Infrared Calibration Development at Fluke Corporation Hart Scientific Division

Frank E. Liebmann, [a] Marco A. Cabrera Carrasco [b]

[a] Fluke Corporation
799 Utah Valley Dr., American Fork, Utah, Estados Unidos de América.
Frank.Liebmann@hartscientific.com

[b] INyMET Instrumentación, S. A. de C. V.
Salvatierra 32-3, Col. San Bartolo Atepehuacan, 07730, Distrito Federal, México.

ABSTRACT

A flat plate calibrator is one instrument used in calibrating infrared (IR) thermometers, primarily in the 8 µm to 14 µm band. One such family of flat plate calibrators is the 418X Precision IR Calibrator from Fluke Corporation Hart Scientific Division. This product is calibrated with a radiometric calibration. To support this radiometric calibration and its traceability, a number of developments have been made at Hart Scientific. These developments include the construction of a new IR calibration laboratory with radiometric traceability. This presentation discusses the research done to establish IR calibration capabilities. Among the topics discussed are the need for radiometric traceability for flat plate calibrators, the traceability chain to national laboratories included in radiometric calibrations at Hart Scientific, the development of blackbody cavity baths in Hart's IR calibration laboratory, and Hart Scientific's IR uncertainty budgets.

1. INTRODUCTION

In the world of infrared (IR) thermometry, there has been much concern about the accuracy of IR thermometers. Contributing to this concern is a general misunderstanding of their use and operation. The two main aspects of this misunderstanding are a lack of knowledge of surface emissivity and a lack of knowledge of size of source or spot size. This is true as it applies to their use, and it is also true as it applies to their calibration.

To address these two issues, Fluke - Hart Scientific has developed two new flat plate IR calibrators. These products are calibrated with a radiometric (non-contact) calibration. To properly support this calibration, Hart has developed an IR calibration laboratory with traceable blackbody cavities. The establishment of this metrology has been the result of much research and experimentation involving IR temperature measurement. It has resulted in NVLAP accreditation for the 418X calibration as well as the calibration of the radiometric transfer standard.

2. 418X PRECISION IR CALIBRATOR

The 418X products are flat plate IR calibrators. The major application for these IR calibrators is the calibration of handheld IR thermometers in the 8 – 14 µm band. This range includes a bulk of the handheld IR thermometers sold today. A near blackbody cavity is the ideal calibrator for an IR or radiation thermometer. However, due to the large spot size or size of source effect of many handheld IR thermometers, the cavity's use is impractical for calibrating devices with larger spot sizes. This necessitates the use of a flat plate for IR thermometer calibrations.

The 418X products consist of 2 models, the 4180 and 4181. The two products have a combined temperature range of −15 °C to 500 °C. They have a number of features that make them an improvement on previous flat plate offerings. Among these features are their radiometric calibration and the metrology and traceability behind that calibration. Along with the radiometric calibration comes a robust uncertainty budget calculated to account for numerous factors and calibration support for the radiometric calibration. Both will be discussed later in this paper.

2.1. Radiometric Calibration

The 418X is calibrated with a radiometric calibration. The display temperature on the unit is based on this radiometric calibration. This display temperature shows the user what an IR thermometer with a given emissivity setting should read. This is called apparent temperature. In other words, the display temperature shows what temperature the target appears to be to the IR thermometer.

The radiometric calibration is done with a calibrated Heitronics KT19.82II, referred to as a KT19 in this paper. This KT19 is an 8 µm – 14 µm radiometer which serves as a radiometric transfer standard. The KT19 is calibrated using blackbody cavities at Hart that will be discussed later in this paper. The purpose for the radiometric calibration is to account for factors that cannot be accounted for with a contact calibration. The two main factors are the difference between contact temperature and surface temperature, and the difference between UUT emissivity and the target's surface emissivity.

The first problem with relying on a contact calibration is a lack of knowledge of the surface temperature. This is due to the fact that a contact calibration would not take place on the calibrator's surface, but below it, between the calibrator and the heat source. Heat flow creates a temperature drop. Tests at Hart Scientific have shown that this error can be up to 1,1 °C at 500 °C [1]. The second problem with relying on a contact calibration is the lack of knowledge of emissivity. Emissivity is especially troublesome because it can be both wavelength and temperature dependent. This makes assuming emissivity to be an arbitrary value questionable. Such an assumption can cause large temperature uncertainties.

A surface's emissive dependence on wavelength and temperature can be verified by Fourier Transform Infrared (FTIR) tests [2, 3]. Results from two such tests are shown in Fig. 1. These graphs show how non-gray a material can be. Gray is defined as a material having the same emissivity regardless of wavelength [4].

