-Hattori and Non-linearity Problem

The Sakuma-Hattori Equation (2) has been suggested for use in radiation thermometry measurement equations. [1][2][3] Equation (2) shows the Sakuma-Hattori, $S(T)$, as well as the inverse Sakuma-Hattori equation. [3] However, work done by Fluke – American Fork has shown that it may not be adequate over a wide range of temperature. [4] This is likely caused by a non-linear relationship as is shown in the graph in Figure 1. This graph shows the ratio of KT19 output data and the idealized Sakuma-Hattori Equation. [3] It has been shown that this is not a problem related to the blackbodies used, since they pass normal equivalence comparison when compared to blackbodies at a national metrological institute. [5]

$$S(T) = \frac{C}{\exp\left(\frac{c_2}{AT+B}\right) - 1} \quad (2)$$

$$T = \frac{c_2}{A \ln\left(\frac{C}{S} + 1\right)} - \frac{B}{A}$$

where:

- A, B, C: curve-fitting parameters
- c_2 : Second Radiation Constant
- T: blackbody temperature
- S: radiometric signal

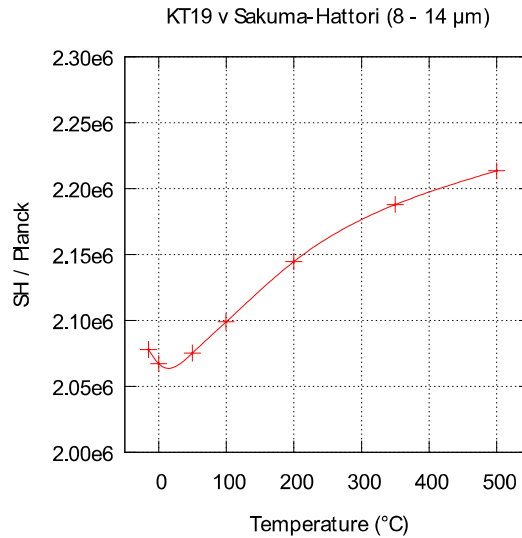


Figure 1. Ratio of KT19 Output and Planckian Spectral Response

It is interesting to note in Figure 1 that the curve has a minima close to ambient or the housing temperature of the radiation thermometer. The laboratory temperature for this data is $23\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$. In other research done at Fluke - American Fork, it has been shown that the housing temperature for radiation thermometers can be several degrees higher than the laboratory's ambient temperature.

EXPLORING SOLUTIONS

To start exploring solutions to this theorized non-linearity problem, sources of non-linearity were examined. Based on these examinations, proposed modifications to the Sakuma-Hattori Equation (2) were made. These modifications were curve-fitted using a sample set of data. Their results were compared to criteria and to the results using the polyfunction (1). There were two criteria that the data must meet to be considered. First, the curve fit must pass a chi-squared test of goodness of fit. [6] Second, the residual of any point considered for the curve fit must have an error less than one half of the expanded uncertainty for the measurement at that point. The data used for the evaluation were picked because they showed little noise when examined on a control chart. Therefore, it is expected that the data have no residuals that are greater than one half of the expanded uncertainty. A similar study was done with lower wavelength narrowband radiation thermometers when the Planckian form was found to provide the overall best fit. [7]

Sources of Non-linearity

Challenges to traditional mathematical representations of source temperature in terms of energy detection confront the actual operation of all infrared thermometers, notwithstanding the pyroelectric detector type. In order for improvements to the mathematical representations or algorithms to be successful, they must rely on an understanding of the thermometer's operation and its potential errors. To visualize both, a generic signal flow depiction is useful. [8] Figure 2 shows two basic operation sections in a hypothetical pyroelectric thermometer. [9] These are the Input Optics and Signal Processing sections, and each is shown with its respective sub-component blocks.

