"INFRARED THERMOGRAPHY,"
an expanded practical non-contact image forming temperature measurement concept. A tutorial.

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Abstract:

A tutorial is presented that attempts to describe, clarify and connect together the many aspects of the field of thermal infrared. This includes description of the IR wavelength spectra, blackbody radiation, detectors and detection methods used, non contact temperature measurements, some typical applications and practical uses.

Introduction.

As we live in our world in the universe, we are aware of the surroundings only through the limited perception of our five known senses. The ability to hear, to smell and to see makes it possible for us to keep in contact with our surroundings without the physical touch. Through our touch we can recognize if an object is warm, hot or cold. Our body can also, in a crude way, detect the invisible heat radiation from an object, for instance from a burning fire.

Then, what is infrared radiation?

If our eyes were sensitive in the infrared wavelength band, we would see ourselves as glowing objects, since we are emitting infrared (thermal) energy. The human eye, however, is tuned to the radiation output from the sun that we know as the visible light. The light wavelength peaks at about 0.5 micron (the yellow part of white light), and is below the thermal infrared wavelength band. To see the infrared energy that surround us we need to use some specific tools. Let us try to explain how this can be done.

Visible light and infrared radiation are part of the electromagnetic waves that includes the whole spectrum from Gamma rays to millimeter radar. The Infrared radiation has a wave length between 0.75 micron and 40 micron. The practical thermal infrared band for imaging systems normally covers 2 to 15 micron.

Infrared radiation is also considered to be radiated black body energy radiating from any object.

IR-theory, Max Planck's Law, Wien's displacement law, Stefan-Boltzmann's law.

What is blackbody radiation and what is a blackbody?

The definition of a blackbody is as follows, "An object that absorbs all radiation at any wavelength that impinge upon its surface". A blackbody that can absorb all the energy received at any wavelength is also equally capable of emitting or radiating energy at any wavelength. There are three mathematical expressions that can be used to understand the mechanics of the radiation emitted from a blackbody.

Planck's Law.

Max Planck describes the spectral distribution of the radiation from a blackbody as follows:

$$W\lambda_b = \frac{2\pi hc^2}{\lambda^5(e^{hc/\lambda kT}-1)} \times 10^{-6} \ [\text{Watts/m}^2\mu\text{m}]$$

where

$W\lambda_b$ = the blackbody spectral radiant emittance at wavelength λ

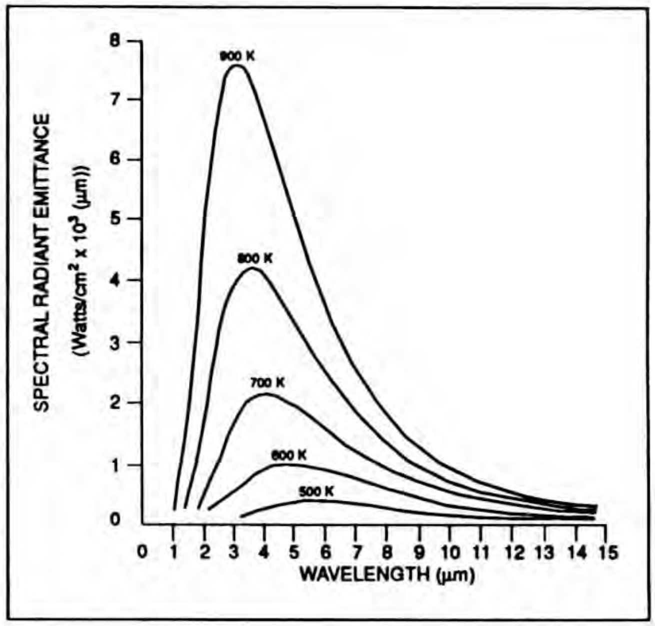
c = the velocity of light = 3×10^8 m/sec.

h = Planck's constant = 6.6×10^{-34} Joule sec.

k = Boltzmann's constant = 1.4×10^{-23} Joule/K.

T = the absolute temperature (K) of a blackbody.

λ = wavelength (m)



The factor 10^{-6} is used to provide spectral emittance in $Watts/m^2\mu m$.

When the Planck's formula is plotted graphically for various temperatures, a family of curves will be produced where it is shown that the spectral emission is 0 at Lambda=0 and then increases rapidly to a peak at a wavelength of lambda max. It then approaches 0 at very long wavelengths. The higher the temperature, the shorter the wavelength at peak emission.