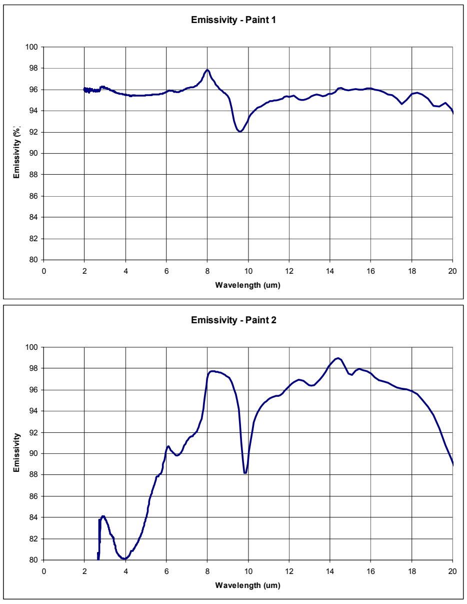

Fig 1. Results of FTIR Testing.

2.2. Use of the 8 μm – 14 μm Band

The 418X is meant for use in the 8 μm – 14 μm band. This is because this band is common to most handheld IR thermometers.

2.3. Larger Target Size

The 418X products provide the user with a 152 mm diameter flat plate. This gives the user a larger temperature controlled surface to calibrate IR thermometers. The target size needed to calibrate a given IR thermometer is dependent on the IR thermometer's optical system. Many IR thermometers come with a spot size diagram. These diagrams can be misleading because not all of the energy the IR thermometer detects is within the given spot diagram.

To determine an IR thermometer's size of source effect, ASTM provides a method [5]. Also, the IR thermometer manufacture may be able to provide you with information on the target size needed for calibration. The distance between the IR thermometer and the IR calibrator is also important for an IR thermometer calibration.

From testing done at Hart Scientific on a variety of IR thermometers [6], the spot-size diagram contained anywhere from 81 % to 98 % of the energy received by the IR thermometer. ASTM suggests that target size for a radiation thermometer be determined by the diameter where 99 % of the energy is received by the IR thermometer [5].

3. RADIOMETRIC CALIBRATION

The 418X calibration is done with a radiometric transfer standard (KT19), which is calibrated with Hart Scientific's blackbody cavity baths. The cavity's radiometric temperature is determined by contact thermometry. To verify the quality of the data, a number of controls and tests have been implemented.

3.1. 418X Calibration

Hart's radiometric calibration for the 418X is done with a KT19 that is calibrated with the cavity baths which are described in detail later in this paper. The 418X is set to a number of set-points. Its surface is measured by the KT19 with an emissivity setting of 0,95. This data is fed back to the 418X controller which makes the proper compensation, so that the display temperature will read within a given tolerance of the KT19's calibrated temperature.

There are a number of steps that have been taken to lessen uncertainties in the 418X calibration. First, the background temperature is controlled at near room temperature. Background temperature is defined as the temperature of any object facing the surface being measured [4]. This radiation can cause the apparent temperature of a surface to change. This is especially true at lower temperatures.

Second, for both the KT19 calibration and the 418X calibration, scatter is controlled by using a cooled aperture that is controlled at a constant temperature. This temperature is close to room temperature. Testing has been done to verify the effect of KT19 scatter on measurements with Hart's cavities [6]. This test follows an ASTM guideline [5] for testing size of source.

Third, the lower temperature range of the 4180 is −15 °C. There are 2 calibration points below ambient, −15 °C and 0 °C. Any radiometric calibration done between −15 °C and the dew point has the risk of causing dew or ice to form on the calibrator surface. To solve the problem with humidity at lower temperatures during calibration of the 4180, a purge system has been developed. This purge system involves enclosing everything between the KT19 and the 4180's surface. This area is purged with a dry gas, so that a positive pressure is maintained within this system. The frost point of the air inside the enclosure is monitored to ensure it is well below the calibration temperature.

3.2. KT19 Transfer Standard

As mentioned above, the KT19 is calibrated using Hart's cavity baths. The KT19 calibration uses the same calibration geometry that is used in the radiometric calibration of the 418X. This means that the calibration uses the same distance from KT19 to aperture, the same aperture size and the same controlled aperture temperatures. All of these values have tolerances and are accounted for in the KT19 and 418X uncertainty budgets. The KT19 is calibrated with the cavities at a number of set points. The temperature of the bath fluid during this calibration is monitored by a platinum resistance thermometer (PRT).

