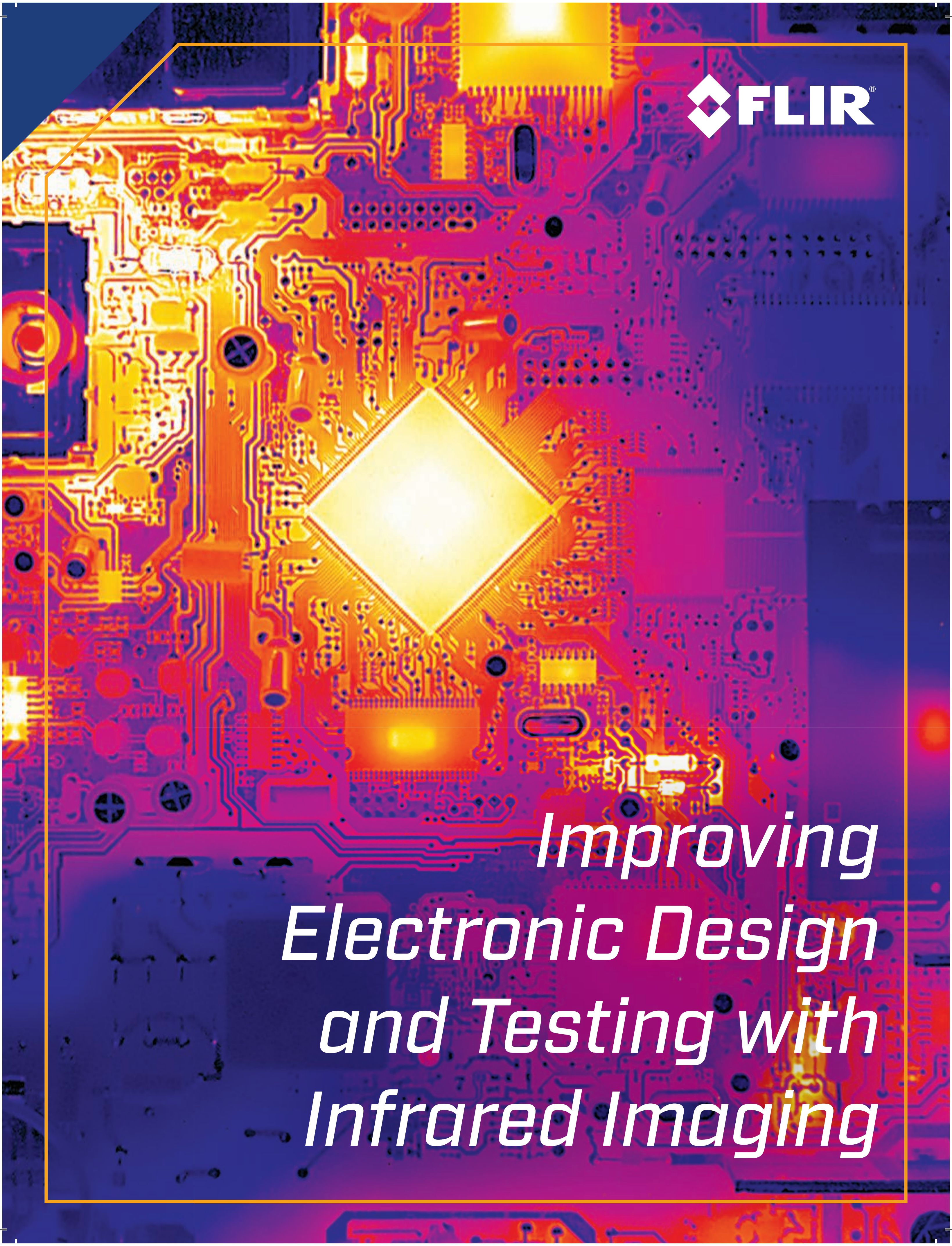


FLIR

Improving Electronic Design and Testing with Infrared Imaging

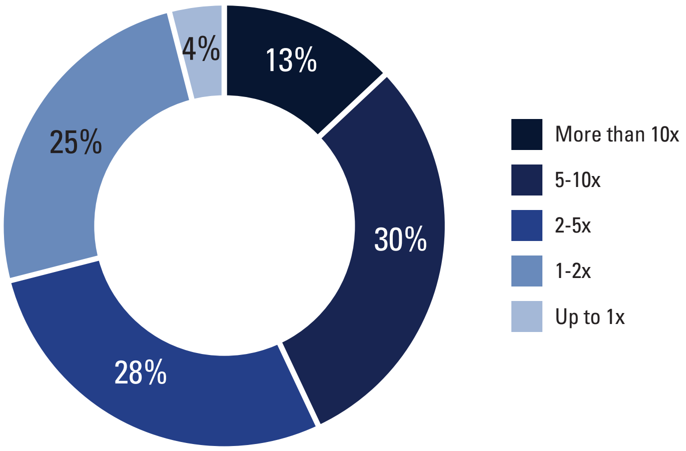
INTRO

SPEED UP TESTING & IMPROVE QUALITY OF ELECTRONICS PCBA & INTEGRATED CIRCUIT DESIGN & TESTING WITH THE USE OF INFRARED TECHNOLOGY

As electronic circuit boards and components get smaller and more powerful, inherent heating becomes a concern. That's why electronic systems designers are looking for ways to keep their components cool while the sizes of their devices shrink. As chips get smaller and their densities within components grow, heat can become a real problem — not only for devices used in civilian life, but in the military as well.

In the latter case, the problem expands beyond inconvenience to one of safety. The armed forces depend on the quality of their electronics to maintain the integrity of weapons and communications systems. Government agencies are spending millions to find new thermal management technologies to help designers make substantial reductions in electronic component size, weight, and power consumption and thus eliminate the problem of heat dissipation.

How much faster was your testing time or product development time after deploying the FLIR camera?



SOURCE: TechValidate survey of 118 users of FLIR Systems

Whether it is in the early rapid prototyping design phase, failure analysis and quality assurance phase, or troubleshooting on product returns, thermal measurement is a key tool for identifying problems and improving thermal management solutions. But the legacy forms of temperature measurement typically used are proving inadequate to meet these new demands for electronics design. Contact forms of temperature measurement, such as thermocouples and RTDs, require physical contact with components that in some cases are smaller than the probe itself. Similarly, noncontact forms of temperature measurement, such as spot pyrometers, don't offer the spot size ratio to image smaller electronic components. And in both examples, they only offer a single point of temperature measurement, not allowing the engineer or technician to properly characterize the device under test.

Temperature calibrated infrared cameras not only offer hundreds of points of accurate noncontact temperature measurement so you can instantly identify hot spots, but they also provide optics that allow you to measure temperatures on components and ICs down below 5 micrometers. And infrared cameras now are offered at price points that are less than standard temperature data logging systems.

Infrared camera technology is helping save electronic design companies money through improved test times and better product design. In this e-book, you'll find insight and advice from some of the industry's subject matter experts on new infrared technologies, innovations, and techniques to help drive similar results within your projects.

IR THERMOGRAPHY — HOW IT WORKS

IR THERMOGRAPHY CAMERAS

Although infrared radiation (IR) is not detectable by the human eye, an IR camera can convert it to a visual image that depicts thermal variations across an object or scene. IR covers a portion of the electromagnetic spectrum from approximately 900 to 14,000 nanometers (0.9–14 µm). IR is emitted by all objects at temperatures above absolute zero, and the amount of radiation increases with temperature.

Thermography is a type of imaging that is accomplished with an IR camera calibrated to display temperature values across an object or scene. Therefore, thermography allows one to make non-contact measurements of an object's temperature.

IR camera construction is similar to a digital video camera. The main components are a lens that focuses IR onto a detector, plus electronics and software for processing and displaying the signals and images. Instead of a charge coupled device that video and digital still cameras use, the IR camera detector is a focal plane array (FPA) of micrometer size pixels made of various materials sensitive to IR wavelengths. FPA resolution can range from about 160 × 120 pixels up to 1024 × 1024 pixels. Certain IR cameras have built-in software that allows the user to focus on specific areas of the FPA and calculate the temperature. Other systems utilized a computer or data system with specialized software that provides temperature analysis. Both methods can supply temperature analysis with better than ±1°C precision.

