Infrared Uncertainty Budget Determination in an Industrial Application

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Abstract

In infrared (IR) temperature measurement there is quite a bit of concern about how uncertainties affect the accuracy of temperature measurements. This is especially the case when non-blackbodies are being measured. Among the larger uncertainties that can effect an infrared temperature measurement are emissivity, spectral response, blackbody or gray body temperature uncertainty, optical scatter, size of source effect, and transfer standard uncertainty. Emissivity coupled with spectral response when measuring a non-blackbody can be especially troublesome since emissivity can vary with wavelength. Other factors that are minor contributors to uncertainty are alignment, calibration geometry, atmospheric losses and background temperature. Even though these factors are generally not as large, they should be considered as well. For an adequate radiometric uncertainty budget, all of these uncertainties must be evaluated.

This paper discussions the calculation of uncertainty budgets for infrared thermometry in an industrial application. It discusses the measurement equation used for uncertainty budget calculation and covers the merits of using this equation as opposed to other equations. It goes into the major uncertainties in these infrared uncertainty budgets and speaks to how they are applied to the measurement equation.

1. Introduction

Infrared (IR) thermometry is a useful technology. This is due in large part to quick response times and ability to measure temperature without contacting the system being measured. A major criticism of IR thermometry has been a lack of knowledge of measurement uncertainty. Indeed, without a proper uncertainty analysis, one cannot know how accurate measurements are. However, one can gain good information about the accuracy of IR measurements with a proper uncertainty analysis.

2. Hart's IR Metrology

Fluke - Hart Scientific established radiometric temperature metrology to support the calibration of the 418X IR Calibrator models. The 418X products are flat plate calibrators used for calibration of handheld IR thermometers. The 418X calibration is performed with a Heitronics KT19. The KT19 used for this calibration is an 8-14μm radiation thermometer used as a transfer standard between a series of blackbody cavities [1] and the 418X. A brief description of these calibrations is listed below.

2.1. KT19 Calibration

The KT19 is calibrated at 7 points in a temperature range from -15°C to 500°C. The radiance at each calibration point is observed. This data is applied to a curve fit to get a set of 5 parameters which are used in the polyfunction shown in (1). This polyfunction was found to provide the best curve fit for this calibration. The data is quality checked before the instrument is used in the factory [1].

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

The cavity's bath fluid is measured by use of a Model 5626 platinum resistance thermometer (PRT). The difference between the bath fluid temperature and the radiometric temperature of the cavity is included as the cavity effects portion of the KT19 uncertainty budget.

2.2. 418X Calibration

Hart's radiometric calibration for the 418X is done with the KT19 using the same calibration geometry that is used for the KT19's calibration [1]. The 418X uses 5 points for its calibration. This data is used to make an adjustment to the 418X. The 418X's calibration is then checked by checking all 5 of these points. This data must meet test requirements meaning the final residuals of the calibration must be within a certain guard band of the 418X calibration uncertainties.

Through these steps, the 418X has a radiometric calibration traceable to a national laboratory [1]. This traceability is shown in Figure 1.

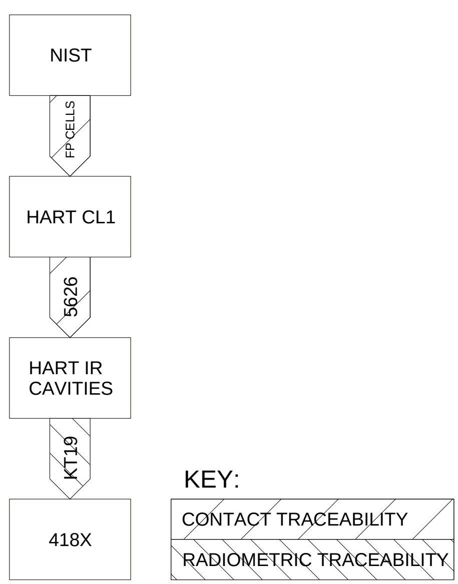

Figure 1. 418X Calibration Traceability.

3. Calculation of Uncertainties - Theory

There are many uncertainties that need to be considered when assembling an uncertainty budget for IR thermometry or radiation thermometry. Similar uncertainties apply for the calibration of an IR thermometer, a blackbody calibrator or a gray body calibrator. A proper evaluation of uncertainties in IR thermometry requires a measurement equation. This is important because it shows the influence quantities [2] that affect the measurement. It also gives us a mathematical tool to model uncertainties.