3.3. Self Consistency Checks

To show the quality of Hart Scientific's radiometric measurement data, a number of tests have been performed to show that Hart's data is self consistent. First, there are a limited number of points within Hart's cavity bath temperature range that are covered by more than one bath. At those points, radiometric temperature has been compared between cavities. A summary of one such comparison done with a TRT is listed in Table 1. The 2nd column lists the difference in radiometric temperature between the two cavities. The 3rd column lists Hart's radiometric uncertainty for the cavity.

Table 1. Comparison of radiometric temperature.

Temperature	Temperature Difference (°C)	U_{HART} (°C)
100 °C	0.0173	0.1000
200 °C	0.0814	0.1600

Second, a Heitronics TRTII (TRT) [7] has been used to measure Hart's cavities over their entire temperature range. This TRT is a dual band radiation thermometer. The data is curve-fit to the Sakuma-Hattori Equation [8]. This curve-fit is compared to Hart's uncertainties. A summary of this data is shown in Fig. 2. The error bars in these graphs represent the uncertainty with a coverage factor of 2 (k=2).

Similarly, the transfer standard's calibration has been curve-fit to the Sakuma-Hattori Equation. It has been found that the KT19 calibration can be better curve-fit into a polyfunction. The Sakuma-Hattori Equation contains 3 parameters while the polyfunction uses 5. The calibration of the KT19 uses 7 points making the curve fit over-determined.

Finally, the 418X calibration uses an over-determined curve fit to calculate apparent temperature from the control sensor resistance. After the calibration is performed, the adjustments are verified by an as-left calibration. Additional testing has been done at Hart to evaluate temperature set-points between the calibration points. A summary of one such check is shown in Fig. 3. The 418X calibration uses 5 points (-15 °C, 0 °C, 50 °C, 100 °C and 120 °C for the 4180 and 35 °C, 100 °C, 200 °C, 350 °C and 500 °C for the 4181). The additional points from these tests are taken between the standard calibration points for these units. Note that no additional error is observed on the points between the calibration points. The error bars indicate the 418X calibration uncertainty with a coverage factor of 2 (k=2).

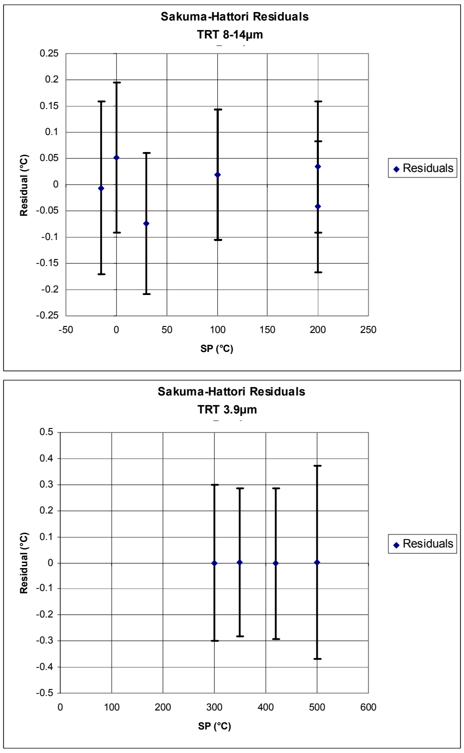

Fig. 2. Residuals from Sakuma-Hattori Curve-Fit of TRT Data.

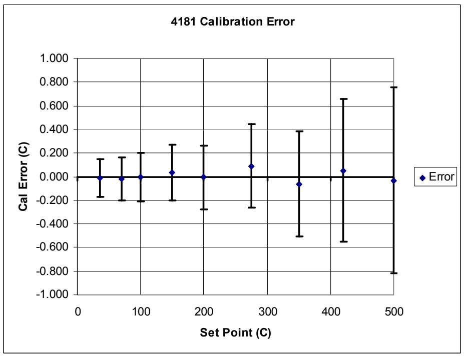

Fig 3. Error at Points between Calibration Points

4. DEVELOPMENT OF CAVITY BATHS

Part of Hart Scientific's radiometric calibration of its flat plates necessitated a calibrated transfer standard, the KT19. It was determined to be more favorable to have the transfer standard calibrated on site rather than rely on an outside laboratory to calibrate this instrument. This was mainly due to concerns of drift during transit. This necessitated constructing blackbody cavities for use on site.

4.1. NIST Cone

One of Hart's earliest designs of a cavity came from work done with NIST [9]. The NIST cone was a blackbody cavity with a spectral surface. The cone had an angle of 36,4 ° and was constructed of copper. The cone's temperature was maintained by a Hart Scientific model 6024 bath. It had a temperature range of 20 °C to 200 °C.