FPA detector technologies are broken down into two categories: thermal detectors and quantum detectors. A common type of thermal detector is an uncooled microbolometer made of a metal or semiconductor material. These typically have lower cost and a broader IR spectral response than quantum detectors. Still,

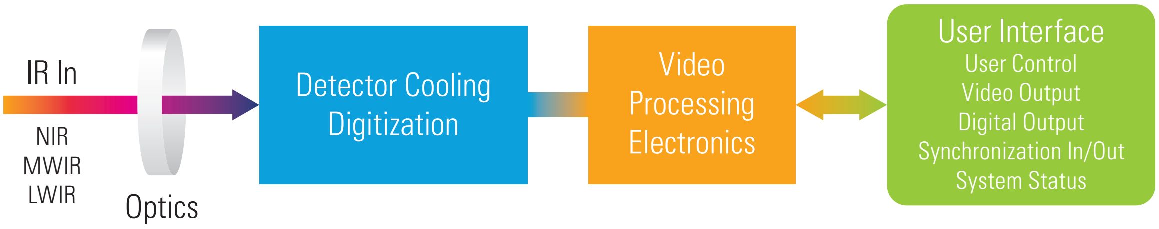


FIGURE 1: Simplified block diagram of an IR camera

microbolometers react to incident radiant energy and are much slower and less sensitive than quantum detectors. Quantum detectors are made from materials such as InSb, InGaAs, PtSi, HgCdTe (MCT), and layered GaAs/AlGaAs for QWIP (Quantum Well Infrared Photon) detectors. The operation of a quantum detector is based on the change of state of electrons in a crystal structure reacting to incident photons. These detectors are generally faster and more sensitive than thermal detectors. However, they require cooling, sometimes down to cryogenic temperatures using liquid nitrogen or a small Stirling cycle refrigerator unit.

IR SPECTRUM CONSIDERATIONS

Typically, IR cameras are designed and calibrated for a specific range of the IR spectrum. This means that the optics and detector materials must be selected for the desired range. Figure 2 illustrates the spectral response regions for various detector materials.

Because IR has the same properties as visible light regarding reflection, refraction, and transmission, the optics for thermal cameras are designed in a fashion similar to those of a visual wavelength camera. However, the types of glass used in optics for visible light cameras cannot be used for optics in an infrared camera, as they do not transmit IR wavelengths well enough. Conversely, materials that are transparent to IR are often opaque to visible light.

IR camera lenses typically use silicon (Si) and germanium (Ge) materials. Normally Si is used for MWIR (medium wavelength IR) camera systems, whereas Ge is used in LW (long wavelength) cameras. Si and Ge have good mechanical properties, i.e., they do not break easily, they are non-hygroscopic, and they can be formed into lenses with modern turning methods. As in visible light cameras, IR camera lenses have antireflective coatings. With proper design, IR camera lenses can transmit close to 100 percent of incident radiation.

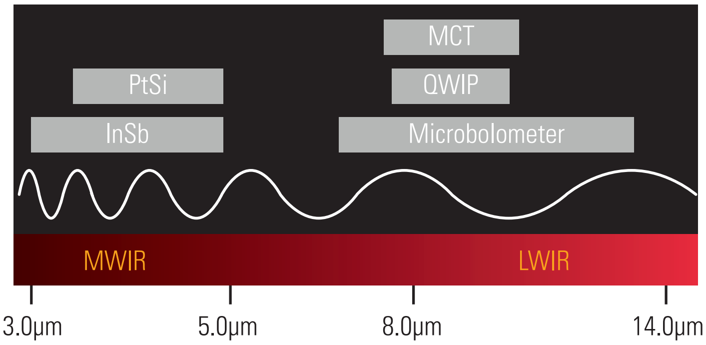


FIGURE 2: Examples of detector materials and their spectral responses relative to IR midwave (MW) and longwave (LW) bands

THERMAL RADIATION PRINCIPLES

The intensity of the emitted energy from an object varies with temperature and radiation wavelength. If the object is colder than about 500°C, emitted radiation lies completely within IR wavelengths. In addition to emitting radiation, an object reacts to incident radiation from its surroundings by absorbing and reflecting a portion of it, or allowing some of it to pass through (as through a lens). From this physical principle, the Total Radiation Law is derived, which can be stated with the following formula:

$$W = \alpha W + \rho W + \tau W,$$

which can be simplified to:

$$1 = \alpha + \rho + \tau.$$

The coefficients α, ρ, and τ describe the object's incident energy absorbtion (α), reflection (ρ), and transmission (τ). Each coefficient can have a value from zero to one, depending on how well an object absorbs, reflects, or transmits incident radiation. For example, if $\rho = 0$, $\tau = 0$, and $\alpha = 1$, then there is no reflected or transmitted radiation, and 100 percent of incident radiation is absorbed. This is called a *perfect blackbody*.

In the real world, there are no objects that are perfect absorbers, reflectors, or transmitters, although some may come very close to one of these properties. Nonetheless, the concept of a perfect blackbody is very important in the science of thermography because it is the foundation for relating IR radiation to an object's temperature.

Fundamentally, a perfect blackbody is a perfect absorber and emitter of radiant energy. This concept is stated mathematical as Kirchhoff's Law. The radiative properties of a body are denoted by the symbol ε, the *emittance* or *emissivity* of the body. Kirchhoff's law states that $\alpha = \varepsilon$, and since both values vary with the radiation wavelength, the formula can take the form $\alpha(\lambda) = \varepsilon(\lambda)$, where λ denotes the wavelength.

The total radiation law can thus take the mathematical form $1 = \varepsilon + \rho + \tau$, which for an opaque body ($\tau = 0$) can be simplified to $1 = \varepsilon + \rho$ or $\rho = 1 - \varepsilon$ (i.e., reflection = 1 – emissivity). Since a perfect blackbody is a perfect absorber, $\rho = 0$ and $\varepsilon = 1$.

The radiative properties of a perfect blackbody can also be described mathematically by Planck's Law. Since this has a complex mathematical formula and is a function of temperature and radiation wavelength, a blackbody's radiative properties are usually shown as a series of curves (Figure 3).

These curves show the radiation per wavelength unit and area unit, called the spectral radiant emittance of the blackbody. The higher the temperature, the more intense the emitted radiation. However, each emittance curve has a distinct maximum value at a certain wavelength. This maximum can be calculated from Wien's displacement law,

$$\lambda_{max} = 2898/T,$$

where T is the absolute temperature of the blackbody, measured in Kelvin (K), and λ_{max} is the wavelength at the maximum intensity. Using blackbody emittance curves, one can find that an object at 30°C has a maximum near 10µm, whereas an object at 1000°C has a radiant intensity with a maximum of near 2.3µm. The latter has a maximum spectral radiant emittance about 1,400 times higher than a blackbody at 30°C, with a considerable portion of the radiation in the visible spectrum.

From Planck's law, the total radiated energy from a blackbody can be calculated. This is expressed by a formula known as the Stefan-Boltzmann law,

$$W = \sigma T^4 \ (W/m^2),$$

where σ is the Stefan-Boltzmann's constant (5.67×10^{-8} W/m^{2}K^4). As an example, a human being with a normal temperature (about 300 K) will radiate about 500W/m^2 of effective body surface. As a rule of thumb, the effective body surface is 1m^2, and radiates about 0.5kW — a substantial heat loss.

The equations described in this section provide important relationships between emitted radiation and temperature of a perfect blackbody. Since most objects of interest to thermographers are not perfect blackbodies, there needs to be some way for an IR camera to graph the temperature of a "normal" object.

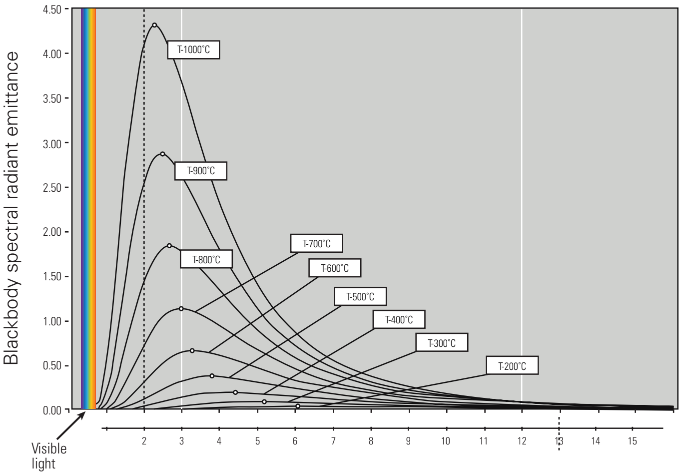


FIGURE 3: Illustration of Planck's Law

EMISSIVITY

The radiative properties of objects are usually described in relation to a perfect blackbody (the perfect emitter). If the emitted energy from a blackbody is denoted as W_{bb}, and that of a normal object at the same temperature as W_{obj}, then the ratio between these two values describes the emissivity (ε) of the object,

$$\varepsilon = W_{obj} \,/\, W_{bb}.$$

Thus, emissivity is a number between 0 and 1. The better the radiative properties of the object, the higher its emissivity. An object that has the same emissivity ε for all wavelengths is called a *greybody*. Consequently, for a greybody, Stefan-Boltzmann's law takes the form

$$W = \varepsilon \sigma T^4 \ (W/m^2),$$

which states that the total emissive power of a greybody is the same as that of a blackbody of the same temperature reduced in proportion to the value of ε for the object.

Still, most bodies are neither blackbodies nor greybodies. The emissivity varies with wavelength. As thermography operates only inside limited spectral ranges, in practice it is often possible to treat objects as greybodies. In any case, an object having emittance that varies strongly with wavelength is called a *selective radiator*. For example, glass is a very selective radiator, behaving almost like a blackbody for certain wavelengths, whereas it is rather the opposite for other wavelengths.

