Understanding Two-Color (Ratio) Pyrometer Accuracy

Myth: Ratio pyrometers (Two-Color) are more accurate because they are emissivity independent.

Fact: In some applications, the ratio pyrometer is emissivity independent, but a certain important condition must exist. This condition is that the ratio of emissivities must remain constant throughout the application. In general, ratio pyrometers are not more accurate. In fact, when this certain important condition does not exist, they are much less accurate than the single wavelength (single color) pyrometer at or near the same operating wavelength. This application note is an attempt to explain why this is so.

Every ratio pyrometer uses two single wavelength or single "color" channels at the beginning. The equation driving each channel is

(1) $I_{\lambda 1} = \varepsilon_{\lambda 1} L_{\lambda 1}$

(2) $I_{\lambda 2} = \varepsilon_{\lambda 2} L_{\lambda 2}$

Where:
$I_{\lambda 1}$ = channel 1 signal (not linearized to temperature)
$\varepsilon_{\lambda 1}$ = target emissivity at channel 1 wavelength
$L_{\lambda 1}$ = the target's energy at channel 1 wavelength equivalent to a blackbody at equal temperature.

$I_{\lambda 2}$ = channel 2 signal (not linearized to temperature)
$\varepsilon_{\lambda 2}$ = target emissivity at channel 2 wavelength
$L_{\lambda 2}$ = radiant energy at channel 2 wavelength equivalent to a blackbody at equal temperature.

The "ratio" function divides these two signals. If $\varepsilon_1 = \varepsilon_2$, emissivities cancel out. If ε_1 does not equal ε_2, then an adjustment must be made which is typically called "Slope" in ratio pyrometers. Slope = $\varepsilon_1 / \varepsilon_2$; the ratio of emissivities. (On some instruments, Slope = the inverse of the ratio).

To understand ratio measurement accuracy, one has to examine the uncertainties (or accuracies) of each channel (color) separately.

Single Color Pyrometer (or one channel of a ratio pyrometer)

A single wavelength pyrometer receives this signal (I) from the infrared target

(1) $I_{\lambda 1} = \varepsilon_{\lambda 1} L_{\lambda 1}$

Where:
$I_{\lambda 1}$ = signal
$\varepsilon_{\lambda 1}$ = target emissivity at measurement wavelength

$L_{\lambda 1}$ = radiant energy at measurement wavelength equivalent to a blackbody at equal temperature.

If aiming at a blackbody with emissivity = 1.0. The equation is now

(3) $I_{\lambda 1} = L_{\lambda 1}$

Typical uncertainties when N.I.S.T performs a radiance calibration of a pyrometer at their blackbody where the measuring wavelength is 655nm are listed in the table below. (Actual numbers may be better (or worse) depending on the instrument undergoing calibration. The numbers below do not represent the best possible uncertainties that N.I.S.T. is capable of delivering.) *Reference to N.I.S.T. could be replaced with "calibration lab of your choice" as long as they list uncertainties in their calibration reports.*

Table 1

Temperature °C	Uncertainty °C *(k=2)*	Temperature °F	Uncertainty °F *(k=2)*
800	0.5	1472	0.9
1100	0.7	2012	1.3
1500	0.9	2732	1.6
1900	1.1	3452	2.0
2700	3.0	4892	5.4

How to read this table:
The uncertainty numbers can be read as +/- °C (and +/- °F). The definition of the confidence level, "k=2", can be loosely translated as follows:
If you were to take 100 measurements, 95 of them would be equal to or less than the uncertainties listed in the above table (or inside the uncertainty window).

Example 1: You send a single wavelength pyrometer to N.I.S.T. for calibration. You receive a report similar to above. At 800°C, your single color pyrometer of the same wavelength as N.I.S.T's pyrometer may read anywhere from 800-0.5 to 800+0.5 °C (or 1472 – 0.9 to 1472 + 0.9 °F), for 95 out of 100 readings if you were to aim them *at the blackbody at N.I.S.T.*

Now, imagine you have two identical pyrometers that you just sent to N.I.S.T. for calibration. Each one could behave as just described above independently if you were to aim them at the blackbody at N.I.S.T. Pyrometer #1 might read 800 – 0.5 °C and pyrometer #2 might read 800 + 0.5°C and they both would be within the uncertainty or "accuracy". Two identical instruments aimed at N.I.S.T.'s blackbody could possibly read 799.5 and 800.5°C. This scenario describes the "worst of the best" possible accuracy; you take your two pyrometers to N.I.S.T. and aim them at their blackbody. At 800°C, the two pyrometers could have a 1°C delta-T the next day when the delta-T was 0°C the previous day. Different blackbody and/or target emissivities have not even been discussed yet.

Emissivity sensitivity vs. wavelength for single color pyrometers

This function must be understood before applying the ratio pyrometer.

So far, emissivity has not been discussed as a source of measurement uncertainty. This section will address this important issue. Notice that the above discussions mentioned the phrase "if you were to aim them at the blackbody at N.I.S.T.". This is because the blackbody used for calibration must be used to test the calibration uncertainty to avoid any emissivity contributions.