4.2. IR Calibration Facilities at HS

To facilitate the KT19 calibration, Hart Scientific has developed 3 cavity baths for use in Hart's new Infrared Calibration Laboratory. The cavity inside these baths is shown in Fig. 4. They are based on existing Hart models and use a cylinder-cone cavity that is 304 mm deep and 51 mm in diameter with a conical angle of 120°. The cavities have emissivity greater than 0,999. This number was verified by modeling with STEEP3 [10-12] which is discussed later in this paper.

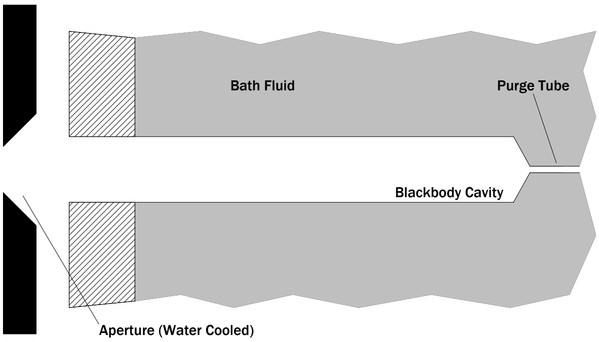

Fig 4. Blackbody cavity in bath.

Hart's cavity bath fluid temperature is monitored by Hart Scientific Model 5626 PRTs that are calibrated in Hart's Primary Calibration Laboratory. Their calibration is traceable to NIST. An illustration of this traceability is shown in Fig. 5.

4.3. STEEP3 Modeling

To gain better temperature uniformity on the cavity walls, the end of the cavity is purged with dried shop air that is heated to the bath temperature by a heat exchanger in the bath fluid. Hart has done experimentation to measure the temperature on the cavity walls by contact thermometry. The results from these tests are used in the STEEP3 model. This model reveals the results in Table 2. This table shows the effective emissivity at various temperatures plus the isothermal emissivity.

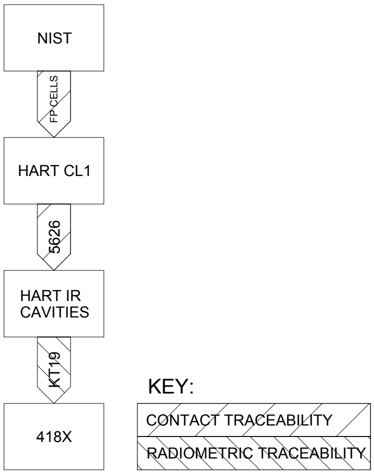

Fig 5. Radiometric traceability at hart.

Table 2. Effective Emissivty of Hart's Cavity Bath's

Bath	Bath Temperature	Effective Emissivity
LT & MT	Isothermal	0.9996
LT	−15°C	0.9998
LT	0°C	0.9997
LT	50°C	0.9995
LT	100°C	0.9994
HT	Isothermal	0.9996
HT	200°C	0.9993
HT	350°C	0.9992
HT	500°C	0.9991

To verify Hart's cavity modeling technique, STEEP3 was used to model cavities in a number of published papers [13-15].

5. HART'S IR UNCERTAINTY BUDGETS

Hart's IR uncertainty budgets are the result of much research into the uncertainties related to IR thermometry. The determination and calculation of these uncertainties involves a complex process of calculation and experimentation.

5.1. Determination of Uncertainties

The determination of Hart's uncertainties is an involved process. Where possible, experimentation has been performed to provide the uncertainty budgets with type 'A' uncertainties. Where experimentation is not possible, modeling has been performed to provide knowledge of the uncertainty. Two examples of this are the determination of cavity effects and determination of the effects of aperture temperature. Cavity effects are the effects of the cavity not acting as a perfect blackbody. These effects are evaluated in STEEP3. The effects of aperture temperature were evaluated by experimentation. The aperture temperature was varied, and the change in radiometric temperature was noted at several temperatures. The knowledge of the change in radiometric temperature versus the change in aperture temperature was used to calculate the effect of aperture temperature uncertainty in the KT19 uncertainty budget.

5.2. Evaluation of Uncertainties

As suggested by uncertainty budget guidelines [16], uncertainties are evaluated using the system's measurement equation. This measurement equation is based on Planck's Law evaluated over the 8 µm – 14 µm band [6]. This implementation of the measurement equation takes into account the effects IR thermometer's spectral response and considers the calibrator's emissivity, aperture geometry and background temperature. This implementation of Planck's Law is difficult to solve. Previous publications suggest the Sakuma-Hattori Equation or a narrow band form of Planck's Law should be used [8, 17]. In the case of the 418X, these were not used because of the wide band effects of emissivity and spectral response.