ATMOSPHERIC INFLUENCE

Between the object and the thermal camera is the atmosphere, which tends to attenuate radiation due to absorption by gases and scattering by particles. The amount of attenuation depends heavily on radiation wavelength. Although the atmosphere usually transmits visible light very well, fog, clouds, rain, and snow can prevent us from seeing distant objects. The same principle applies to infrared radiation.

For thermographic measurement we must use the so-called *atmospheric windows*. As can be seen from Figure 4, they can be found between 2 and 5µm, the *mid-wave windows*, and 7.5–13.5µm, the *long-wave window*. Atmospheric attenuation prevents an object's total radiation from reaching the camera. If no correction for attenuation is applied, the measured apparent temperature will be lower and lower with increased distance. IR camera software corrects for atmospheric attenuation.

Typically, LW cameras in the 7.5–13.5µm range work well anywhere that atmospheric attenuation is involved because the atmosphere tends to act as a high-pass filter above 7.5µm (Figure 4). The MW band of 3–5µm tends to be employed with highly sensitive detectors for high-end R&D and military applications. When acquiring a signal through the atmosphere with MW cameras, selected transmission bands must be used where less attenuation takes place.

TEMPERATURE MEASUREMENTS

The radiation that impinges on the IR camera lens comes from three different sources. The camera receives radiation from the target object, plus radiation from its surroundings that has been reflected onto the object's surface. Both of these radiation components become attenuated when they pass through the atmosphere. Since the atmosphere absorbs part of the radiation, it will also radiate some itself (Kirchhoff's law).

Given this situation, we can derive a formula for the calculation of the object's temperature from a calibrated camera's output.

1. *Emission from the object* = $\varepsilon \cdot \tau \cdot W_{obj}$, where ε is the emissivity of the object and τ is the transmittance of the atmosphere.
2. *Reflected emission from ambient sources* = $(1-\varepsilon) \cdot \tau \cdot W_{amb}$, where $(1-\varepsilon)$ is the reflectance of the object. (It is assumed that the temperature T_{amb} is the same for all emitting surfaces within the half sphere seen from a point on the object's surface.)
3. *Emission from the atmosphere* = $(1-\tau) \cdot W$ the emissivity of the atmosphere.

The total radiation power received by the camera can now be written:

$$W_{tot} = \varepsilon \cdot \tau \cdot W_{obj} + (1-\varepsilon) \cdot \tau \cdot W_{amb} + (1-\tau) \cdot W_{atm},$$

where ε is the object emissivity, τ is the transmission through the atmosphere, T_{amb} is the (effective) temperature of the object's surroundings, or the reflected ambient (background) temperature, and T_{atm} is the temperature of the atmosphere.

To arrive at the correct target object temperature, IR camera software requires inputs for the emissivity of the object, atmospheric attenuation and temperature, and temperature of the ambient surroundings. Depending on circumstances, these factors may be measured, assumed, or found from look-up tables.

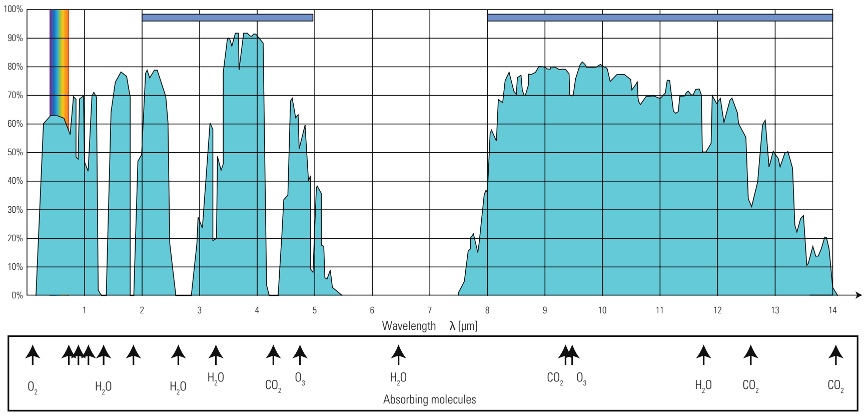


FIGURE 4: Atmospheric attenuation (white areas) with a chart of the gases and water vapor causing most of it. The areas under the curve represent the highest IR transmission.

ELECTRONIC COMPONENT TESTING: A NON-CONTACT SPORT

As electronic circuit boards and components get smaller and more powerful, inherent heat can cause significant damage. Infrared thermography can identify hot spots, allowing for improved thermal management and greater advances in circuit board design.

Electronics don't like it hot. That's why electronic systems designers are looking for ways to keep their components cool while the sizes of their devices shrink. As chips get smaller and their densities within components grow, heat can become a real problem — not only for devices used in civilian life, but in the military as well. In the latter case, the problem expands beyond inconvenience to one of safety. The armed forces depend on the quality of their electronics to maintain the integrity of weapons and communications systems.

Government agencies are spending millions to find new thermal management technologies to help designers make substantial reductions in electronic component size, weight, and power consumption and thus eliminate the problem of heat dissipation.

CONTACT VS. NON-CONTACT TESTING

One designer of VXI boards was experiencing a greater-than-normal flow of returns, with complaints about the boards overheating. The engineers were using simulation modeling to determine where to design in heat sinks and add fans to dissipate heat. They also mounted thermocouples to the board during testing and quality phases, hoping to identify potential design issues. With few results, they finally considered scanning the boards using an infrared camera.

Chris Bainter, U.S. national sales director for FLIR, says infrared has an advantage over thermocouples. "First of all, how do you know where to mount the thermocouples if you don't know where the hotspots are?" he asks. "Imagine mounting hundreds of probes to a board. It's unrealistic and not really effective."

Bainter visited the manufacturing site with an infrared camera. After turning it on and aiming it at a board, the hot spots were instantly apparent — and they were nowhere near the heat sinks, fans, or thermocouples.

"In that first instant we saw the thermal image, we knew exactly where the hottest points on the board were, and which chips were hotter than anything else," Bainter says.

Knowing where to start troubleshooting is just the first step. Infrared can also be constructive in designing a circuit board's thermal management system. For this particular board design, the engineers realized their fans and heat syncs were not mounted near the hottest components. That begged the question: were they really needed? Or rather, had the engineers designed in additional weight and power draw with thermal management components that were no longer required? Knowing more about the device's true thermal properties and heat dissipation can be keys to improving simulation models, improving overall design, and speeding up the rapid prototyping phase of the development cycle.

ACCOUNTING FOR SHRINKAGE

As devices continue to shrink, the challenges of heat grow. Imagine going from a VXI board that is roughly 9" x 13," down to a device the size of a smart phone with individual components a few hundredths of a micron. Components of that size can't even accommodate a thermocouple to measure heat. The solution is to attach an RTD probe, which is similar to but smaller than a thermocouple. But even this smaller probe can skew heat measurements by acting as a heat sink.

"It's challenging, maybe impossible, to measure temperature on really small devices with contact forms of temperature measurement," explains Bainter. "When they get small enough, a probe can affect the thermoresponsivity of the device." In these cases, a non-contact form of temperature measurement, such as infrared imaging, is required.

Another common use for infrared thermal cameras among electronics designers and manufacturers is detecting hot spots for failure analysis. In this case, measuring absolute temperatures isn't as important as finding small hot spots that are causing subtle thermo-differentials. These hot spots can be indicative of failure points or troubles with the device. While passive thermal imaging works well, a technique called "Lock-In Thermography" can improve the sensitivity of the camera by more than 10 times, making it much easier to detect small, subtle hot spots.

FLIR T1K Handheld HD Infrared Camera

Infrared inspection can also help with quality assurance by identifying insufficient solder. Insufficient solder increases circuit resistance at the solder joint and therefore raises the temperature sufficiently to be detected by an infrared camera. A faulty circuit will show up as a different temperature profile from a good one, and that can help determine whether the circuit should pass or fail.

IS THERMOGRAPHY COST JUSTIFIABLE?

The cost justification for thermography is growing as electronic components shrink. Today's infrared cameras offer up to 16 times the resolution of cameras used 10 years ago for nearly the same cost. Bainter believes that as costs continue to come down, thermal infrared cameras will become a standard thermal measurement tool on every test bench, alongside digital multimeters, oscilloscopes, and voltage analyzers. Technology advances will also factor in.

Where testing in electronics inspection is concerned, thermal imaging still has opportunities for advancement. One challenge to thermal imaging is correcting for surface emissivity. Many electronic boards have components with varying emissivities, some of which are shiny, and therefore, have a low emissivity. This makes them more challenging to measure for absolute temperatures. Techniques such as high emissivity coatings, image subtraction, and emissivity mapping are examples of ways to compensate.

In image subtraction, the infrared inspection system software captures an image before the device is energized in order to create a thermal baseline. That baseline image is then subtracted from subsequent images after the device is turned on, thereby removing the static reflected temperature values, leaving only the true temperature deltas due to the heating of the device. Image subtraction effectively removes all the apparent thermal hot spots due to erroneous static reflected temperatures from lower emissivity devices and lets you focus on true thermal hot spots generated from the device itself.

ATTACKING COUNTERFEIT PRODUCTS

There are opportunities for thermography to advance into new applications, such as counterfeit product detection — another growing problem in military purchasing.

