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Improving Radiometric Accuracy

If you observe a person's face with a camera, you can often detect temperature differences smaller than 0.1°C. This is the sensitivity of the camera.

Many thermographers have experienced situations where their measurement accuracy has come into question. This usually occurs when the reading from the camera is compared to another instrument. It has been my experience that some thermographers are quick to disbelieve the camera reading even when there is no sound reason to do so.

This article will attempt to define the parameters that can affect radiometric accuracy and repeatability, as well as some methods to minimize their effect. It will also discuss possible reasons for discrepancy in readings with other devices.

Background

In this discussion radiometric accuracy will be defined as the accuracy of the temperature measurement obtained by the radiometric device compared to that of the true undisturbed surface temperature. Repeatability defines the consistency of this accuracy from measurement to measurement. Uniformity means the deviation of a single measurement when measured from different points over the entire field of view. Sensitivity is the [operator] detectable temperature difference on a surface. One should be careful not to mix these concepts. When a manufacturer states an accuracy figure they will often confuse these issues, or at least not define them in a manner that makes it easy to compare instruments. All figures of merit produced by manufacturers are usually defined only for blackbody surfaces, and will usually be the best-case numbers at a specific absolute temperature (typically 303°K; 30°C; 86°F).

If you observe a person's face with a camera, you can often detect temperature differences smaller than 0.1°C. This is the sensitivity of the camera. You may also see that one side of the face looks slightly cooler than the other, yet when the camera is turned upside down the opposite side of the face (the same side of the image) looks cooler. This effect is due to non-uniformity in the instrument. You may measure the tear duct at 38°C and the tip of the nose to be 32°C when the real temperatures are in fact 37°C and 31°C. This is the (in)accuracy. You may come back tomorrow and measure the tear duct to be 37.5°C and the nose to be 31.7°C when in fact they still are the same temperatures. This is the repeatability. You may note that in this case uniformity, accuracy, and repeatability all get wrapped up together, since it unlikely that you will have positioned the person's face in exactly the same place and hence are using different parts of the image to perform the measurement. You should always get the exact figures of sensitivity, accuracy, and repeatability from your manufacturer. In addition you should ask about image uniformity, and how it is included in the above numbers.

Parameters Affecting Radiometric Accuracy

There are a number of parameters that ultimately define the accuracy and repeatability of a radiometric measurement. These include: the object, the surface, the thermal en-

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vironment, the atmosphere, and the instrument. Consideration should also be given to the measurement method or instrument that is establishing the deviation as it may be the source of error rather than the infrared instrument. While each one of these parameters will define a specific accuracy limit, the cumulative effect defining the overall accuracy, there are many situations in which they will work against one another producing an apparently high measurement accuracy. If the thermographer is not aware of this interactive effect and these variables change, the accuracy will not be repeatable. An example of this effect is the measurement of a low-emissivity surface that is close to the temperature of its ambient surroundings. The thermographer may obtain a measurement of the surface temperature that agrees completely with a contact measurement independent of the emissivity setting on his camera. This is quite accidental and occurs only because the camera is subtracting off the energy from the background ambient temperature in an equal amount to which it is increasing the value of energy that should be emitted from the surface if it were a blackbody. Should the temperature of the background or surface change significantly, an inaccurate result will occur if not properly corrected by setting the correct emissivity and background temperature.

The Object

Object thermal equilibrium occurs, by definition, when the object temperature equals that of the surroundings. In fact, it is by no accident that this is also very close to the definition of temperature. We tend to think of temperature being an entity unto itself, when in fact temperature is a measurement which makes a statement about thermal equilibrium. When heat is being transferred at a constant rate because of temperature difference the heat transfer is said to be at steady state. When the heat transfer rate is varying with time, we state the heat transfer to be transient. Transient heat transfer can have many causes, but the most common for solid materials is that created by the thermal capacitance of the materials. Surface temperature is even more complicated than object temperature. Surface temperature is a response to the heat arriving or leaving the surface by conduction from the inside of the object combined with the heat transfer arriving and/or leaving the surface to the surroundings by radiation and convection. At any instant in time there must be a balance in the net heat energy arriving at the surface with that leaving the surface. The heat generated from a constant internal energy generation (e.g., by an electrical fault) must be equal to the sum of heat energy leaving (or arriving) at the surface by radiation and convection. In this case, should the rate of convective heat transfer increase, then the amount of radiative heat transfer must consequently decrease since the rate of energy generated is a constant determined by I2R. This truly results in a transient heat transfer condition, as indicated by a surface temperature changing with wind condition.