Both the 418X and KT19 uncertainty budgets are included at the end of this paper in Tables 2, 3 and 4. Explanations of these uncertainties are covered in Section 4 of this paper. The creation of IR uncertainty budgets at Hart involved much calculation. In many cases the uncertainties could not be measured. This meant theoretical methods involving modeling were considered.

3.1. Current Standards Considered

It has been suggested that the Sakuma-Hattori equation (2) be used as the measurement equation for radiation thermometry uncertainty budgets [3]. At Hart Scientific it was not used because of the dynamic nature of the KT19's spectral response when measuring a non-gray [4] surface. In this case, calculation of the parameters for Sakuma-Hatori would be difficult, if not impossible. In fact, a curve-fit would need to be performed for each variation of spectral response and emissivity as shown in Figures 2 and 3. A curve fit for the Sakuma-Hattori requires nonlinear regression. Figure 2 is based on information provided by the KT19's manufacturer. The graph in Figure 3 is based on Fourier Transform Infrared (FTIR) testing [5, 6] of the coating used on the 418X.

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

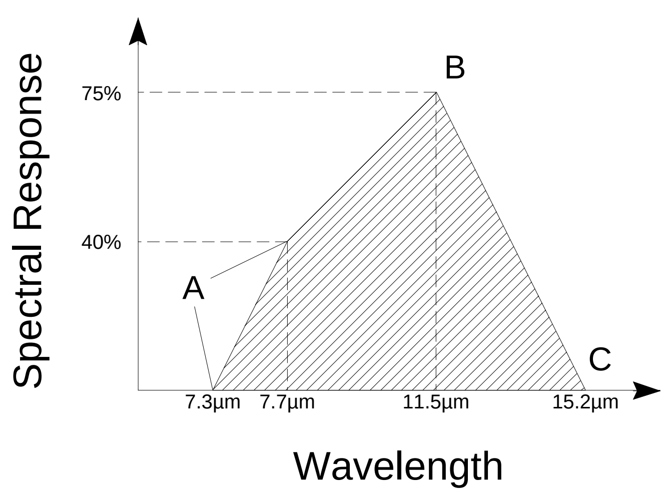

Figure 2. KT19 Spectral Response as Modeled in Hart's Uncertainty Budgets.

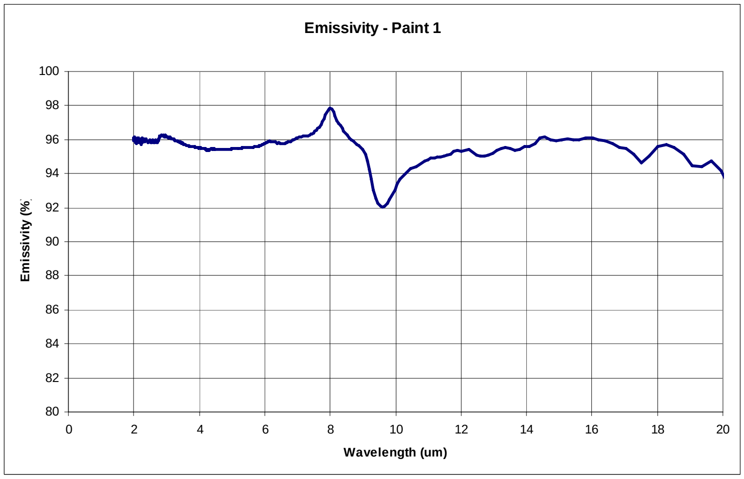

Figure 3. Spectral Response of 418X Emissivity.

3.2. Measurement Equation

The measurement equation used in these uncertainty budgets is derived from Planck's Law [4]. It models the radiant power density in a radiation thermometer measurement system. This equation can be used for evaluating uncertainties for IR thermometer calibrations such as the KT19 and IR calibrator calibration such as the 418X's calibration.