"Phony devices using cheaper materials and knockoff designs may have different thermal signatures from the originals, even if on the outside, they look similar," Bainter says.

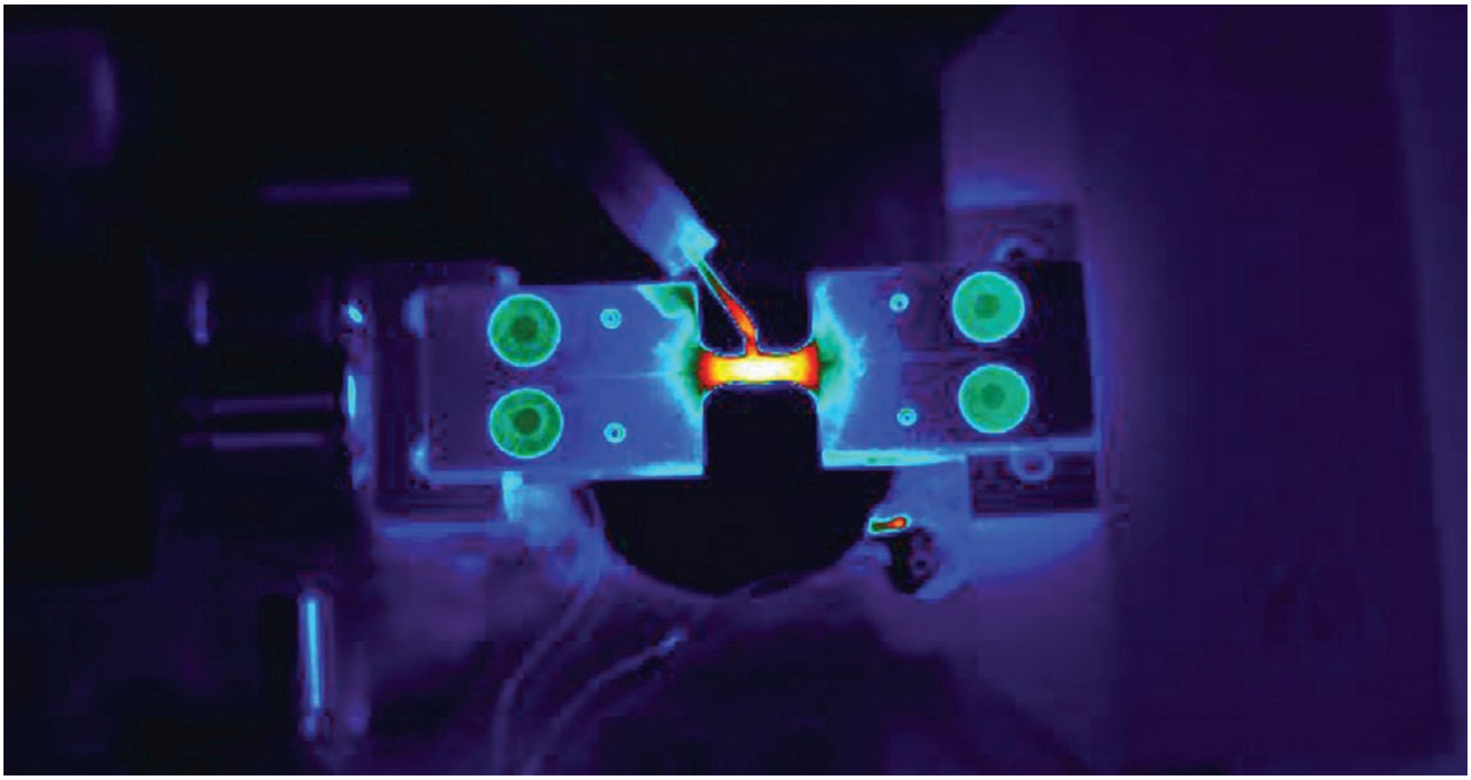
Those devices are widely available at bargain prices via the internet, and according to a Government Accountability Office (GAO) study, suspect counterfeit and bogus military-grade electronic parts can be found on many internet purchasing platforms. In fact, none of the vendors provided to the GAO during a recent study were legitimate. After submitting requests for quotes, the GAO received responses from 396 vendors, of which 334 were located in China; 25 in the United States; and 37 in other countries, including the United Kingdom and Japan. The GAO selected the first lowest price bids, and all 16 parts were provided by vendors in China.

THE PAYOFF

With infrared imaging, where the rubber hits the road is testing and identifying problems that once were impossible to find, or at least difficult to locate quickly. For manufacturers, their ROI would be images that pinpoint a design flaw, thus reducing test times and time-to-market. Another advantage to thermal imaging is it allows engineers to see a complete thermal map of the circuit board, with temperature values for each pixel. There's no concern about mounting thermocouples or RTDs in the wrong place, resulting in erroneous readings. Thermal images show exactly where the hottest points on a board are.

Of course, thermal imaging can be employed in many stages of the research and development process, beyond simple circuit board imaging.

Thermal image of a surface mount thermocouple installed on a material sample



INFRARED CAMERA ACCURACY AND UNCERTAINTY IN PLAIN LANGUAGE

It's tough to trust measurements from instruments when you don't have a clear understanding of how their sensitivity and accuracy is derived, and many times infrared cameras fall in this category. Additionally, discussions of infrared camera measurement accuracy typically involve complex terms and jargon that can be confusing and misleading. This can ultimately prompt some researchers to avoid these tools altogether. However, by doing so, they miss out on the potential advantages of thermal measurement for R&D applications. In the following discussion, we strip away the technical terms and explain measurement uncertainty in plain language, providing you with a foundation that will help you understand IR camera calibration and accuracy.

CAMERA ACCURACY SPECS AND THE UNCERTAINTY EQUATION

You'll notice that most IR camera data sheets show an accuracy specification such as ±2ºC or 2 percent of the reading. This specification is the result of a widely used uncertainty analysis technique called "Root-Sum-of-Squares," or RSS. The idea is to calculate the partial errors for each variable of the temperature measurement equation, square each error term, add them all together, and take the square root. While this equation sounds complex, it's fairly straightforward. Determining the partial errors, on the other hand, can be tricky.

"Partial errors" can result from one of several variables in the typical IR camera temperature measurement equation, including:

- Emissivity
- Reflected ambient temperature
- Transmittance
- Atmosphere temperature
- Camera response
- Calibrator (blackbody) temperature accuracy

Once reasonable values are determined for the "partial errors" for each of the above terms, the overall error equation will look like this:

$$\text{Total Error} = \sqrt{\Delta T_1{}^2 + \Delta T_1{}^2 + \Delta T_1{}^2} \ \text{... etc.,}$$

where the ΔT1, ΔT2, ΔT3, etc. are the partial errors of the variables in the measurement equation.

Why do this? It turns out that random errors sometimes add in the same direction, taking you farther from the true value, while other times they add in opposite direction and cancel each other out. Taking the RSS gives you a value that is most appropriate for an overall error specification. This has historically been the specification shown on FLIR camera data sheets.

It's worth mentioning that the calculations discussed so far are only valid if the camera is being used in the lab or at short range (less than 20 meters) outside. Longer ranges will introduce uncertainty in the measurement because of the atmospheric absorption and, to a lesser extent, its emission. When a camera R&D engineer performs an RSS analysis for almost any modern IR camera system under lab conditions, the resulting number is around ±2ºC or 2 percent – making this a reasonable accuracy rating to use in camera specifications.

However, practice shows us that high performance cameras give much better results than economical cameras, so we still have some work to do to better explain this observation.

LABORATORY MEASUREMENTS AND ±1°C OR 1% ACCURACY

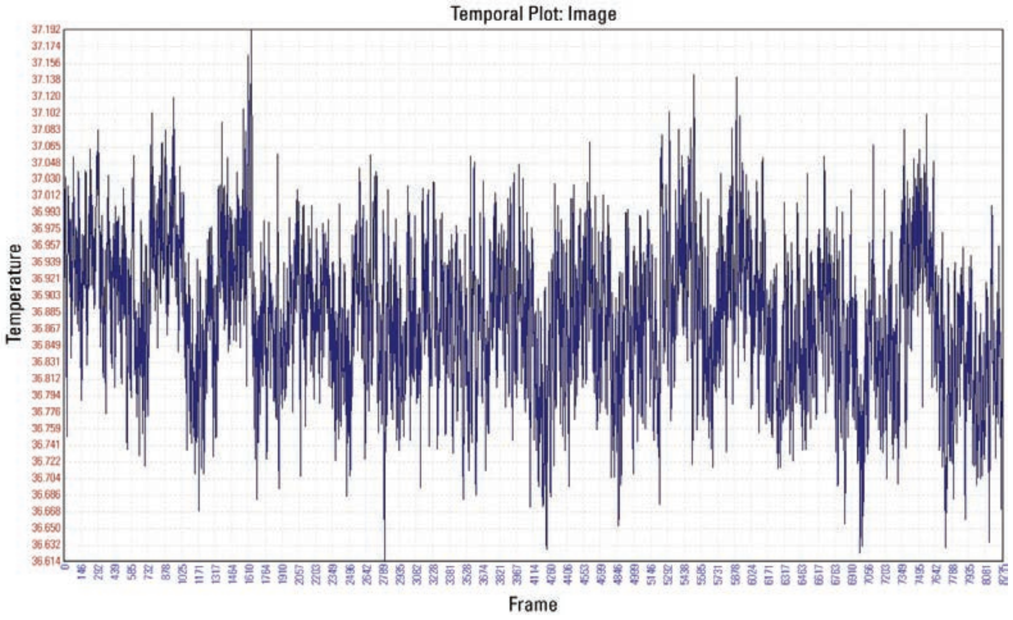
In this section, we take a look at the temperature measurements a camera actually produces when looking at an object of known emissivity and temperature. Such an object is commonly referred to as a "blackbody." You may have heard this term before in reference to the theoretical concept of an object with known emissivity and temperature. It is also used to describe a piece of lab equipment which closely emulates this concept.