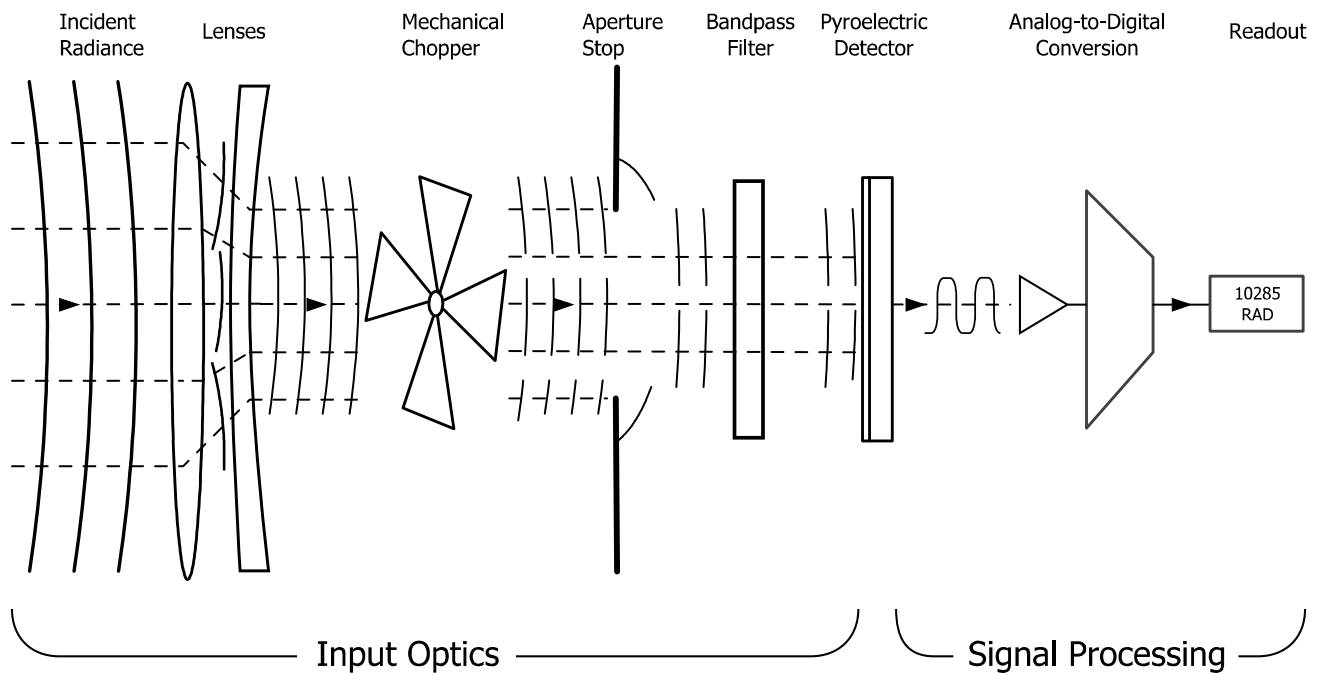


Figure 2. Radiation Thermometer Block Diagram

Infrared radiant energy in the form of spherical waves from the source impinges on the glass-like lenses that constitute the first sub-component of the thermometer's input optics. Nearly transparent to infrared radiation, the lenses shape the incident radiance, accomplishing this with lenses that at first converge and later diverge the wave front. The optical property index of refraction 'n' is partially responsible for re-directing waves at media boundaries. As useful as 'n' is in reshaping the waves, it varies with energy wavelength, causing chromatic aberration which reduces the optical system's ability to focus sharply [10]. This may produce an error in the corresponding signal count.

As the incident waves continue along their path to the right, a mechanical chopper rotates rapidly through them, blocking transmission of a portion of the wave front. The chopper causes an on-and-off cycling of the radiance from the source which is necessary for the pyroelectric detector to operate properly [11]. However,

the chopper's speed and motion through the waves could present more problems for accurate energy detection and the resulting signal that is displayed on the readout.