The table below illustrates the measurement errors vs. single color wavelengths for the temperatures shown in the above temperature/uncertainty table. The delta-T's shown represent the error introduced by a 1% change in emissivity. For example, a blackbody with emissivity of 0.98 instead of 0.99.

Table 2

Temperature °C	.65µm	0.9µm	0.95µm	1.3µm	3.9µm
800	-0.5	-0.8	-0.8	-1.1	-3.0
1100	-0.9	-1.2	-1.3	-1.8	-4.7
1500	-1.5	-2.0	-2.2	-2.8	-7.4
1900	-2.2	-3.0	-3.3	-4.2	-10.4
2700	-4.1	-5.6	-6.1	-7.5	-16.9

Temperature °F	.65µm	0.9µm	0.95µm	1.3µm	3.9µm
1472	-0.9	-1.4	-1.4	-2.0	-5.4
2012	-1.6	-2.2	-2.3	-3.2	-8.4
2732	-2.7	-3.6	-4.0	-5.0	-13.3
3452	-4.0	-5.4	-5.9	-7.6	-18.7
4892	-7.4	-10.1	-11	-13.5	-30.4

Typical observed delta-T caused by -1% emissivity shift (single color)

From this table, it becomes obvious that the shorter the wavelength, the less effect emissivity has on the measurement with single color pyrometers.

It also becomes clear that if the uncertainty of the emissivity is +/-1%, large errors can begin to build. A pyrometer with effective wavelength of 0.9µm aimed at a blackbody or other target that is 1500°C and the emissivity is known within +/-1%, the error from emissivity alone will be +/- 2°C (3.6°F).

Not only emissivity uncertainty, but optical path transmission plays an equal role.

Example 2: There is a protective window on the optical pyrometer that has collected enough dirt or evaporated film to lower its transmission by only 1%. The exact same errors will appear as listed in the above table. The actual equation that the pyrometer reads as a signal is

(5) $I_{\lambda 1} = t_{\lambda 1} \varepsilon_{\lambda 1} L_{\lambda 1}$

Where t1 = window transmission at the measurement wavelength! (This term usually = 1 during a laboratory calibration)

A target emissivity reduction of only 1% and window transmission reduction of 1% will introduce – 4°C (-7.2°F) to the measurement (at 1500°C).

Ratio Pyrometer

Now, knowing the single color uncertainties from a calibration, the emissivity and optical path sensitivities, we try to apply these to the ratio pyrometer.

Again, the ratio pyrometer operates on these two signals

(1) $I_{\lambda 1} = \varepsilon_{\lambda 1} L_{\lambda 1}$

(2) $I_{\lambda 2} = \varepsilon_{\lambda 2} L_{\lambda 2}$

Where:

I_1 = channel 1 signal (not linearized to temperature)
ε_1 = target emissivity at channel 1 wavelength
L_1 = radiant energy at channel 1 wavelength equivalent to a blackbody at equal temperature.
I_2 = channel 2 signal (not linearized to temperature)
ε_2 = target emissivity at channel 2 wavelength
L_2 = radiant energy at channel 2 wavelength equivalent to a blackbody at equal temperature.

The "ratio" function divides these two signals. Assuming that $\varepsilon_1 = \varepsilon_2$, emissivities cancel out. If ε_1 does not equal ε_2, then an adjustment must be made which is typically called "Slope" in ratio pyrometers. Slope = $\varepsilon_1 / \varepsilon_2$; the ratio of emissivities.

Emissivity ratio sensitivity for two-color pyrometers.

Unfortunately, there is a price to pay (not dollars) for the ability of the ratio pyrometer to be able to cancel out the emissivity term in the above two equations (1 and 2). This price is the emissivity ratio sensitivity that can become as large as 10 times that of a single color pyrometer (See equation 6 below). For every 1 degree measurement difference between channels (in C or F), there could be up to 10 degrees shift in the two-color temperature.

The equation that drives the emissivity ratio correction (or "slope") is

(6) $1/T_{new} = 1/T_{old} + (\lambda_1\lambda_2/14388(\lambda_{2\_}\lambda_1)) \ln(\varepsilon_{\lambda 2}/\varepsilon_{\lambda 1})$

Where:

T_{new} = new temperature (in Kelvin)
T_{old} = old (before slope adjustment) temperature (in Kelvin)
λ_1 = effective wavelength for channel 1 (_m)
λ_2 = effective wavelength for channel 2 (_m)
$\varepsilon_{\lambda 1}$ = emissivity (of target) for channel 1
$\varepsilon_{\lambda 2}$ = emissivity (of target) for channel 2
ln( ) = natural log function

The following tables are the outputs of this equation for the following examples.