Laboratory measurements of uncertainty involve pointing a calibrated camera at a calibrated blackbody and plotting the temperature over a period of time. Despite the careful calibrations, there will always be some random error in the measurement. The resulting data set can be quantified for accuracy and precision. Figure 1 demonstrates the results from calibrated blackbody measurement.

The below plot shows more than two hours of data from a FLIR thermal camera looking at a 37ºC blackbody at a range of 0.3 meter in an indoor environment. The camera recorded the temperature once per second. The data plotted is the average of all pixels in the image. A histogram of this data would make it clearer, but most of the data points were between 36.8ºC and 37ºC. The widest ranging temperatures recorded were 36.6ºC and 37.2ºC.

Looking at this data, it would be tempting to claim an expected accuracy of 0.5ºC for the average of all the pixels. One could even claim ±1ºC for the camera being tested and any other camera using the same detector. However, one could also argue that the graph below shows an average of all of the pixels and may not be representative of an individual pixel.

FIGURE 1: Typical FLIR A325sc camera response when looking at a 37°C blackbody.



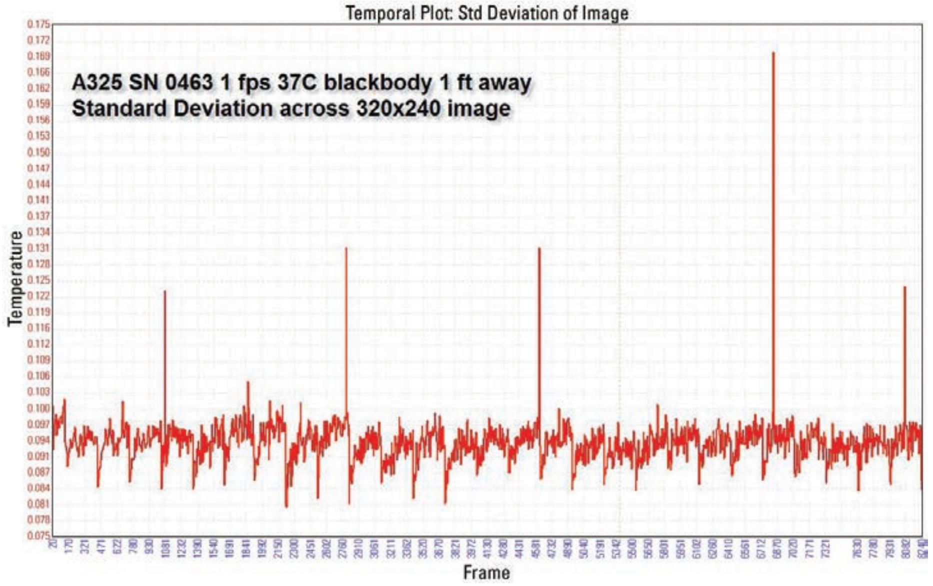


FIGURE 2: Standard deviation of typical A325sc when looking at 37°C blackbody

One way of knowing how well all of the pixels agree with each other is to look at standard deviation versus time. This is represented in Figure 2. The graph shows that the typical standard deviation is less than 0.1ºC. The occasional spikes to around 0.2ºC are a result of the camera's 1-point update, a type of self-calibration procedure that all microbolometer-based cameras must perform periodically.

So far we have discussed collecting data from uncooled microbolometer cameras. How will the results differ for a high-performance quantum detector camera?

Figure 3 shows the response of a typical 3-5 µm camera with an Indium Antimonide (InSb) detector. That camera's documentation shows the accuracy tested at ±2ºC or 2 percent. On the graph below, you can see that the results fall well within those specifications: the accuracy reading on that day was around 0.3ºC, and the precision reading was around 0.1ºC. But why is the offset error at 0.3ºC? This could be caused by the calibration of the blackbody, the calibration of the camera, or any of the partial error terms mentioned in section 2. Another possibility is the camera was simply warming up at the beginning of the measurement. If the optics or the inside of the camera body are changing temperature, they may offset the temperature measurement.

The conclusion we can draw from these two calibration tests is that both microbolometer and photon-counting quantum detector cameras can be factory calibrated to provide accuracies of less than 1ºC when looking at 37ºC objects of known emissivity under typical indoor environmental conditions.

AMBIENT TEMPERATURE COMPENSATION

One of the most critical steps in factory calibrations is ambient temperature compensation. Infrared cameras – whether thermal or quantum detecting – respond to the total infrared energy falling on the detector. If the camera is designed well, most of this energy will be from the scene; very little results from the camera itself. However, it's impossible to completely eliminate the contribution from the materials surrounding the detector and the optical path. Without proper compensation, any changes to the temperature of the camera body or lenses will significantly alter the temperature readings the camera provides.

The best method for achieving ambient temperature compensation is to measure the temperature of the camera and optical path in up to three different locations. The measurement data is then included in the calibration equation. This can ensure accurate readings through the entire range of operating temperatures (typically -15ºC to 50ºC). This is particularly important for cameras that will be used outdoors or otherwise subjected to temperature swings.

Even with ambient temperature compensation, it's important to allow the camera to fully warm up before making critical measurements. Also, keep the camera and optics out of direct sunlight or other sources of heat. Changing the temperature of the camera and optics will have an adverse effect on measurement uncertainty.

We should note that not all camera makers include ambient temperature compensation in their calibration process. By not properly compensating for ambient temperature drift, the data from these cameras could show significant inaccuracies – as much as 10°C or more. Therefore, be sure to ask about calibrations and how they're performed before investing in an IR camera.

OTHER MEASUREMENT CONSIDERATIONS

While not directly related to camera calibration, considerations such as emissivity and spot size can impact camera accuracy. An incorrect emissivity setting or improper testing conditions will affect the camera's ability to measure your subject correctly.

Emissivity – or an object's ability to emit rather than reflect infrared energy – must be properly accounted for. This means taking the time to determine the emissivity of your subject and entering that information in the camera. It also means paying attention to whether the subject is completely reflective and taking steps to resolve that (e.g., coating the surface with non-reflective paint) before measuring.

Another factor to consider is the spot size, or how much area each pixel covers on your target. Let's say an infrared camera with a default 25-degree lens is measuring a lit match that is 60 feet away. Each pixel covers about an inch square area of the total scene. But a match head is only about 1/8" square – much smaller than the pixel covering it. Nearly all of the infrared energy striking that pixel actually comes from the area behind the match ember. Only 1/64ths of the contribution is coming from the ember we intended to measure. If the background is at room temperature, the camera will severely under-report the temperature of the ember.

The solution would be to attach a telescopic optic to the camera, or simply move it closer to the target. Either would bring the pixel size closer to a 1:1 ratio with the ember. If we want the closest to absolute temperature accuracy, we must ensure that the smallest object of interest is fully subtended by at least a 10 x 10 pixel grid. However, even considering the spot size to be a single pixel or a 3 x 3 pixel grid will get you very close to true measurement.

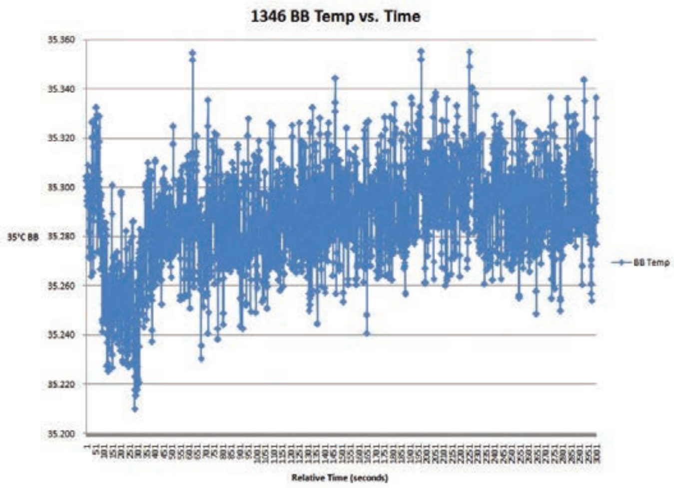


FIGURE 3: Response of a typical Indium Antimonide (InSb) camera looking at a 35°C blackbody

CONCLUSION

As we have seen, the RSS uncertainty analysis technique allows us to determine the accuracy of infrared cameras, and that these cameras may have, at most, a 2ºC margin of error. With proper calibration and attention to factors such as ambient temperature, emissivity, and spot size, the possible margin of error can be less than 1ºC.