A phase-to-phase temperature rise made between a normal connector and a connector with a contact resistance fault may differ by more than 60% between a no-wind and a 20 km/hr (approximately 15 mph) wind condition. In other words, if the normal phase is running close to ambient at 20°Celsius, and with no wind the fault is running at 40° Celsius (a rise of 20°C), then with a 20 km/hr wind the normal phase will not change but the hot spot may drop to about 28°C and the phase-to-phase rise to only 8°C.

If an object is under a condition of transient heat transfer, the surface temperature may be changing in value. This may mean that surface temperatures collected at one point in time *will not agree with others taken at a different point in time. This may be blamed on instrument inaccuracy or repeatability when, in fact, the difference occurred because the heat transfer was varying.*

The object size and measurement distance relative to the instrument's resolving capability is also an important factor, which will be discussed further under the instrument category.

The Surface

Emissivity is the most obvious factor when making a radiometric measurement. The most common misconception about emissivity, however, is the impact of errors in the emissivity measurement on the actual temperature measurement. One cannot assume that a 10% error in the emissivity value will bring a consequent 10% error in temperature. The real error in temperature may actually be a much larger, or smaller percentage depending on a number of factors. The two main factors determining the error include the instrument response at the actual surface temperature, and the magnitude of the ambient reflectance temperature with respect to the surface temperature.

Emissivity can vary with wavelength, temperature, surface condition, and angle. As a general rule of thumb for most opaque materials wavelength will not vary significantly within the respective waveband. There are, however, exceptions to this, the most notable being glass in the long-waveband. In the event that the material is a spectral emitter (i.e., its emissivity is changing within the wavelength sensitivity of your camera) then a band-pass filter for your camera should be selected to limit the spectral response to a region where the emissivity is constant. The use of a filter, however, may decrease the accuracy and sensitivity, so there is a trade-off that must be made between the inaccuracy from the emissivity variance versus the inaccuracy created by loss of signal.

Since emissivity may change with angle, and often is at a maximum value at a normal to the surface, the most accurate and highest repeatable reading of emissivity is usually made when aiming the camera at right angles to the surface.

One should not assume that textbook or published values of emissivity may be correct for a particular camera. The emissivity values are those which are obtained with the camera on objects which have similar surface characteristics. If this is not possible, then values obtained from other users who own similar models of camera, or values published by the manufacturer for that specific model of camera are preferable over generic textbook values. Many textbook values are published for heat transfer calculations that assume broadband hemispherical emission. Radiometric measurements, however, are made over a relatively narrow band and narrow angular degree at right angles to the surface rather than averaged over 180° view angle of the surface. Since emissivity may change with angle, and often is at a maximum value at a normal to the surface, the most accurate and highest repeatable reading of emissivity is usually made when aiming the camera at right angles to the surface.

The stated accuracy of an infrared camera will decrease as the emissivity decreases and the proportional inaccuracy of the emissivity value increases. Field emissivity measurements are rarely better in absolute accuracy than ±0.02. While this makes little difference when the emissivity values are high, it may have a significant impact when the emissivity value is low. The correction for emissivity must always be done using the instruments response curve rather than by direct percentage or any theoretical calculation. More on this will be discussed under the section on instrument accuracy.

With modern emissivity correction built in to cameras and software, the process of estimating errors in emissivity is quite easy. Simply change the emissivity value from the maximum expected value to the minimum expected value and note the consequent change in temperature. Report this change as the expected error in temperature. Ensure that the background reflected temperature and other parameters including the proper calibration constants for your camera, are included.

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The Thermal Environment

The thermal environment may significantly influence the accuracy of apparent surface temperature, particularly when the surface emissivity is low and/or the thermal environment temperature is high. By thermal environment we mean the sources of temperature that may be reflecting in the surface being measured. Also referred to as background temperature, reflected temperature, or "ambient" temperature, it should not be confused with the ambient air temperature surrounding the surface.