6. CONCLUSION

Developments behind the 418X project have resulted in a new measurement capability for Fluke - Hart Scientific. A radiometric calibration has been established as the standard calibration for these units. As a result, an infrastructure to support this calibration has been developed. This infrastructure includes radiometric transfer standards and blackbody cavities to support the 418X calibration. These developments plus education of the user will help to bring more accuracy and metrology to lower temperature IR thermometry.

ACKNOWLEDGMENTS

The author greatly appreciates the help of many people in developing this technique in calculating IR thermometry uncertainties. Among the people who have helped are Tom Wiandt, Mike Hirst and Rick Walker of Fluke Corporation Hart Scientific Division; Ingrid Gooding of Fluke; Patrick Parker, Alex Nikittin, Steve King, Medwin Schreher, Thomas Heinke and Reno Gärtner of Raytek; Leonard Hanssen, Benjamin Tsai, Sergey Mekhontsev and Howard

Yoon of NIST and Kendall Johnson of the Space Dynamics Laboratory at Utah State University.

REFERENCES

[1] F. Liebmann, "Infrared Thermometer Calibrator Development at Fluke Corporation Hart Scientific Division", Proceedings of NCSLI 2007.

[2] L. M. Hanssen, A. V. Prokhorov, V. B. Khromchenko, S. N. Mekhontsev, "Comparison of Direct and Indirect Methods of Spectral Infrared Emittance Measurement", Proceedings of TEMPMEKO 2004, pp. 539-544, 2004.

[3] L. M. Hanssen, V. B. Khromchenko, S. N. Mekhontsev, Infrared Spectral Emissivity Characterization Facility at NIST", Proceedings of SPIE, 5405, pp. 1-12, 2004.

[4] D. P. DeWitt G. D. Nutter, *Theory and Practice of Radiation Thermometry*, Wiley Interscience, New York, 1988, pp. 41-43, 72-73, 194.

[5] 1256 – 95, *Annual Book of ASTM Standards Vol. 14.03*, ASTM International, West Conshohocken, PA, 2005, pp. 490-491.

[6] F. Liebmann, "Determining Size Of Source For Handheld Infrared Thermometers – Theory And Practice", Proceedings of MSC 2008.

[7] O. Struß, "Transfer Radiation Thermometer Covering the Temperature Range from -50°C to 1000°C", AIP Conference Proceedings, Vol. 684, pp. 565-570, 2003.

[8] F. Sakuma, M. Kobayashi, "Interpolation Equations of Scales of Radiation Thermometers", Proceedings of TEMPMEKO '96, pp. 305-310.

[9] J. B. Fowler, "A Third Generation Water Bath Based Blackbody Source", Journal of Research of the National Institute of Standards and Technology, Vol. 100, Num. 5, pp. 591-599, 1995.

[10] A. V. Prokhorov, L. M. Hannsen, "Effective Emissivity of a Cylindrical Cavity with an Inclined Bottom", Metrologia, Vol. 41, pp. 421-431, 2004.

[11] V. I. Sapritsky, A. V. Prokhorov, "Spectral Effective Emissivities of Nonisothermal Cavities Calculated by the Monte Carlo Method", Applied Optics, Vol. 34, No. 25, pp. 5645-5652, 1995.

[12] A. V. Prokhorov, "Monte Carlo Method in Optical Radiometry", Metrologia, Vol. 35, pp. 465-471, 1998.

[13] J. Ishii, M. Kobayashi, F. Sakuma, "Effective Emissivities of Black-body Cavities with Grooved Cylinders", Metrologia, Vol. 35, pp. 175-180, 1998.

[14] F. Sakamura, L. Ma, "Cavity Emissivity of Fixed-Point Blackbody", SICE 2003 Annual Conference, Vol. 2, pp. 2187-2190, 2003.

[15] C. K. Ma, "Method for the Measurement of the Effective Emissivity of a Cavity", Proceedings of TEMPMEKO 2004, pp. 575-580, 2004.

[16] *U. S. Guide to the Expression of Uncertainty in Measurement*, John A. Wehrmeyer, Chair (National Conference of Standards Laboratories, Boulder, CO, 1997), pp. 4-8.

[17] Saunders, Fischer, Sadli, Battuello, Park, Yuan, Yoon, Li, van der Ham, Sakuma, Ishii, Ballico, Machin, Fox, Hollandt, Matveyev, Bloembergen, Ugur, Uncertainty Budgets For Calibration Of Radiation Thermometers Below The Silver Point, Paper presented at TEMPMEKO 2007, not yet published