The aperture stop permits the central sections of the incident wave front which are normal to the detector's surface to contact it. The edges of the aperture stop interact with the very outer, off-axis portions of the wave, slightly bending their direction away from the detector's surface. This may interfere with detecting the optimum amount of energy in the wave front, some of which is already missing due to blockage by the edges of the stop [12].

Filter networks ideally limit the energy spectral region incident upon the pyroelectric detector to the band of wavelengths the atmosphere passes. A common pass band filter is the 8 to 14 μm type. Non-linear attenuation due to the filter network can pose problems for correct signal measurement.

The pyroelectric detector is the primary sensing device in the thermometer and possibly the most important sub-component in the signal processing section for determining source temperature. Furthermore, the detector must sense quickly and differentially. It functions by receiving two different amounts of energy on alternate cycles, from two locations, the source and the thermometer housing, at a frequency determined by the chopper. The energy is received from the source part of the time and from the thermometer housing the rest of the time [11]. The efficiency with which the detector produces analogues of the two different energy fields presents possibly the greatest component of error. This can appear as slew rate distortion on the output signal to the analog-to-digital conversion section.

The analog-to-digital conversion section conditions the signals it receives. It corrects the signals for emissivity settings as well as compares them to other reference signals in the conversion block. The readout presents the final measurement information, largely concerning attributes of the source.

Finally, in the course of discussing the blocks of operation in a hypothetical radiation thermometer with a pyroelectric detector, potential errors were indicated that can challenge the efficiency of traditional algorithms that specify source temperature as a function of measured signal. To that end, two alternative approaches which enhance the Sakuma-Hattori method for fitting source temperature and signal count are discussed with respect to the actual behavior of these radiation thermometers.

Approach 1: Input Optics

The input optics approach to providing a better curve fit focuses in on everything that happens to the radiance between the incident radiance and the detector as shown in Figure 2. In other words, it is an attempt to account for any optical effects before and including the detector. This would mean the optical system essentially changes the Planckian amount of radiation between a perfect blackbody emittance and the pyroelectric detector. To evaluate this method, the Planckian form of the Sakuma-Hattori Equation (2) is rewritten as shown in Equation (3). The term ' $f(T)$ ' is substituted for. For the Planckian form of the Sakuma-Hattori Equation, $f(T) = AT + B$ in Equation (3). In this case, it is assumed that the relationship between the radiance incident on the detector and the readout radiance is perfectly linear.

$$S(T) = \frac{C}{\exp\left(\frac{c_2}{f(T)}\right) - 1} \quad (3)$$

where:

- C: curve-fitting parameter
- c_2 : Second Radiation Constant
- T: blackbody temperature
- $f(T)$: variation considered
- S: radiometric signal

Approach 2: Signal Processing

The second approach is to consider electronic non-linearity between the pyroelectric detector and the readout. To evaluate this, the inverse Sakuma-Hattori equation (2) is considered. Two approaches were used. The first is shown in Equation (4) where $f(S)$ is substituted using a polynomial or a polyfunction. The second is shown in Equation (5) where $g(S)$ is substituted using a polynomial or a polyfunction. For the Planckian form, $g(S) = S$ or $f(S) = C/S + 1$. The signal processing method assumes that the relationship between the input radiance and the radiance incident on the pyroelectric detector is linear.

$$T = \frac{c_2}{A \ln(f(S))} - \frac{B}{A} \quad (4)$$

where:

A, B: constants
 c_2 : Second Radiation Constant
T: blackbody temperature
 $f(S)$: variation considered
S: radiometric signal

$$T = \frac{c_2}{A \ln\left(\frac{C}{g(S)} + 1\right)} - \frac{B}{A} \quad (5)$$

where:

A, B, C: constants
 c_2 : Second Radiation Constant
T: blackbody temperature
 $g(S)$: variation considered
S: radiometric signal

Results of Curve-fit

The results of the curve fit are shown in Table 1. The 'pass' column indicates the goodness of fit and the maximum error criteria were met. Only two of the input-optics variants passed the criteria. In general, the input-optics variants fared better than the signal processing variants.