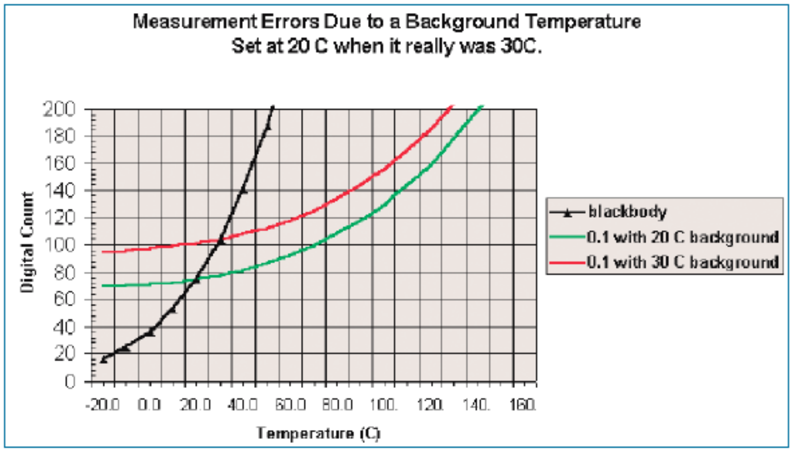

Figure 1

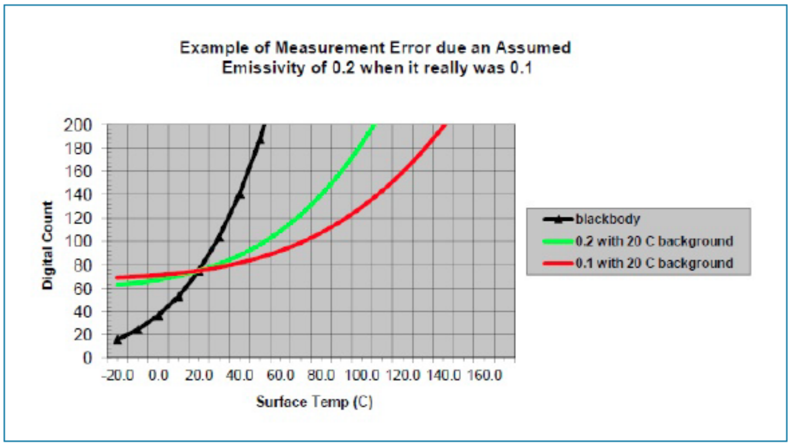

Figure 2

A uniform background can sometimes be created by adjusting the camera angle or erecting a radiation barrier such as a drop cloth or piece of cardboard.

For diffuse surfaces, this temperature will be the average temperature of the entire background hemisphere. This can easily be estimated by turning the camera around 180°and observing the thermal background. If your camera has an area averaging function, set the area to be the entire field of view and record the average temperature of the area. If there is considerable variance in background temperature and you don't have an area function, then put the camera out-of focus and take some measurements of the background.

For a specular surface, the background object temperature will be the temperature within the complementary viewing angle of the detector IFOV. Measurements on specular surfaces should be done very carefully, preferably with a uniform background temperature. A uniform background can sometimes be created by adjusting the camera angle or erecting a radiation barrier such as a drop cloth or piece of cardboard. If this is not possible, then try to work at close focus distances with the background out of focus.

Measurement may be significantly affected by the background temperature when the emissivity is low. This is due to Kirkhoff's law, which states that absorptivity is equal to emissivity, and therefore for opaque surfaces emissivity equals 1-reflectivity. As the emissivity drops, the reflectivity increases, as does the error associated with measurement of the background temperature. If the background temperature is varying, or you cannot measure it, then change the value of the background to the maximum and minimum limits of what they might possibly be and observe the consequent impact on the surface temperature measurements. This must be done in conjunction with changing the limits of possible emissivity values.

Set the emissivity at the lowest value that you believe it could be and then vary the background temperature to the two extremes that you believe it could be. Note the two temperatures. Then dial the emissivity to the highest possible value that you believe it could be and then once again vary the background temperature between the two limits and note the resultant two surface temperatures. From the four possible temperatures, select the two extreme temperatures to be the error limits of your uncertainty due to the variance of background and emissivity. At low emissivity values, this variance may be quite significant.

The Atmosphere

Both in long-wave and in short-wave, the atmosphere will attenuate the infrared signal. This is primarily due to the presence of CO2 and H20. A 2-3% error in temperature measurement on a 90° source is typical when the distance is changed from 1 to 10 meters (3 to 33 feet). Most modern cameras, however, compensate for this error by allowing the user to input the object distance -- and sometimes even other parameters, such as relative humidity and air temperature. This correction often reduces the error to an insignificant amount, as long as the atmosphere is standard and the distances not extremely large (i.e., greater than 100 meters).