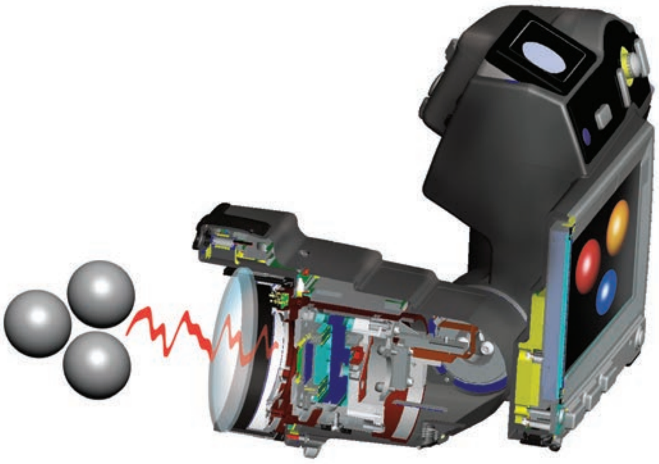
One final note: the information presented in this paper was primarily written with factory calibrated infrared cameras in mind. While the physics are applicable to user calibrations, the tools and methods needed for user calibrations vary depending on the system being discussed. In addition, being able to perform a good user calibration would allow you to perform a custom uncertainty analysis – making generalized specifications discussed in this paper less relevant.

TEMPERATURE GUNS VERSUS THERMAL IMAGING TECHNOLOGY

Thermal imaging cameras are used for non-contact temperature measurements in companies all over the world. Another common tool for non-contact temperature measurements widely used in industrial applications is the spot pyrometer. Both spot pyrometers and thermal cameras work according to the same principle: they detect infrared radiation and translate it into a temperature reading. Thermal cameras, however, have several advantages compared to spot pyrometers:

- A spot pyrometer just gives you a number; thermal imaging cameras generate an image.
- A spot pyrometer reads the temperature of one single spot; a thermal imaging camera gives you temperature readings for each pixel of the entire thermal image.
- Because of advanced optics, thermal imaging cameras can also resolve temperatures from a longer distance. This allows you to quickly inspect large areas.

The spot pyrometer is also known as a temperature gun or infrared thermometer. Because it works according to the same physical principle as a thermal camera, a spot pyrometer can be seen as a thermal camera with only one pixel. Such a tool can be very useful for many tasks, but because it only measures the temperature of one single spot, the operator can easily miss crucial information. The high temperature of certain critical components that are near failure and need repair might go unnoticed.



Infrared energy coming from an object is focused by the optics onto an infrared detector. The detector sends the information to sensor electronics for image processing. The electronics translate the data coming from the detector into an image that can be viewed in the viewfinder or on a standard video monitor or LCD screen.

USE THOUSANDS OF SPOT PYROMETERS AT THE SAME TIME

A thermal imaging camera also provides non-contact temperature readings, just like a spot pyrometer does. Unlike a spot pyrometer, though, thermal imaging cameras produce not one, but thousands of temperature readings at the same time, one for each pixel in the thermal image. Using one thermal imaging camera, therefore, corresponds to thousands of spot pyrometer measurements. Some middle-grade thermal imaging cameras can provide 19,200 temperature readings at once, and higher-end versions can give you 786,432.

SAVE TIME AND 'SEE' THE HEAT

A thermal imaging camera not only gives you thousands of temperature readings, but it also translates these readings into a thermal image. This conversion into an image results in a complete overview over the inspected equipment and allows the operator to immediately see small hot spots that would be easily missed with a spot pyrometer. Using a thermal imaging camera also saves time. Scanning large areas with many components using a spot pyrometer is a very time consuming task because you have to scan every component separately. A thermal imaging camera can be used to check heat dissipation on printed circuit boards, to do quality checks or inspect thermal impact in the automotive sector, or to do failure analysis in the lab.

In order to accurately measure an object's temperature with a spot pyrometer, the target object needs to entirely cover the measurement spot. This limits the distance from which temperatures can be measured accurately.

Another advantage of thermal imaging cameras compared to temperature guns is that they can accurately measure temperatures from larger distances. The distance at which a certain spot pyrometer is able to measure a target of a given size is often described with the “Distance to spot size ratio” (D:S) or “Spot Size Ratio” (SSR). But where does that value come from, and what does it stand for? The “spot size” of a spot pyrometer is the smallest area that still can be measured accurately with the device. That means that the object of which you want to measure the temperature, also referred to as the target, needs to cover the entire spot size. The infrared radiation that is emitted by the target passes through the spot pyrometer’s optics and is projected onto the detector. If the object is smaller than the spot size, the detector will also be hit by parts of the radiation coming from the object’s surroundings. Hence, the device will not read the object’s temperature only but a mixture of the temperatures of the object and its surroundings.

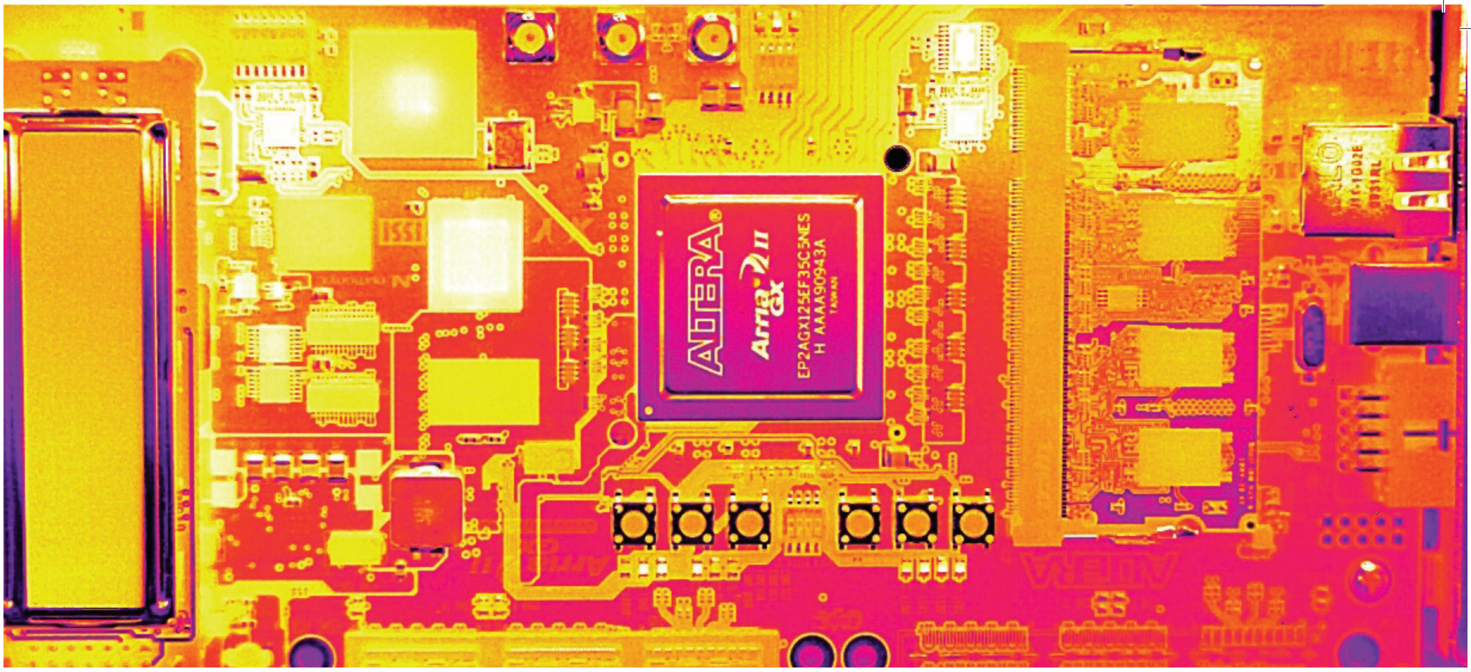
The farther away you hold the spot pyrometer from the object that you want to measure, the larger the spot size will become, due to the nature of optics. Consequently, the smaller the target, the closer you need to hold the spot pyrometer in order to accurately measure its temperature. It is, therefore, very important to keep an eye on the spot size and make sure that you stand close enough to cover the entire spot size with the target, preferably even a bit closer to create a safety margin. The Spot Size Ratio defines a spot pyrometer’s spot size for any given distance to the target.

If the SSR of a spot pyrometer is 1:30, for instance, this means that the temperature of a spot with a size of 1 cm in diameter can be accurately measured at a distance of 30 cm. The temperature of a spot having a size of 4 cm can be measured from a distance of 120 cm (1.2 meters). Most spot pyrometers have an SSR between 1:5 and 1:50. This means that most spot pyrometers can measure the temperature of a target of 1 cm in diameter from a distance of 5 - 50 cm. Thermal imaging cameras are very similar to spot pyrometers in that infrared radiation is projected onto a detector matrix, with each single pixel in the image corresponding to a temperature measurement.