Variant Number	Equation	Variation	χ^2	Parameters	Max error/U	Pass
0	(1)		0.85	5	0.34	x
1	(2)		81.94	3	2.26	
2	(3)	$f(T) = AT + B + D/T$	1.88	4	0.37	x
3	(3)	$f(T) = DT^2 + AT + B$	18.34	4	1.10	
4	(3)	$f(T) = AT + B + DT^{1/2}$	1.57	4	0.38	x
5	(4)	$f(S) = a_3/S^3 + a_2/S^2 + a_1/S + a_0$	270.82	4	4.29	
6	(4)	$f(S) = a_2/S^2 + a_1/S + a_0 + a_{N1}S$	216.57	4	4.59	
7	(4)	$f(S) = a_1/S + a_0 + a_{N1}S + a_{N2}S^2$	218.55	4	5.00	
8	(4)	$f(S) = a_1/S + a_H/S^{1/2} + a_0$	254.26	3	6.25	
9	(5)	$g(S) = a_3S^3 + a_2S^2 + a_1S + a_0$	201.78	4	4.52	
10	(5)	$g(S) = a_2S^2 + a_1S + a_0 + a_{N1}/S$	108.64	4	2.80	
11	(5)	$g(S) = a_1S + a_0 + a_{N1}/S + a_{N2}/S^2$	1116.41	4	9.46	
12	(5)	$g(S) = a_1S + a_0 + a_{N1}/S + a_L \ln(S)$	868.50	4	8.16	
13	(5)	$g(S) = a_3S^{1/3} + a_2S^{1/2} + a_1S + a_0$	30.84	4	1.85	

Table 1: Comparison of Sakuma-Hattori Variants

FURTHER EXAMINATION OF BEST SOLUTION

To further examine the feasibility of using these proposed equations, a comparison was done using data taken at Fluke – American Fork over a period of nearly three years using four different KT19.82 radiation thermometers. This data include results from 59 calibrations. The results of this analysis are shown in Figure 3. The shaded areas in Figure 3 represent areas where the curve-fit would fail the goodness of fit check.