There are situations, however, such as combustion processes, that are usually more complicated due to the presence of both the by-products of combustion and intense short wave radiation from flames. In the best combustion cases (such as with a natural gas fuel), the products are water vapor (H20) and carbon dioxide (C02). Without spectral filtering, these gases will be observable as a dynamic variable thermal "mist" ob-

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scuring the actual image, creating false temperature patterns and measurements. Since these products of combustion are at their greatest concentrations near the flame front, not only is the flame visible, but its radiant interaction with the surfaces is also observable, yielding confusion as to actual temperature variance versus reflective. Fortunately, the two primary products of combustion have very distinct and different absorption bandwidths in the short-wave spectrum, separated by a narrow waveband of high transmission centered near 3.9 microns. The use of a narrow band spectral filter at this wavelength allows, in many cases, the almost total elimination of the effects of these two gases. This filter, known as a (through) flame filter, also eliminates most of the flame effects and their radiant reflectance in other wavelengths.

In traditional IR studies, the atmospheric effects are primarily a concern when dealing with targets at long distances. However, in combustion environments, even low concentrations of combustion by-products can lead to signal attenuation by low concentrations of other gases such as Ozone (O3), Nitrogen Oxides, and Carbon Monoxide (CO). While the absorption by these gases is relatively insignificant in normal atmospheric conditions, in combustion atmospheres the elevated concentrations and temperatures of these gases effectively reduce the accuracy and repeatability of radiometric measurements. Therefore, in combustion environments, rather than use theoretical values of atmospheric transmission, it is important to have an object of known temperature and distance in the field of view, in order that an empirical value for the atmospheric absorption be obtained. If this can be accomplished at two or three different distances, the transmission value vs. distance relationship can be established and modeled for a specific set of firing conditions.

Unfortunately, not all combustion processes have even such simple by-products. Oil and coal fuels produce both other gases and particulates that complicate, if not totally eliminate, the use of infrared techniques. The particulates are the primary culprit, absorbing, re-emitting, and scattering the infrared, creating a broad-band thermal noise often impossible to eliminate—except perhaps well away from the combustion area—and even then often making only qualitative evaluations feasible. Some non-combustion environments, such as paint ovens, while not having the gas absorption problem, may have high particulate concentrations that create the same absorption, emission, and scattering problems. Conversely, some contained environments have inert gases, which while having no impact on the qualitative imagery, may create a measurement over-compensation due to the assumption that a standard atmosphere is present. In this case, the computed transmission value should be overridden with an actual empirical measurement.

When dealing with non-standard atmospheric (gas) conditions, spectral filtering should be considered. It is always best to have known temperature references in the field of view at the same distance as the objects being measured. This will allow an accurate estimation of the atmospheric attenuation that should be applied to the entire image. In cases where the atmospheric has a high and variable particulate concentration, it is doubtful that meaningful temperature measurements can be made.

External Windows and Filters

There is one general rule when considering the use of external filters and windows and radiometric measurement: if you can possibly can, **avoid using them**. There are a num-

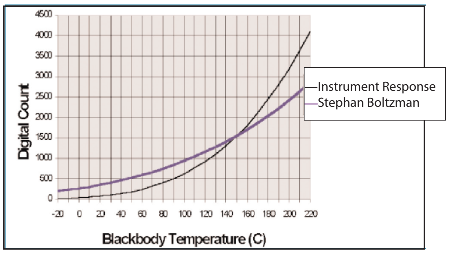

Figure 3

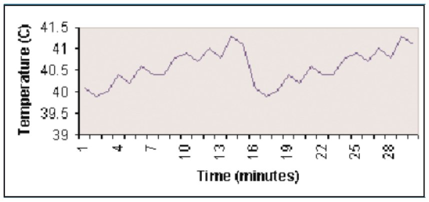

Figure 4

ber of reasons for this, including attenuation of the signal, emission from the optical element itself, refraction, narcissus, spectral absorption, and difficulties in calibration. There are instances where a window must be used, such as when a process must be contained, or the camera lens must be protected against intense energy or harsh chemicals. When using filters, avoid external spectral filters and use internal filters supplied, installed, and calibrated by the manufacturer. With any optic (window or filter) external to the camera, difficulties arise in the correct modeling of the signal response. Infrared manufacturers are usually quite secretive in their signal modeling and correction techniques and are often quite hesitant to either release the calibration information or include an external optical transmission into their calculation. While it would be straightforward to perform such a correction if the window had a broadband uniform transmission and constant temperature, this is often not the case. External optics in extreme conditions can often change their response with temperature, as the material ages over time, as they get dirty, or as coatings come off.