One way to visualize where the peak emission of the blackbody item is situated in the wavelength band as a function of the temperature, is as follows: We know that our eyes are sensitive to the electromagnetic wave band around the peak emission of the Sun. This wave length provides the white light, in it self a mixture of colors, as can be seen when it is divided up in its spectral components by a rainbow after a rain shower. This spectra can also be produced through the use of a glass prism. (Sir William Herschel used this technique when he investigated the energy content of the visible sunlight and found that a certain amount of energy was missing i the visible. Using a thermometer as an infrared detector and positioning it outside the "rainbow", he found that it was detecting an increase in temperature above the color red. He called this Infrared.) If we, with our eyes, look at a piece of black iron heated to room temperature, what we will see is just a piece of black material. However, if we heat the iron piece, it will eventually get warm enough to glow a very dark red. This means that the peak emission of the test piece now has changed so that it is at the very edge of the electromagnetic spectra that our eyes can detect. Its peak is moving out of the infrared part of the spectrum.

If we continue to heat up the piece of iron, for instance with a welding torch, it will change color to red, cherry red, orange, orange-white and, perhaps with the addition of oxygen to really boost the temperature, to white. Its energy radiation thus positioned right in the middle of the detection range for our eyes.

Conversely, if the iron piece is cooled, the peak blackbody emission will move away from the sun spectra and further into the infrared, towards the longer wavelengths. This phenomena is of interest when deciding upon what detection system should be used for a particular object temperature span.

Wien's displacement law.

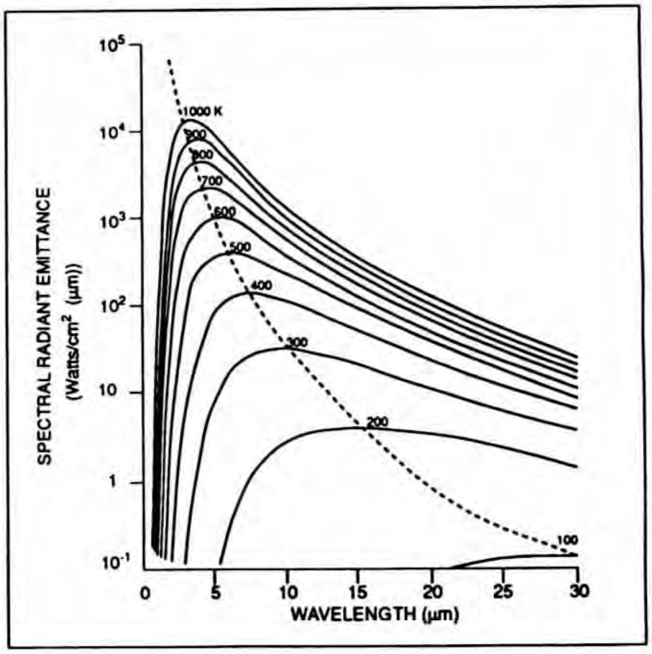
The Wien's formula gives us a mathematical explanation to the effects we just discussed. By differentiating Plank's formula with respect to wavelength (Lambda), and finding the maximum, we can show:

$$\lambda_{max} = \frac{2898}{T}\ [\mu m]$$

This is the Wien's formula. The wavelengths of the color is the same as the wavelength calculated for Lambda max. If we enter the absolute temperature of the sun (about 6000K) into the formula, we will find that Lambda max is 0.483 micron - sun yellow. If we enter the absolute temperature of 300K (room temperature) we find Lambda max to be 9.66 micron - longwave IR. Should we enter the temperature of LN2, Liquid Nitrogen, 77K, we find Lambda max to be 37.64 micron - well into the extreme long wave IR.

See chart on next page.

Planck curves plotted from 100 to 1000 degrees Kelvin. The maximum radiant emittance is shown for each temperature in accordance with Wien's law.



The Stefan-Boltzmann law.

The Stefan-Boltzmann formula shows that the total power emitted from a blackbody is proportional to the fourth power of the absolute temperature of the blackbody.
Integrating the Planck's formula from Lambda = 0 to Lambda = infinity, we will obtain the total radiant emittance (Wb) of a blackbody as:

$$W_b = \sigma T^4 \text{ [Watts/m}^2\text{]}$$

where

σ = the Stefan-Boltzmann constant = 5.7×10^{-8} Watts/m^2.