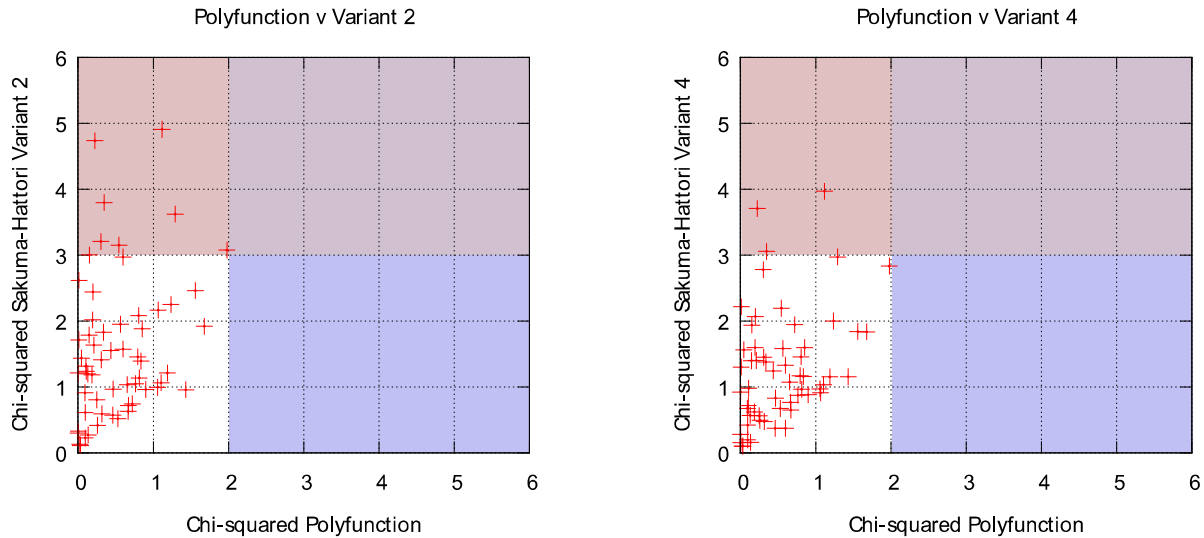


Figure 3. Goodness of Fit Comparison

As it can be seen in Figure 3, Variant 4 performed better than Variant 2. The polyfunction performed better than either of the variants. That being said, the variants do have the advantage that they only use 4 fitting parameters while the polyfunction uses five. With the seven calibration points used, the polyfunction must have a chi-squared of less than 2 to pass goodness of fit. The variants may have a chi-squared of up to 3 to pass goodness of fit. The polyfunction has the additional advantage that it can be solved using linear regression, while the Sakuma-Hattori must be solved using non-linear regression. [1]

CONCLUSION

The research presented in this paper demonstrated that a curve fit using the Sakuma-Hattori Equation in the Planckian form may not provide the best curve fit for the radiation thermometer studied in this work. This appears to be a phenomenon mostly related to the optical system and particularly a phenomenon when the radiation thermometer measures temperatures below ambient. However, there are feasible equations that can be used that are still Planckian in nature. While this experience may not be the case with narrowband radiation thermometers or other models of wideband radiation thermometers, others may benefit from considering this approach.

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REFERENCES

- [1] J. Fischer, P. Saunders, M. Sadli, M. Battuello, C. W. Park, Y. Zundong, H. Yoon, W. Li, E. van der Ham, F. Sakuma, Y. Yamada, M. Ballico, G. Machin, N. Fox, J. Hollandt, M. Matveyev, P. Bloembergen and S. Ugur, *CCT-WG5 on Radiation Thermometry, Uncertainty Budgets for Calibration of Radiation Thermometers below the Silver Point*, BIPM, Sèvres, France, 2008.
- [2] MSL Technical Guide 22 - Calibration of Low Temperature Infrared Thermometers, Measurement Standards Laboratory of New Zealand, 2008.
- [3] ASTM E2758-10, Standard Guide for Selection and Use of Wideband, Low Temperature Infrared Thermometers, ASTM International, West Conshohocken, PA, 2010.

- [4] F. Liebmann, Infrared calibration development at Fluke Corporation Hart Scientific Division, *Proceedings of SPIE Thermosense XXX*, 6939, 5, 2008.
- [5] F.E. Liebmann, T. Kolat, M. J. Coleman, T. J. Wiandt, Radiometric Comparison between a National Laboratory and an Industrial Laboratory, *Proceedings of Simposio de Metrología 2010*, Centro Nacional de Metrología, 2010.
- [6] C.F. Dietrich, Uncertainty, Calibration and Probability: The Statistics of Scientific and Industrial Measurement, 2nd Edition, Adam Hilger, Philadelphia, 1991, pp. 282-283.
- [7] F. Sakuma, M. Kobayashi, Interpolation equations of scales of radiation thermometers, *Proceedings of TEMPMEKO 1996*, 1996, pp. 305–310.
- [8] Component order in the Diagram based on a discussion with Peter Winter, Wintronics Inc., Dec. 2010.
- [9] VDI/VDE 3511 Blatt 4, *Technische Temperaturmessung Strahlungsthermometrie*, Verein Deutscher Ingenieure / Verband der Elektrotechnik Informationstechnik, 2010, p. 44.
- [10] E. Hecht, *Optics*, 2nd Edition, Addison Wesley, 1987, pp. 232.
- [11] Chopped Radiation Method Technote, Wintronics Inc., most likely written by Walter Glockmann of Heimann, circa 1990.
- [12] E. Hecht, *Optics*, 2nd Edition, Addison Wesley, 1987, pp. 128 – 129, 149.