The measurement equation is shown in (3). The letter S refers to the power or radiance the radiation thermometer measures. In this model, the radiation thermometer's signal is the S_{CAL} part of the model. The radiation thermometer's use is modeled be the S_{MEAS} part of the model. The readout of the radiation thermometer is calibrated so that its readout matches T_{CAV}. This happens when the radiation thermometer receives S_{CAL} radiance. Then during its use it receives S_{MEAS} radiance. Through a mathematical algorithm, it computes a temperature T_{TGT} based on this received radiance. For a radiometric flat plate or cavity calibration, S_{MEAS} is the radiance coming off the unit under test and S_{CAV} is the radiance received by the radiation thermometer during its calibration. In (3), α represents spectral response of the radiation thermometer. β represents transmission between the measured surface and the radiation thermometer. ε represents the emissivity of the surface. The values for S(T) are calculated using Planck's Law evaluated over the KT19's spectral response (4).

$$
\begin{aligned}
S_{CAL} &= \beta\left(\alpha_{CAL}(\lambda)\varepsilon_{CAV}(\lambda)S(T_{CAV}) + \alpha_{CAL}(\lambda)[1-\varepsilon_{CAV}(\lambda)]S(T_{BG-CAL})\right) + (1-\beta)S(T_{APE-CAL}) \\
S_{MEAS} &= \beta\left(\alpha_{MEAS}(\lambda)\varepsilon_{TGT}(\lambda)S(T_{TGT}) + \alpha_{MEAS}(\lambda)[1-\varepsilon_{TGT}(\lambda)]S(T_{BG-MEAS})\right) + (1-\beta)S(T_{APE-MEAS}) \\
S_{CAL} &= S_{MEAS}
\end{aligned} \tag{3}
$$

$$
S = \int_0^\infty \frac{\pi c_{1L}}{\lambda^5\left[\exp\left(\frac{c_2}{\lambda T_{CAV}}\right)-1\right]} d\lambda \tag{4}
$$

4. Calculation of Uncertainties - Practice

To calculate the uncertainties a number of methods have been employed. Where possible, experimentation has been done to determine the effect of an uncertainty. Where this is not possible, the measurement equation was used to model these uncertainties. The following subsections contain an explanation of the uncertainties included in the 418X and the KT19 uncertainty budgets. A summary of these uncertainties is listed in Table 1.

Table 1. 418X and KT19 Uncertainty Budget Elements.

Uncertainty	**KT19 Calibration**	**418X Calibration**	**Calculated by**
Ambient Temperature	X		Manufacturer Specifications
Aperture Losses	X	X	Modeled
Aperture Temperature	X	X	Tested
Atmospheric Losses	X	X	Modeled
Background Temperature		X	Modeled
Cavity Effects	X		Modeled
Hysteresis		X	Historical
Display (Readout) Resolution	X	X	Calculated
Noise	X	X	Controlled
PRT calibration and characterization	X		Calculated
PRT self-heating	X		Historical
PRT stem effect	X		Historical
Radiometric Curve Fit		X	Tested
Readout accuracy	X		Manufacturer
Repeatability	X	X	Tested
RT Calibration		X	Calculated
RT Spectral Response and Target Emissivity		X	Modeled
Stability (long term)	X	X	Controlled
Temperature settling		X	Tested
Uniformity		X	Tested
Z-axis temperature loss		X	Tested

4.1. Ambient Temperature

Hart's laboratory's ambient temperature limits are 23°C ±3°C. For the KT19 calibration, the effects of ambient temperature were determined by observing a blackbody with fixed temperature and the laboratory with varying ambient temperature. During this test the error caused by effect of ambient temperature was within the noise level of the KT19. It is assumed that this effect is smaller than the noise of the KT19. This uncertainty was based on the manufacturer's specifications.

4.2. Aperture Losses

This uncertainty is based on the uncertainty of the alignment of the KT19. Since practical testing of this uncertainty revealed that this uncertainty was below the noise floor of the KT19 measurements, this uncertainty was based on size of source testing and modeling.

The results of the KT19 size of source testing are shown in Figure 4. The uncertainty was modeled by taking this size of source data and modeling tolerance of the aperture diameter, error due to angular displacement, and error due to radial displacement.