The power of the total emission from a blackbody can be illustrated graphically, where the area under a Planck curve for a specific temperature shows this power in Watts per square meter. As an example, let us calculate the power radiated from a human body at the body temperature of 300 degrees K. We assume a surface area of about 2 square meter and we then find the power radiated to be about 2,300 Watt. Through appropriately heated surroundings and insulating clothing the heat loss is kept within limits that can be sustained by the normal chemical generation of heat in the human body.

If we are interested in seeing the infrared radiation that surrounds us, it is necessary to convert the invisible infrared waves to visible waves. This conversion can be performed with the help of various IR Detectors and detection systems.

Many Infrared Detectors are available. For example: (A) Various semiconductors such as Indium Antimonide, MCT, Gold doped germanium, PtSi, etc.(B) The Thermocouple and Thermistor. (C) The thermochromic liquid crystals.(D) The Baird Evaporograph. (E) The Goulay cell, a pneumatic detector. (F) The Thermometer. (G) The Human skin is a very crude detector. Hold a hand close to a hot plate and you will detect ir radiation. (H) The Rattle Snake has a forehead pit that detects heat. (I) The common Mosquito detects IR-radiation during the night that may lead it to warm blooded animals. (Or humans).

To see an image of the infrared radiation emitted from an object, a detector need to be teamed with an image forming apparatus.

The most used image forming systems is either the 2-Axis mechanical or the electronic scanning system. The mechanical system can be implemented rather easily and it works well. It is the system employed in the majority of Thermal Imaging systems now in use. It consists of a detector, were the object is projected onto it via the optical scanning unit and then shifted over the detector in a grid fashion. The electronically scanned system is normally used with focal plane arrays or vacuum tube systems.

Some history.

Various military non measuring and classified systems are using mechanical scanning and have been produced and used as FLIR (Forward Looking Infra Red) systems for more than 30 years.

One of the earliest commercial thermal imaging systems was the Barnes Engineering Thermograph. It was already used in medical and other research prior to 1965. It produced a single image on a printer during the scanning of the object. (Up to 15 minutes for an image.)

The Swedish AGA Corporation (Aktiebolaget Gas Accumulator), introduced the AGA Thermovision Real Time measuring fast scanning (16 fields per second) system in Sweden 1965. It was originally developed as a passive military night sight for a Swedish tank, but was used, in its commercial version, for medical research and for detection of overheated power utility line connections. It used a Refractive Prism Mechanical scanning system.

The AGA Thermovision 652 was introduced on the US market in the spring of 1966. Main applications were then medical research, power utility inspection, military research.

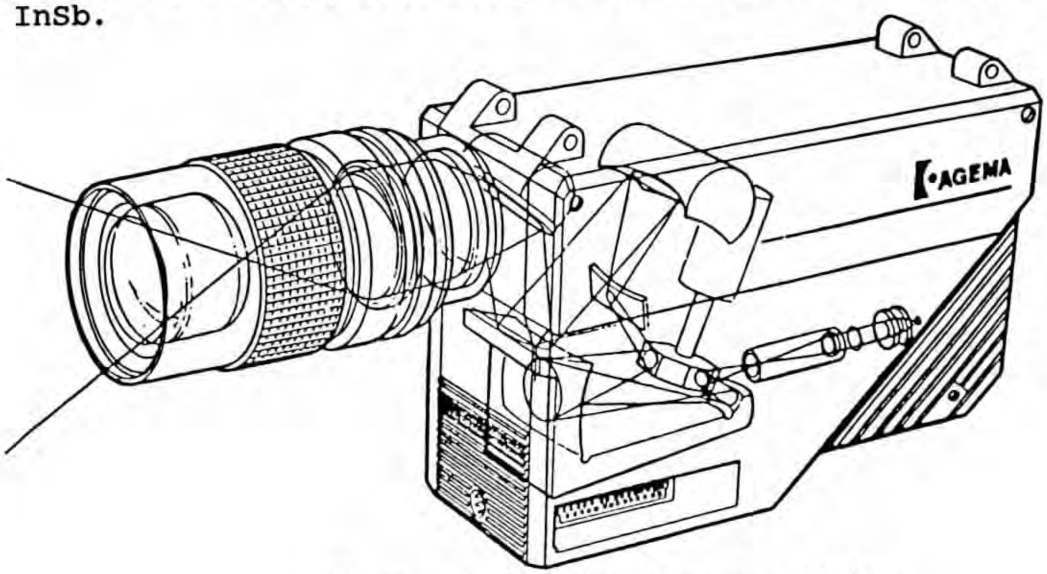
Other early mechanically scanned commercial systems came from: Barnes/Bofors, Dynarad, Texas Instruments and Hughes.