Thermal imaging camera producers usually do not specify SSR values to describe the spatial resolution of their products but use instead the Instantaneous Field of View (IFOV). The IFOV is defined as the field of view of a single detector element of the camera’s detector array.

Theoretically, the IFOV directly determines the spot size ratio of a thermal imaging camera. As the infrared radiation that is emitted by the target passes through the optics and is projected on the detector, the projected infrared radiation should completely cover at least one detector element, which corresponds to one pixel in the thermal image. So in theory, covering one pixel in the thermal image should be sufficient to ensure correct temperature measurements. The IFOV is usually expressed in milliradians (one thousandth of a radian).

The term radian describes the ratio between the length of an arc and its radius. One radian is mathematically de-



Thermal image of PCI Express Interface Card

fined as the angle formed when the length of a circular arc equals the radius of the circle. Since the circumference equals 2 π times the radius, one radian equals 1/(2 π) of the circle, or approximately 57.296 angular degrees and one mrad 0.057 angular degrees. In the situation where a thermal imaging camera is used to measure the temperature of a certain target, we assume that the distance to the target equals the radius of the circle, and we also consider the target to be rather flat. Since the viewing angle of a single detector element is small, we can assume that the tangent of this angle is approximately equal to its value in radian. Therefore, the spot size calculates as IFOV (in mrad) divided by 1000 and multiplied by the distance to the target.

$$\text{Spot Size} = \left[\frac{\text{IFoV}}{1000}\right] \text{x Distance to target}$$

where the IFOV is expressed in mrad.

IDEAL AND REAL OPTICS

Using the formula, you can calculate that a camera with an IFOV of 1.4 mrad will have a theoretical SSR of 1:714, so in theory, you should be able to measure an object of 1 cm in diameter at a distance of more than 7 meters. However, as was stated previously, this theoretical value does not correspond to real life situations because it does not take into account the fact that real life optics are never completely perfect. The lens that projects the infrared radiation onto the detector can cause dispersion and other forms of optical aberration. You can never be sure that your target is exactly projected onto one single detector element. Projected infrared radiation can also "spill over" from neighbor detector elements. In other words: the temperature of the surfaces surrounding the target might influence the temperature reading.

Just like with a spot pyrometer, where the target should not only cover the spot size entirely but should also cover a safety margin around the spot size, it is advisable to employ a safety margin when using a microbolometer thermal imaging camera for temperature measurements. This safety margin is captured in the term Measurement Field of View (MFOV). The MFOV describes the real measurement spot size of a thermal camera; in other words: the smallest measureable area for correct temperature readings. It is usually expressed as a multitude of the IFOV, the field of view of a single pixel.

A commonly used guideline for microbolometer cameras is that the target needs to cover an area at least 3 times the IFOV to take into account optical aberrations. This means that in the thermal image the target should not only cover one pixel, which in an ideal situation would have been sufficient for the measurement, but also the pixels around it. When this guideline is observed, the formula to determine the spot size ratio can be adapted to take into account the factor of real optics. Instead of using 1xIFOV, we can use the 3xIFOV guideline, which leads to the following, more realistic, formula:

$$X = \frac{1}{\left(\frac{3 \text{ x IFoV}}{1000}\right)}$$

where the IFOV is expressed in mrad.

Based on this formula, a camera with an IFOV of 1.4 mrad will have an SSR of 1:238, which means that you should be able to measure an object of 1 cm in diameter at a distance of just under 2.4 meters. This theoretical value is likely on the conservative side because of the safety margin observed. The real life SSR might, therefore, be higher, but using these conservative SSR values, the accuracy of the temperature readings is safeguarded.

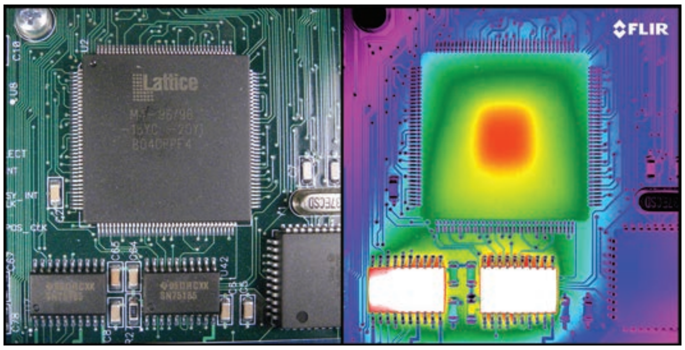
Spot pyrometers have an SSR that usually falls between 1:5 and 1:50. Most of the affordable models have an SSR of 1:5 to 1:10, while the more advanced, and therefore more expensive, models reach SSR values up to 1:40 or even 1:50. Note, however, that spot pyrometers also have the same problem as thermal imaging cameras when it comes to optics. When comparing spot pyrometer specifications, you must know if the SSR number refers to the theoretical value or to the one which is compensated for the imperfection of the optics.

DETECT TEMPERATURES FROM A DISTANCE

Even when the factor of ideal versus realistic optics is taken into account, the difference between thermal imaging cameras and spot pyrometers in measuring distance is huge. Most spot pyrometers cannot be held any farther away than 10 to 50 cm, assuming a 1 cm target. Most thermal imaging cameras can accurately measure the temperature of a target of this size (1 cm) from several meters away. Even a low-cost thermal imaging camera with an IFOV of 2.72 mrad can measure the temperature of a spot of this size (1 cm) from more than 120 centimeters away. Some advanced camera models for industrial inspections can measure temperature of a target of this size at a distance of more than 7 meters with a standard 28° lens. These values are calculated assuming that the standard lens is used. Many of the more advanced thermal imaging cameras feature interchangeable lenses.

SEE WHETHER YOU NEED TO MOVE IN CLOSER

Thermal imaging cameras clearly outperform spot pyrometers when it comes to the SSR values, but the SSR values only refer to the distance from which an accurate temperature measurement can be made. In real life, detecting a hot spot does not always require an accurate temperature reading. The hot spot can be discernible in the thermal image even when the target covers only one pixel in the thermal image. The temperature reading might not be perfect, but the hot spot is detected, and the operator can move closer to make sure that the target covers more pixels in the thermal image, ensuring that the temperature reading is correct.



Thermal imaging cameras allow you to “see” the heat.

Spot pyrometers also have challenges with measuring temperature on small objects. This capability is increasingly important for electronics inspection. As devices continue to get faster in processing speed, yet are required to fit into smaller packages, finding ways to dissipate the heat and identify hot spots is a real problem. A temperature gun can effectively detect and measure temperature, but its spot size is simply too large. However, thermal cameras with close-up optics can focus down to less than 5μm (micrometers) per pixel spot size. This allows engineers and technicians to make measurements on a very small scale.

STOP GUESSING, START SEEING

A spot pyrometer can only give you a number. That number might be inaccurate, which leaves you guessing. A thermal imaging camera allows you to “see” the heat, giving you not only temperature measurements, but also an instant image of heat distribution. This combination of visual information and accurate temperature measurements enables you to find faults quickly and accurately.

BENCHTOP THERMAL IMAGING: A SIMPLE-TO-USE, COST-EFFECTIVE SOLUTION FOR TROUBLESHOOTING COMPLEX PRINTED CIRCUIT BOARDS

Electronic products used in aerospace applications and for scientific research have two key requirements: they must have both the high performance and the reliability to withstand intense environments. To attain that performance, electronics designers often use small parts and routinely push them to their limits. As overstressed components tend to overheat, they are at a high risk of failure, thereby threatening the integrity of the board as a whole.

All-in-one meters with integrated thermal imaging allow for fast inspections of electronics systems

That's the challenge San Francisco-based Highland Technology found itself facing on a daily basis. Founded in 1984, Highland designs and manufactures standard and custom electronics for demanding aerospace, defense, scientific, and industrial applications. Its products have very high performance and reliability requirements, with PCBs that are often populated by upwards of 1,200 very small parts.

Highland's design process starts with a specification and then the design. Its engineers iterate between the two until they learn what specifications the design can and can't meet and how they can improve the design. Once the schematic is worked out, a PCB is designed and laid out. Manufacturing then builds a prototype, and testing in the laboratory begins.

Highland routinely pushes the parts it uses both electrically and thermally to deliver the cutting-edge performance customers demand, particularly picosecond range speeds. Hence, many of the bugs it finds are caused by components that overheat. For Highland's engineering and test teams, the challenge is finding out exactly which components in a given design are heating up.

As John Larkin, president and chief engineer at Highland Technology, explains, "We don't want to make unreliable products. We want products that have high performance. Thermal stress is a key part of that because small parts switching high currents and high speeds get hot. We don't

Thermal imaging helps engineers and technicians quickly identify design flaws with thousands of points of non-contact temperature measurement.

have the analytical tools to predict what component temperatures are going to be within 10, or even 20, degrees Celsius sometimes. So we have to physically measure the temperatures in engineering and testing."