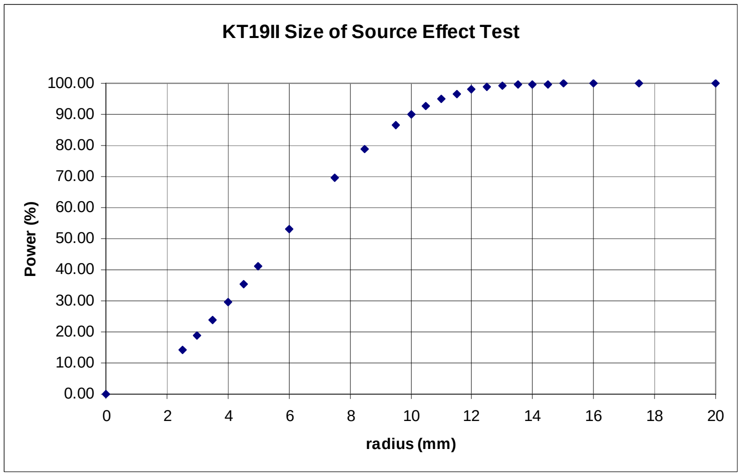

Figure 4. KT19 Size of Source Effect.

4.3. Aperture Temperature

During measurements using the KT19, the aperture is maintained at a temperature within a tolerance. This tolerance is specified in the KT19 and 418X test procedures.

Testing was done to determine what the effect of aperture temperature was on KT19 readings. Results of one such test is shown in Figure 5. In this test, the change in aperture temperature was exaggerated to be able to clearly observe the effects of change in aperture temperature versus change in KT19 readout. The limits on the aperture probe drift are the second component of this uncertainty.

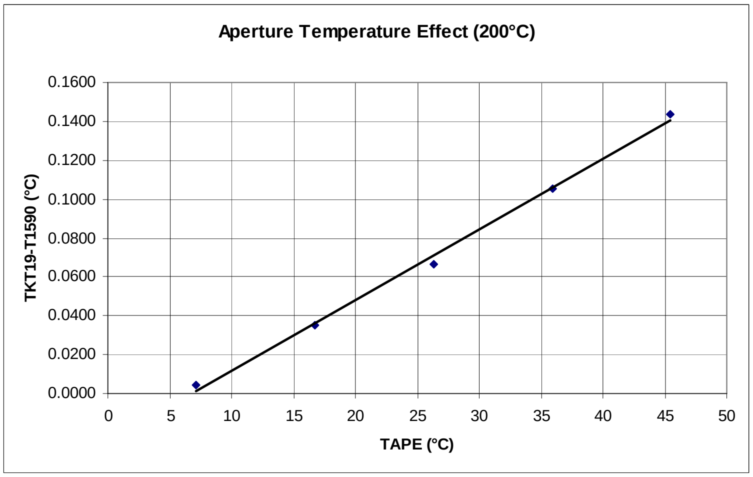

Figure 5. Aperture Temperature Test.

4.4. Atmospheric Losses

Data is calculated based on modeling of transmission through an air path [7]. Since the transmission path for the KT19 and 418X calibration is short, the atmospheric losses are small. This ratio of energy transmitted between the source and the KT19 is computed. The transmission is multiplied by the total power per wavelength at each temperature to get transmission of exitance radiance. Since the uncertainty in radiance will be less than this number, this number is used for the uncertainty budget. This uncertainty is likely overestimated. However, since it is such a small uncertainty, it has almost no impact on the total uncertainty.

4.5. Background Temperature

Background radiation is the reflected radiation from a surface [4]. It is modeled by T_{BG} in the measurement equation. The effect of background temperature is one that does not affect a perfect blackbody. It is a concern for flat surfaces and is more of a concern at lower temperatures than higher temperatures, especially when the background temperature is greater than the temperature of the object being measured.

Since the aperture plate provides the 418X's background during calibration, the effect of background temperature is calculated by taking the effect of a 1°C change on background temperature and multiplying it by the aperture's temperature uncertainty. Hart uses the aperture temperature since it is the source of the target's background.

4.6. Cavity Effects

Cavity effects are those effects that cause the cavity not to behave as a perfect blackbody. The calculation of this uncertainty was based on STEEP 3 [8, 9, 10] modeling of the cavities [1]. Uncertainties below 0.1K are rounded up to 0.1K. Testing has been performed to observe the temperature uniformity on cavity walls. This data is used as part of the STEEP 3 model. The results of one such test is shown in Figure 6.