Some of the current Infrared Imaging systems with mechanical scanning include AGEMA Thermovision (new name for AGA), Inframetrics (Successor to Dynarad), Magnavox, Barnes Engineering, FLIR Systems, Hughes, Micron, NEC.

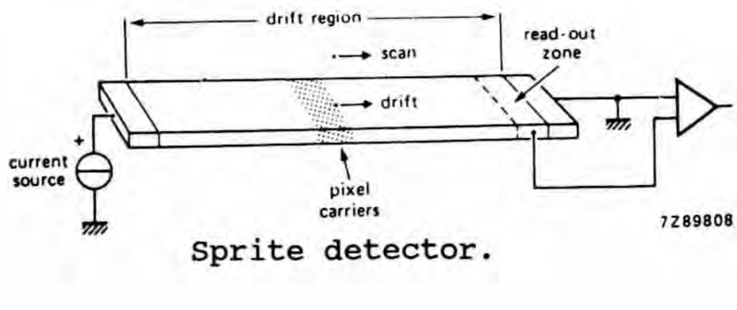
Basic principles of image forming systems.
Mechanically scanned systems:

A typical modern scanning system may be described as follows. The IR camera contains a mechanical scanning module for vertical and horizontal scanning. Within the module are two micro black body temperature references that are continuously scanned by the scanning system to provide stable temperature references for the calibrated operation of the scanner at all times, even during changes in the ambient temperature.

The scanning optics consist of diamond turned aluminum alloy mirror sections combined with a rotating reflective prism system with ten reflective facets. The front facets of the prism system provide the scanning of the object in space. The rear facets, 180 angular degrees out of phase with the front facets, scan over the detector (if SPRITE) following the movement of the carriers in the detector. This provides the TDI (Time Delay & Integration) effect in the SPRITE detector. The vertical scan tilting mirror is controlled by the scanner microprocessor to provide linear scan and is servo-linked with the horizontal scan. Other detector modules are also used, typically single element MCT or two element InSb.



Thermovision 800 Scanner Unit.



Sprite detector.

The microprocessor within the scanner accesses the detected temperature output from the micro-black body references plus four other passive temperature sensors within the scanner body and attached lenses, to assure zero temperature drift at all times.

The output from the detector is digitized at twelve bit depth right after the preamplifier and is sent, in digital format, to the controller unit via regular cables or even fiber optic links. A very high dynamic range and a minimum of interference can thus be assured.

The controller unit converts the electronic signals from the scanner to a visible image normally presented on a television monitor. Either greytone or color format is used. Various methods are used to read out the calibrated temperature values.

Many scanned fields of views of the scanner/camera can be selected with interchangeable and electronically connected IR-lenses. Lens materials for refractive lenses are normally Silicon for the 2-5.6 micron range and Germanium for the 8-12 micron range. Multilayer anti-reflection coating is employed. Some lenses use reflective lens elements.

"Staring" Oil film membrane system.

This is probably the first practical staring system. The principle used for this system was first described in 1846 by Sir William Herschel. It produces an infrared image that is not calibrated and can be seen by the human eye through the use of visible light interference reflections off a variable thickness thin film. The film in this case consists of a layer of oil evaporated onto a very thin membrane.

When infrared radiation is focused through a germanium lens onto this membrane, it will evaporate the oil film in a pattern depending on the infrared radiation level. This will change the thickness of the oil film and produce an interference image where different colors outline different ir radiation flux. The only instrument that uses this principle, is the "Evaporograph", made by Baird Atomic between about 1950 - 1968. It was used successfully for a long time in many of the now "standard" applications, particularly in the electric utility powerline inspection.

"Staring" Liquid Crystal system.

When the Liquid Crystal technology emerged, it was found that the thermochromic liquid crystal would change its color depending upon the formulation and the temperature of it. Thus the familiar "creditcard & plastic strip" thermometers were invented. The same technique is used in a TLC staring infrared detection system. Infrared radiation focused onto a thin film formulation of the TLC will result in an image that resembles the thermal radiation emitted from an object.