Example 3: You just sent your two-color pyrometer to N.I.S.T. for calibration. One channel operates at 0.9µm and the other at 0.95µm. You hook it up in your lab and aim at your own blackbody and suddenly see a large error. You already know from the single color discussion above that even if you traveled back to N.I.S.T. and aimed this pyrometer at their blackbody at 1100°C, one channel could read 0.7°C (1.3°F) low and the other 0.7°C (1.3°F) high and they would still fall within the calibration report's listed uncertainty for each single color channel. The delta-T between the two channels would now be 1.4°C (2.5°F). It so happens that the ratio temperature sensitivity (actually, effective ratio wavelength) of this instrument is about 10 times that of single color of equal wavelength. Now, out of frustration, you hand carry your newly, N.I.S.T. calibrated, two-color instrument back to N.I.S.T. to verify its calibration and suddenly you see a 14°C (25°F) shift there, too! Note that each individual channel is still within the N.I.S.T. calibration report's listed uncertainties. When the ends of the single color uncertainties are passed through a ratio pyrometer's *emissivity ratio sensitivity equation (6) or "slope"*, the results are shown in the table below. It is assumed that channel 1 is at the + side of the uncertainty limit and channel 2 is at the - side of the uncertainty window.

In other words, at 1100°C, channel 1 reads 1100.7, channel 2 reads 1099.3, °C. In such a case, each single channel is within the calibration uncertainty, but look what happens to the 2-color uncertainty as a result. Again, all of the errors shown in this table could occur even if you brought your freshly calibrated instrument back to N.I.S.T. to aim at their blackbody.

Table 3
U(single color, 2-color), etc. = Uncertainty (k=2) of the single color measurement, 2-color, etc. at the time of calibration aimed at the blackbody.

Temp °C	U (single color)	U (2-color) °C	U (2-color) °F	Equivalent e-ratio or "slope"
800	0.5	11.2	20.2	0.987
1100	0.7	15.8	28.4	0.989
1500	0.9	20.1	36.2	0.991
1900	1.1	24.6	44.3	0.993
2700	3.0	66.4	119.5	0.990

This table reveals that at 1100°C, a +/-15.8°C uncertainty could be observed even by returning your ratio pyrometer to N.I.S.T. the next day. Your own blackbody or process measurement is not yet a part of this discussion.

Now, let's examine the errors that could occur due only to your blackbody or process target emissivities. Let's assume your N.I.S.T. calibrated, two-color instrument behaves perfectly at N.I.S.T. at 1000°C. Your own blackbody emissivity might be 0.97 at 0.9µm and 0.98 at 0.95µm.

Table 4

Wavelength 1 Temperature °C	Wavelength 2 Temperature °F	Emissivity at Wavelength 1	Emissivity at Wavelength 2	Emissivity Ratio	Resulting Ratio Temperature	Delta T (°C)
1000	1000	0.970	0.980	0.990	985.2	-14.8

The table above is again the output of the emissivity ratio equation (6) showing the two color error generated by the differences of emissivity of each wavelength; wavelength 1 emissivity (ε_1) = 0.97, wavelength 2 emissivity (ε_2) = 0.98.

The e-ratio or "slope" jumps to 0.990. The freshly N.I.S.T. calibrated ratio pyrometer reads 14.8°C (26.7°F) low. In addition, we are assuming that the single color uncertainties discussed earlier do not exist (each single channel error = 0° at the N.I.S.T. calibration).

So far the discussion has been around usage of ratio pyrometers aimed only at blackbodies. Knowing the sensitivity to delta-emissivity, apply this to a real process. It becomes difficult to know or measure the target's emissivity for each wavelength (spectral emissivity). In addition, the target's spectral emissivity may change with time and/or temperature.

Example 4: You are monitoring a metal during a heat-up cycle. It's emissivity at channel 1 (wavelength 1) starts out at 0.78 and finishes at 0.83. The target's emissivity at channel 2 starts at 0.78 and finishes at 0.85. You wish to heat up the metal from 800 to 1100°C. At the start of the process, all is fine. The emissivity ratio = 1. At the end of the cycle, the emissivity ratio = 0.83/0.85 = 0.976. Using the equation (6) above, the pyrometer will read 33°C low at the end of the heating cycle. If a single color pyrometer operating at the same wavelength were used instead, the error introduced by the emissivity shift from 0.78 to 0.83 would only be +7.8°C! Clearly, in this application, the single color is more accurate.

Now, add to all of this the fact that different manufacturers use slightly different wavelengths, different blackbody designs, etc., relatively large errors can quickly build when attempting to equalize different brand ratio pyrometers on one process.

The rules for the proper selection of any pyrometer are:

1. Will a short wavelength single color pyrometer work for my process?

Find out your material emissivity properties, and then refer to table 2 or test your process with a single color pyrometer.

2. Why do you desire a two-color pyrometer?

Occasionally the Field of View becomes partially obstructed, but the measurement must continue. Two-color is a good choice as long as your process is not similar to Example 3.

Summary:

Two color pyrometers can serve an important function for limited applications; namely constant emissivity ratio targets and when partial blocking of the pyrometer's optical path can occur. Once the cause of potentially large measurement errors is understood, the user can properly evaluate the application and select the type of pyrometer that will produce the best results.