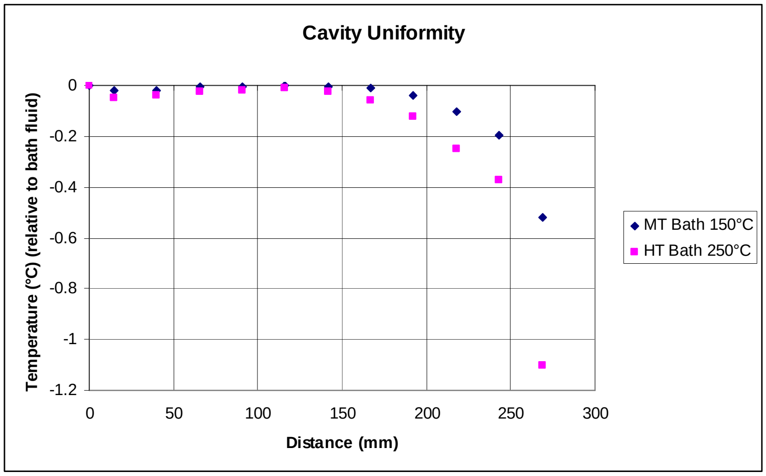

Figure 6. Temperature Uniformity of Cavity Walls.

4.7. Display (Readout) Resolution

For the KT19, this is based on 1 unit of radiance (±0.5 RAD). This data is evaluated against the dT/dS as shown in (5) to obtain this uncertainty in temperature.

$$\Delta T(T) = \frac{\partial T(T)}{\partial S} \Delta S(T) \qquad (5)$$

For the 418X uncertainty budget, temperature is displayed to two decimal places. Thus, the uncertainty based on display resolution is ±0.005°C.

4.8. Hysteresis

This is the uncertainty due to hysteresis of control sensor in the unit under test. It is based on historical data of products of similar construction using an identical control sensor. It is not measured using the KT19 since this hysteresis is less than the noise floor of the KT19.

4.9. Noise , Measurement Noise and Precision of Measurement (Noise)

This uncertainty has bounds set in the calibration procedures. Any time a calibration exceeds the limits for noise, that measurement is rejected and must me retaken. Measurement times for all these calibrations are at least 5 minutes.

4.10. PRT calibration and characterization

This uncertainty is based on Hart Scientific's NVLAP scope. The uncertainties in the scope are propagated to the temperatures used in the KT19 calibrations.

4.11. PRT Self-Heating

This is the contribution due to differences in PRT self-heating [11] between the PRT's calibration apparatus and operation in the unit under test. This uncertainty is based on experience measuring this uncertainty in Hart's calibration laboratory.

4.12. PRT Stem Effect

This is the contribution due to the stem effect [12] during measurement in the cavity bath. The stem effect is the effect of heat flow losses through the PRT's stem. This uncertainty has been obtained by measurement of PRTs in differing thermal situations.

4.13. Radiometric Curve Fit

This is error due to curve fitting the KT19's calibration to the polyfunction (1). It was evaluated by experimentation and modeling.

4.14. Readout Accuracy

The Hart Model 1590 Superthermometer is the readout used for measuring the cavity bath fluid temperature. When the internal resistor of the 1590 is used, the accuracy specification for the 1590 is 6 PPM. The temperature equivalent of this uncertainty in resistance is calculated and used in the uncertainty budget.

4.15. Repeatability

This is the contribution from the difference in measurements at different times. It is meant to account for any uncertainties that have not been included in the uncertainty budget. As of the date of this paper, Hart has not been able to determine any additional uncertainties that have not been covered elsewhere in the uncertainty budgets.

4.16. RT Calibration

This is an element of the 418X IR calibrator calibration uncertainty budget. This uncertainty is the combined expanded uncertainty of the KT19 uncertainty budget.

4.17. RT Spectral Response and Target Emissivity

This is a rather complex uncertainty to describe. It is also complex to calculate. This uncertainty is the contribution from the uncertainty in the spectral response of the RT measuring the plate. Since the plate is not a perfect gray body, the spectral response of the emissivity of the target's surface must be taken into account. The contribution from the spectral response is based on information given by Heitronics. The spectral response of the paint is based on FTIR testing. These two data are modeled mathematically to determine the effect of the spectral response uncertainty. Hart Scientific has given the user the data in Figures 2 and 3 for calculation of uncertainty. These same figures are used to calculate Hart's uncertainties.

4.18. Stability (Long-Term)

This is the long-term stability of the temperature measurement device, sometimes referred to as drift [12]. It applies to both the 5626 PRT used to measure temperature in the cavity baths and the KT19's calibration. Hart's calibration procedures specify these instruments will fall within this limit. Calibration intervals are adjusted to ensure that this happens.