The formulation of the TLC makes it possible to provide calibrated temperature readout. The slow reaction speed and the low sensitivity plus the inability to easily change the temperature range and level, make this principle quite impractical as a system. However, liquid crystal solutions can be applied directly to an object, and will then provide temperature readouts within the formulation limits. An intermediate media (such as a thin plastic film) can be coated with TLC and pressed against an object to present a temperature image.

"Staring" semiconductor system - Focal Plane Arrays. (FPA)
(Electronically scanned)

This latest and most practical concept of a "staring" system is "solid state" and electronically scanned. The FPA technology has been made possible due to the practical use of microlithography and the ground level work by the producers of microcircuits. There are currently three practical detector materials available for the fabrication of FPA's. The most popular is Platinum Silicide, (PtSi), Indium Antimonide, (InSb) & Mercury-Cadmium-Telluride, (HgCdTe or MCT). Any of these detector materials need to be cooled to cryogenic temperatures to work properly. Normally liquid Nitrogen or a Stirling Cycle cryogenic cooling is used.

An FPA can be seen as an organized cluster of very small detector elements set in rows of e.g. 256 x 256 elements and electronically accessed and read so as to provide a scan of the field of view without any mechanical means. The information is then reassembled into a picture and presented on a TV-type video screen. Since each detector element is staring out into space through an infrared lens without being disturbed by a mechanical scanning system shortening the dwell time, the efficiency is high. The system sensitivity is enhanced for a given size of the detector element.

These systems work very well in pure imaging applications after a dynamic computer aided modification of the unlinearity of the detector elements is performed. Such a circuit with its software is normally part of an FPA IR camera. The unlinearity of the individual detector elements makes it particularly troublesome to provide a calibrated temperature or energy output from any of the FPA's.

Some of the current manufacturers of FPA Systems are Mitsubishi, Amber, Cincinnati Electronics, Santa Barbara Focalplane, Kodak and David Sarnoff Research to name a few.

For practical high resolution IR imaging energy and temperature measurement applications, the IR cameras/scanners with a mechanical scan principle and single detectors or small multi element detector arrays still remain the reigning systems.

"Staring" Pyroelectric Vidicon with electronic scanning system.

The pyroelectric IR video camera is well known and widely used. It detects infrared energy in a wide spectral band (2 to 40 micron typically) and is normally optimized to 8-12 micron. It has regular TV video output. The imagery has quite high spatial and temperature resolution. Recording can be made with conventional video methods.

The pyroelectric infrared system uses a pyroelectric vidicon as the heart of the system, with its internal "triglycine sulfate" (TGS) or "triglycine fluoroberyllate" (TGFB) retina. It needs mechanical chopping of the infrared signal reaching the vidicon, or moving or panning of the camera, to prevent the retina target from saturation. If saturated, the image on the display will disappear.

Temperature or infrared energy measurements with this type of camera are normally not possible from the image information received. These cameras are used when viewing is of main interest, for instance as passive night vision security devices or for electric utility or industrial energy conservation applications, and when actual temperature readings are of low importance.

Some of the manufacturers of pyroelectric vidicon systems are ISI, Thompson, Philips.

Non contact temperature measurements.

How can we measure the heat radiation we now can see?

The output from a photon detector in an IR camera is proportional to the photon energy striking the detector. It is therefore possible to calibrate the output to very exact values. Typical temperature measurement specifications for a Thermovision System 900 are plus minus one degree Celsius or plus minus 1% when within the calibrated range and corrected for object emissivity.

To produce a reliable calibrated imaging infrared measurement system, it is essential that all building blocks are stable. Starting with the scanner system itself, it is particularly important that it is drift free and immune to changes in the ambient temperature. In the Thermovision 900 scanner, two micro-blackbody temperature references are scanned and sampled by the IR detector before and after each horizontal line scan. The information received, plus temperature information from 4 other sensors, is used by the internal microprocessor to ascertain that a "no drift" condition exists at all times.

With the scanner inherently stable, it is now possible to produce a calibration of scanner, lenses and filters that can be expressed mathematically. Calibration constants can now be stored in a PROM in the scanner and called upon by the main processor so that it may calculate exact temperatures of the viewed object.