Even though a window may have a transmission value specified by the supplier, you cannot apply this value directly to the temperatures obtained, nor apply a theoretical model. You must either apply the attenuation (and re-emission) to the actual signal and re-apply the calibration model, or correct the temperatures through the use of a empirical correction lookup table (assuming you can keep the window at constant temperature).

If you must use a window, consider having the window calibrated along with the system if this is practical. If not, then construct a correction chart of actual temperature versus measured temperature through the window. If the window temperature is close to the object temperatures being measured, then the correction chart should take on a new dimension, including temperature of the window itself. Consider the use of one or two known temperature references in the field of view, on the side of the window opposite from the camera, whose temperatures are at the extremes of the object temperatures being measured.

Instrument Considerations

There are a number of instrument considerations for accurate temperature measurement. These include instrument response, optical design, drift compensation, nonuniformity correction, and radiometric modeling. There is a widespread belief that infrared camera response is a direct function of the Stephan-Boltzman relationship. This assumption would be correct only if the camera was a pure 100% efficient energy detector over an extremely wide band of wavelengths. The reality of most commercial cameras is that 1) they are only detecting a very small percentage of the overall energy emitted; 2) many detectors and optics do not have a combined flat response over their bandwidth; and 3) as the temperature changes, the percentage of energy falling in the particular camera band changes. The net result is that as the surface of an object increases, the resultant detector signal response may be a function of that temperature, ranging from a linear to a power function. Figure 3 illustrates the slope of a typical instrument response curve versus the Stephan-Boltzman curve. Ultimately it is the instrument response which determines its measurement sensitivity to such things as emissivity difference, background temperature, and atmospheric attenuation. The best situation is to have as high an instrument response (gain) for a given increase in temperature (gain equals ds/dt where s is signal and t is temperature). For a given

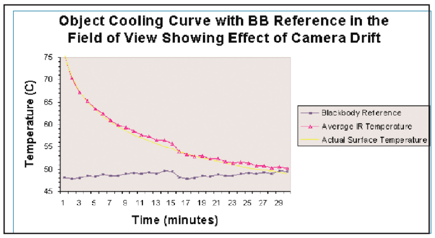

Figura 5

change in a variable, such as emissivity, there will be a consequent change in energy. If the instrument is in a high-gain situation (ds/dt>1), there will be less of an impact on temperature than if the instrument is in a low-gain situation (ds/dt<1).

Optical design plays an important part in measurement accuracy and repeatability. Particularly critical is the prevention of stray radiation. This will minimize errors to due signal changes from intense sources in or close to the field of view. Even with well-designed instruments, try if at all possible to avoid having intense thermal radiation sources, or extreme temperature differences, in or near the field of view.

Instrument drift compensation is also important for repeatable measurements. Drift is the change in output over time on a constant temperature source. It may come about due to internal power generation, change in ambient conditions around the camera, thermal radiation being absorbed by the camera, or change in the voltage power or signal supplying the camera. Drift data should be available from the manufacturer and should be included in the short-term repeatability figure.

The impact of instrument drift on repeatability may be estimated by monitoring a constant temperature source and exposing the camera to a differing ambient such as blowing warm air on the instrument (within, of course, the allowable limits specified by the manufacturer). Some drift is exhibited by most cameras for some period of time after start-up, so you should try to avoid making accurate measurements immediately after power-up.

Figure 5 shows the effect of a non-uniformity correction at 16 minutes into the test, as shown by a simultaneous drop in the infrared reading of both the surface temperature and the blackbody reference temperature. The accuracy of the radiometric model developed by the manufacturer for a specific camera is of importance for precise measurement over the instrument's entire range.

Some manufacturers specify an accuracy figure at one or more temperatures, others specify a percentage of reading with a minimum absolute amount, while even others specify accuracy as a percentage of range. This is usually an indication of the precision of the radiometric model as much as it is of the instrument design. The response of some instruments may be quite complex multiple-slope functions with two or more points of inflection, depending on the detector, filter(s), and optics utilized. Calibration is often performed by viewing multiple black-bodies at different temperatures and best-fitting an empirical curve. If the empirical model does not accurately describe the curve, or enough blackbodies are used, or if one or more blackbodies are out of calibration, or the instrument drifts during calibration, then an inaccurate model will prevail.