4.19. Temperature Settling

This uncertainty is based on experimental information collected at Hart Scientific. This uncertainty refers to how much the 418X's temperature will change or settle once measurements during the calibration begin. The calibration procedure calls for a 15 minute soak time. This means that once the instrument indicates it is stable, measurements will not begin for at least 15 minutes. This uncertainty was determined by experimentation.

4.20. Uniformity

This is the contribution from temperature gradients on the 418X's calibration surface. It is expected that the KT19's aim point on the target may be off center of the target up to 3mm (~1/8"). The target's uniformity has been determined by experiment. This uncertainty is calculated from these experiments.

4.21. Z-axis Temperature Loss

Z-axis temperature loss is the uncertainty between the control sensor temperature and the surface's apparent temperature. This difference is based on the uncertainty of the heat flow between the sensor and the target surface. This heat flow path is illustrated in Figure 7. This uncertainty was calculated based on experimentation. This experimentation was done with a target set at 500°C. The rest of the temperatures' uncertainties were interpolated from the 500°C data.

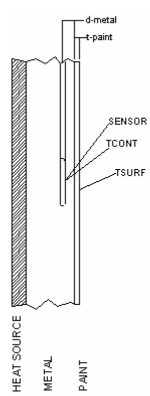

Figure 7. Heat Flow between Control Sensor and Target Surface.

5. 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. To provide traceability for this calibration, an infrastructure has been created including construction of a radiation thermometry calibration laboratory. To analyze the uncertainty in these calibrations, a complete uncertainty analysis has been performed as outlined in this paper. Through these efforts, Hart was able to receive NVLAP accreditation for both the 418X calibration and the KT19 calibration.

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Table 2: 4180 Radiometric Uncertainties.

Uncertainties	Denot.	Type	Dist	Factor	Uncertainty (°C)				
					-15	0	50	100	120
Reference radiometer related uncertainties									
RT calibration	ur1	A	norm	2.00	0.1267	0.1242	0.1216	0.1208	0.1211
RT stability (long term)	ur2	A	norm	2.00	0.1000	0.0700	0.0700	0.1000	0.1000
RT noise	ur3	A	norm	2.00	0.0590	0.0350	0.0390	0.0470	0.0520
RT readout resolution	ur4	B	rect	1.73	0.0031	0.0026	0.0016	0.0011	0.0010
RT spectral response and target emissivity	ur5	B	norm	2.00	0.0681	0.0366	0.0327	0.0802	0.0972
RT ambient temperature	ur6	A	norm	2.00	0.0100	0.0100	0.0100	0.0100	0.0100
Atmospheric losses	ur7	B	norm	2.00	0.0050	0.0054	0.0068	0.0083	0.0090
Aperture temperature	ur8	B	norm	2.00	0.0091	0.0075	0.0047	0.0033	0.0029
Aperture losses	ur9	B	norm	2.00	0.0047	0.0052	0.0070	0.0091	0.0099
Repeatability	ur10	A	norm	2.00	TBD	TBD	TBD	TBD	TBD
Background temperature	ur11	B	rect	1.73	0.0074	0.0063	0.0040	0.0029	0.0027
Control related uncertainties									
Display resolution	ur12	B	rect	1.73	0.0050	0.0050	0.0050	0.0050	0.0050
Hysteresis	ur13	A	rect	1.73	0.0000	0.0010	0.0020	0.0010	0.0000
Repeatability	ur14	A	norm	2.00	0.0050	0.0020	0.0020	0.0040	0.0040
Temperature settling	ur15	A	rect	1.73	0.0100	0.0100	0.0100	0.0100	0.0100
Target temperature related uncertainties									
Uniformity	ur16	B	rect	1.73	0.0120	0.0120	0.0120	0.0200	0.0250
Z-axis temperature loss	ur17	B	norm	2.00	0.0096	0.0056	0.0068	0.0195	0.0244
Radiometric curve fit	ur18	B	rect	1.73	0.0100	0.0100	0.0150	0.0300	0.0300
Combined standard uncertainty	uc	k=1	normal		0.099	0.080	0.080	0.100	0.105
Combined expanded uncertainty (k=2)	U	k=2	normal		0.199	0.160	0.159	0.200	0.210

Table 3: 4181 Radiometric Uncertainties.