The emissivity value of the object need to be known and entered to the main processor through the software prompt. Ambient air temperature and distance to the object are used to automatically calculate the offset caused by the radiation reflected by the object into the scanner.

Through the input of ambient temperature, distance & humidity, the IR attenuation of the atmosphere can be calculated. This value is used to offset possible errors in the measurement due to the distance to the object. Advanced atmospheric models such as LOWTRAN may be used. When close-up or microscope lenses are used, the atmospheric attenuation is 0.

In many applications involving semiconductor materials, it may be necessary to explore the transmissive properties of the object materials. Both Silicon and Germanium are quite transparent in the infrared. Various nontransparent coatings may be used that also will provide high emissivity numbers.

If the emissivity of the object is known, calculation of the exact temperature can now be performed by the controller and its computer.

When working with semiconductors, IC's, printed circuit boards, and other complex objects, emissivity correction can and needs to be made. The use of heating stages or heating boxes makes it possible to record the emitted radiation from the object, at specific known temperature levels, to provide for emissivity calibration. The computer can then calculate the temperature and the emissivity correction for each picture element in the thermal image. Both interpolation and extrapolation methods can be used.

For example, the following steps will provide a correct temperature chart of a power transistor. (1) Capture a thermogram of the transistor at working temperature. The image will not show the true temperature since emissivity of the various areas of the object is unknown. (2) Raise the temperature of the nonpowered transistor to 80 degrees C, using the hot stage, and record. (3) Raise the temperature of the nonpowered transistor to 100 degrees C and record. (4) Run the equalization program. True temperatures will now be presented with the emissivity equalized throughout the image.

With the use of an equalization (heating) box, and using the above method, printed circuit boards (PCB's) can also be evaluated.

An extrapolation program helps us to evaluate a PCB even in its normal environment, when using the following procedure. Let the PCB assume thermal equilibrium in its normal location. At time = 0, take out the PCB and record its thermal image. Record a new thermogram of the PCB after 30 seconds. Record a new thermogram after 60 seconds. Run the program to provide the backwards extrapolated thermogram which shows the temperature pattern of the

PCB in its normal location but without emissivity correction. Record a reference thermogram of the unpowered PCB in the equalization box at 50 degrees C. Run the program to provide the equalized, backwards extrapolated thermogram representing the true temperature of the printed circuit board in its actual working location.

Conclusion.

Infrared Thermography, once a rather unknown novelty, has matured over the years. It is now a well established technology with a multitude of applications. Thousands of Thermographic systems are in use all over the world supported by a number of systems manufacturers. Future application and system developments will provide us with an even better insight into many of the unknowns of the materials sciences and the development and manufacturing of products.

REFERENCES:

(1) Wolfe, William L., "Handbook of Military Infrared Technology", Office of Naval Research, Department of the Navy, Washington, DC, 1965.

(2) Wolfe, William, L., Zissis, George J., "The Infrared Handbook", Environmental Research Institute of Michigan for the Office of Naval Research, Department of the Navy, Washington, DC, 1978.

(3) Hudson, Richard D., "Infrared System Engineering", John Wiley & Sons, New York, 1969.

(4) Kruse, Paul W., McGlauchlin, Laurence D., McQuistan, Richmond B., "Elements of Infrared Technology: Generation, Transmission, and Detection", John Wiley & Sons, New York, 1962.

(5) AGEMA Infrared Systems, "Thermovision 900 Series Users' Manual", Danderyd, Sweden, 1992.

(6) Eklund, Jan K., "Advanced High Performance Reflective Infrared Scanning System with built-in Temperature References", Electronic Imaging '86, Institute for Graphic Communication, Inc., Boston, 1986.

(7) Azar, Kaveh, "Problem Solving Techniques in Electronic Cooling", Fifth IEEE SEMI-THERM Symposium, 1990

(8) Parsley, M., "The use of Thermochromic Liquid Crystals in Research Applications, Thermal Mapping and Non-Destructive Testing", Seventh IEEE SEMI-THERM Symposium, 1992.

(9) Shepherd, Jay W., "A discussion of emissivity correction and its application in infrared microimaging", SPIE Vol. 780, Thermosense IX, 1987.

(10) Eklund, Jan K. & Baeu, Dietrich, "Looking at the World through an Infrared Eye", Industrial Research Magazine, Dun Donnelley Publication, April 1975.

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