If your instrument has been calibrated, you should always ask the manufacturer to supply the curve-fit data. The least that you should obtain is the most recent calibration certification for all of the blackbodies utilized in calibrating your camera.

Instantaneous field of view is a camera/lens parameter describing the minimum detectable object size at a specific distance. When expressed as an angle in milliradians, the IFOV = (minimum object size °— 1000)/object distance. A 1-milliradian resolution camera and lens, therefore, should be able to detect a 25mm (1”) object at 2.5m (1000”). Placing a longer focal length lens on the same camera will increase the IFOV, while a wider angle lens will decrease the IFOV. IFOV, however, is not the figure of merit which should be used for measurement. A lesser-known but more relevant parameter is IFOVmeasure. Not readily available from most manufacturers this parameter is often three to five times greater than the IFOV. IFOVmeasure has historically also been linked by some to a parameter known as the 90% SRF (Slit response function).

When comparing two radiometric instruments of different wavelength ensure that the appropriate emissivity is set for each instrument rather than exactly the same value.

If you do not know the IFOVmeasure of your camera, you should conduct a simple experiment to approximate it. Determine what is the acceptable drop in apparent temperature on a typical object temperature. Then measure the temperature of a high emissivity (0.96+) object at a distance much less (1/20th) than the manufacturer’s stated IFOV. Once this measurement is made back away from the object until the apparent temperature of the object drops to your acceptable limit. Measure the object size, multiply it by 1000 and divide this number by the distance (in the same units). Repeat this a number of times and average the readings.

Minimizing Radiometric Error

In summary, the following are some simple guidelines for trying to minimize the effect of measurement errors:

1. Work in the region of highest instrument response. This includes using the largest aperture, lowest range, and appropriate wavelength.
2. Try to have as low a background temperature as possible, particularly when measuring low emissivity surfaces.
3. Try to raise the emissivity on low-emissivity surfaces.
4. Use field-measured values of emissivity obtained with your camera on similar objects.
5. Have known references in the field of view at the same distance as the object. Preferably two references whose temperatures at the extremes of the object apparent temperature.
6. Keep the camera temperature as consistent as possible.
7. Avoid making measurements immediately after starting the camera.
8. Avoid using windows and external filters, if possible.
9. Ensure that the object size is larger than the IFOVmeasure.
10. Ensure that the object or surface is not in transient heat transfer, or if it is that all relevant parameters are noted, including the time. Do not try to determine the accuracy of this reading by comparing it to other readings taken at a different time or under different conditions unless you are certain as to how the surface temperature has been affected.
11. Be very cautious when comparing a radiometric measurement to a contact measurement. Ensure that the contact measurement is in intimate contact with the surface, is not itself affecting the surface temperature, is not interfering with the convection, or is not receiving radiant energy differently than the surface.
12. When comparing to other radiometric instruments, ensure that both instruments are within their IFOVmeasure. This is particularly true when comparing to spot radiometers whose IFOV is usually much worse than a camera.
13. When comparing 2 radiometric instruments of different wavelength ensure that the appropriate emissivity is set for each instrument rather than the same value.

Some IR instruments assume a fixed ambient temperature, or assume that the reflected ambient is the same as the instrument temperature.

14. When comparing two radiometric instruments, ensure that both are compensating in the same fashion for reflected ambient temperature and atmospheric transmission. Some IR instruments assume a fixed ambient temperature, or assume that the reflected ambient is the same as the instrument temperature.
15. Ensure that all components in the optical path are clean.
16. Make your measurements at right angles to the surface.
17. On diffuse surfaces, try to get a good average reading of the background.
18. On specular surfaces, change the camera angle or use a radiation barrier so as to avoid intense reflections on the measurement area.
19. Avoid trying to make accurate measurements through atmospheres containing high amounts of particulate.
20. Check the camera measurement on known temperatures before and after the measurement.
21. Obtain calibration information on your camera from the manufacturer, including the curve fit accuracy and the last certified calibration date for their blackbodies.
22. Ensure the surface is free from moisture or other fluids.

For additional information about thermography, building inspections, and infrared training, visit www.thesnellgroup.com or contact The Snell Group at 1-800-636-9820.

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