Uncertainties	Denot.	Type	Dist	Factor	Uncertainty (°C)				
					35	100	200	350	500
Reference radiometer related uncertainties									
RT calibration	ur1	A	norm	2.00	0.1231	0.1208	0.1223	0.2262	0.3658
RT stability (long term)	ur2	A	norm	2.00	0.0700	0.1000	0.1000	0.1200	0.4000
RT noise	ur3	A	norm	2.00	0.0380	0.0550	0.0850	0.1400	0.2000
RT readout resolution	ur4	B	rect	1.73	0.0018	0.0011	0.0007	0.0005	0.0005
RT spectral response and target emissivity	ur5	B	norm	2.00	0.0154	0.0802	0.1623	0.2917	0.4369
RT ambient temperature	ur6	A	norm	2.00	0.0100	0.0100	0.0100	0.0100	0.0100
Atmospheric losses	ur7	B	norm	2.00	0.0063	0.0083	0.0120	0.0187	0.0263
Aperture temperature	ur8	B	norm	2.00	0.0052	0.0033	0.0022	0.0025	0.0053
Aperture losses	ur9	B	norm	2.00	0.0064	0.0091	0.0138	0.0224	0.0322
Repeatability	ur10	A	norm	2.00	TBD	TBD	TBD	TBD	TBD
Background temperature	ur11	B	rect	1.73	0.0045	0.0029	0.0020	0.0015	0.0013
Control related uncertainties									
Display resolution	ur12	B	rect	1.73	0.0050	0.0050	0.0050	0.0050	0.0050
Hysteresis	ur13	A	rect	1.73	0.0000	0.0050	0.0050	0.0050	0.0000
Repeatability	ur14	A	norm	2.00	0.0020	0.0040	0.0070	0.0120	0.0170
Temperature settling	ur15	A	rect	1.73	0.0100	0.0100	0.0140	0.0200	0.0300
Target temperature related uncertainties									
Uniformity	ur16	B	rect	1.73	0.0120	0.0180	0.0280	0.0420	0.0620
Z-axis temperature loss	ur17	B	norm	2.00	0.0032	0.0192	0.0444	0.0824	0.1200
Radiometric curve fit	ur18	B	rect	1.73	0.0250	0.0500	0.0500	0.0600	0.0600
Combined standard uncertainty	uc	k=1	normal		0.080	0.104	0.134	0.222	0.393
Combined expanded uncertainty (k=2)	U	k=2	normal		0.159	0.207	0.267	0.444	0.787

Table 4: KT19 Uncertainties.

Uncertainties	Denot.	Type	Dist	Uncertainty (°C)				
				-15	50	100	200	500
Bath Temperature Measurement								
PRT calibration and characterization	u1	A	rect	0.0120	0.0120	0.0120	0.0120	0.0280
PRT stability (long term)	u2	A	norm	0.0100	0.0120	0.0140	0.0180	0.0290
Measurement noise	u3	A	norm	0.0015	0.0019	0.0022	0.0028	0.0038
PRT self-heating	u4	B	norm	0.0015	0.0015	0.0015	0.0015	0.0015
PRT stem effect	u5	A	rect	0.0020	0.0020	0.0020	0.0020	0.0020
Readout accuracy	u6	B	rect	0.0014	0.0018	0.0022	0.0028	0.0050
KT19 Radiation measurement								
RT readout resolution	u7	B	rect	0.0031	0.0016	0.0011	0.0007	0.0005
RT ambient temperature	u8	A	norm	0.0100	0.0100	0.0100	0.0100	0.0100
RT noise	u9	A	norm	0.0400	0.0250	0.0200	0.0200	0.0350
RT repeatability	u10	A	norm	TBD	TBD	TBD	TBD	TBD
Atmospheric losses	u11	B	norm	0.0050	0.0068	0.0083	0.0120	0.0263
Aperture losses	u12	B	norm	0.0047	0.0070	0.0091	0.0138	0.0322
Aperture temperature	u13	B	norm	0.0091	0.0047	0.0033	0.0022	0.0053
Cavity effects	u14	A	norm	0.1000	0.1000	0.1000	0.1000	0.3100
Combined standard uncertainty	Uc	k=1	normal	0.063	0.061	0.060	0.061	0.183
Combined expanded uncertainty (k=2)	U	k=2	normal	0.127	0.122	0.121	0.122	0.366