Of course, Highland can't just put a thermocouple on a component to measure its temperature; the parts are simply too small. Spot pyrometers also don't work. Like the thermocouple, these instruments measure heat only at a single specific point on an object and, therefore, offer an incomplete picture of a target's thermal properties. Plus, troubleshooting an entire PCB with a spot pyrometer would be a slow and arduous process. Visual inspection doesn't work either, since many issues — like a short in a component — are invisible to the naked eye.

THERMAL IMAGING TO THE RESCUE

For companies like Highland that routinely design and manufacture high-performance, high-reliability electronic products, understanding the thermal properties of the components used in those products is critical. It's in these scenarios that the thermal imaging camera thrives.

Thermal imaging cameras work by detecting infrared radiation and translating it into a temperature reading. A single camera can produce thousands of non-contact temperature readings at the same time, one for each pixel in every frame of data. These readings are then converted into a map of the heat distribution of the device. This combination of visual information and accurate temperature measurement enables users to find faults (hot spots and potential points of failure) quickly and accurately — many that might otherwise be missed.

Thermal cameras also have the advantage of being easy to use and customizable to a user's needs. And because they are able to scan large areas at one time, they are well-suited to inspecting heat dissipation on PCBs and performing quality checks. By detecting design flaws that materialize as heat, they even help to significantly shorten product development time. Moreover, with technological advances and demand on the rise, the cost of thermal cameras has come down in recent years.

"Thermal imaging is important in our testing because it often leads us to problems quickly. Suppose you have a complex PCB that is not working, perhaps due to a power supply, voltage regulator, or an FPGA on the PCB. You could do a lot of troubleshooting with oscilloscopes and volt meters to try to find out what's wrong, but thermal imaging provides a really handy way to cut through a lot of complexity and quickly show where the problem is," says Larkin.

With thermal imaging, the engineer or QC technician is able to visually see where all of the current in a PCB is going and which component might be the cause of a hot spot — whether it's a short in a component or an actual component failure. By quickly narrowing the search to a specific component, the thermal camera reduces the time it takes to troubleshoot a problem.

But thermal imaging doesn't just tell Highland Technology where to look for problems, it also tells the company exactly how hot a part is getting. That information is vital in understanding just how far it can push a component and what specifications it can claim on the product before making it unreliable.

THE SEARCH FOR A THERMAL IMAGER HEATS UP

While Highland knew that use of a thermal imager could resolve its issues, finding the right one tailored to its specific needs remained elusive. The FLIR ThermaCAM™ E45 thermal imager it had been using was a bulky instrument with a large germanium lens, making it difficult to move around. Due to its high cost, the company only had one such instrument and had been using it for more than 10 years.

Another key issue with their existing thermal imager, according to Carla Vega, Highland's test program manager, was having to hold onto it during testing. "It's difficult to focus the imager on the component where the heat source is coming from because your hand shakes when you're holding it and trying to focus it on the component."

Despite these drawbacks, the imager proved quite invaluable to the company, so much so that Highlands's engineering and testing teams constantly fought over its control. Buying another such instrument, however, was not an option.

What Highland needed was a smaller, hands-free thermal imaging camera, one that was cost-effective enough that both its engineering and test teams could have their own instruments. The imager also had to be able to image very small parts, very close up, since the majority of what Highland needed to test consisted of integrated circuits, resistors, and capacitors.

According to David Stanislowski, Highland's engineering manager, "What we need in a thermal imaging solution is convenience and ease of use, to just be able to grab it, set it up, and quickly see what's going on. And we need to be able to see, with enough resolution, an individual component. A lot of our components are very small, some smaller than a grain of rice."

A THERMAL IMAGER MADE FOR THE BENCHTOP

The breakthrough for Highland came with the FLIR ETS320 thermal imaging system (see the sidebar). Designed for hands-free use in a lab with a microscopic-style stand that's quick to set up, it provided the stable platform Highland needed to place a PCB under the camera and electrically probe it without any shaking or vibration from the operator. Plus, the camera can easily be moved from one bench to another. The camera maintains a constant, rigid focus point and distance, allowing the company to thermally image components so small they couldn't have measured the temperature of which any other way. The imager's affordable cost means Highland is no longer limited to purchasing just one.

As Stanislowski explains, "The ETS320 is great because it's mounted and has a convenient adjustable focus, and you can just set it up exactly where you need it, leaving your hands free to electrically probe or move the device around exactly as you need to."

Larkin discovered just how useful the benchtop ETS320 imager was recently when he designed a board, built a prototype, tested it until he got it to work very well, and then thermal imaged it. He quickly discovered the transistors were running at almost 200 degrees Celsius. Even though the design worked beautifully, it would not have been reliable at that high temperature. The discovery enabled him to iterate the design and incorporate better transistors.

Likewise, Stanislowski's team had a board with an FPGA that was getting too hot and kept shutting down. Using the ETS320 imager, his team quickly and easily measured the temperature of the FPGA under different circumstances and determined its operating limits. Then, to better handle the heat from the FPGA, the team added a heat sink and more airflow, and tightened up the specification limits on the operating temperature range.

At Highland, thermal imaging is now an integral part of both its engineering and evaluation of reliability and thermal stresses on new designs. It's also used in testing. The ETS320 thermal imager, with its ease of use and hands-free measurement functionality, now makes the company's benchtop thermal measurements faster, easier, and much more affordable. It's a solid investment that has and will continue to return a huge reward for the company.

DAVE BURSELL

Global VP of Strategic Business Development, FLIR, Industrial Business Unit

Dave has held several executive positions at FLIR. He's served as a national sales director for FLIR's R&D/Science team and vice president of global business development for FLIR's Optical Gas Imaging and R&D/Science team, and he most recently is serving as the vice president of global business development for all of FLIR's Instruments Business Verticals. Dave has a bachelor of science degree in mechanical engineering from Brigham Young University and a master's in business administration from Boston University.

CHRIS BAINTER

Chris has over 18 years of experience in the test and measurement industry, with a bachelor of science in computer engineering from Kansas State University and an MBA from the University of Southern California. He has written articles on the use of infrared technologies for electronics inspection, high speed thermal applications, and next generation detector technologies. Chris currently serves as FLIR's global business development director for the Optical Gas Imaging, Premium Handheld, and R&D/Science business verticals.

JERRY BEENEY

Jerry Beeney holds a bachelor of science degree in mechanical engineering and worked for over 11 years as a sales engineer in FLIR Systems' Science Camera Segment. During this time, he provided technical sales and support services to clients across a broad range of industries throughout the upper Midwest. He now uses this sales and customer-facing experience in his current position as the strategic business development manager for FLIR's Premium Business Segment, where he focuses on driving long-term, sustained growth for FLIR Instruments in the Americas.

ABOUT THE AUTHORS

KOEN JACOBS

After attaining his master's degree in engineering electromechanics, Koen Jacobs has been working with advanced IR applications and technology for nearly 10 years. While focusing mainly on SWIR technology during his first professional years, Koen worked as a R&D sales manager for FLIR for many years thereafter. In this role, he provided a wider range of IR solutions to the EMEA R&D/Science community. In his current position as strategic business development manager for FLIR, Koen's vision and strategies have an impact on the global R&D/Science market.

RON LUCIER

Ronald D. Lucier has a bachelor of science degree in mechanical engineering and over 40 years of engineering experience. His infrared experience started in 1983 and continues through publication (over 30 articles and papers), webinars, blogs and other social media. He holds an ASNT NDT Level III – Thermal/Infrared certification (less than 100 exist worldwide) and has conducted an average of 30 training courses per year for the Infrared Training Center since 1999 (part of FLIR Systems, Inc.) Ron's specialties are in the areas of optical gas imaging and refinery furnace inspection.

ROSS OVERSTREET

Ross Overstreet currently serves as the FLIR strategic account manager for military test ranges, Department of Energy National Labs, and NASA facilities. Through a variety of roles, he's been selling and supporting radiometric FLIR cameras to military test ranges, commercial accounts, national labs, and universities for the last 12 years. Prior to FLIR, Ross worked in computer-based measurement and automation and as a thermal vacuum test engineer. Ross has bachelor's and master's of science degrees in mechanical engineering from Auburn University.

PORTLAND

Corporate Headquarters
FLIR Systems, Inc.
27700 SW Parkway Ave.
Wilsonville, OR 97070
USA
PH: +1 866.477.3687

CANADA

FLIR Systems, Ltd.
920 Sheldon Court
Burlington, ON L7L 5K6
Canada
PH: +1 800.613.0507

NASHUA

FLIR Systems, Inc.
9 Townsend West
Nashua, NH 03063
USA
PH: +1 866.477.3687

LATIN AMERICA

FLIR Systems Brasil
Av. Antonio Bardella, 320
Sorocaba, SP 18085-852
Brasil
PH: +55 15 3238 7080

EUROPE, MIDDLE EAST & AFRICA

FLIR Systems, Inc.
Luxemburgstraat 2
2321 Meer
Belgium
PH: +32 (0) 3665 5100

ASIA PACIFIC

FLIR Systems Co., Ltd
Rm 1613-16, Tower II
Grand Central Plaza
138 Shatin Rural Committee Rd.
Shatin, New Territories
Hong Kong
PH: +852 2792 8955