FOUNDATIONS AND APPLICATIONS OF PASSIVE AND ACTIVE INFRARED THERMOGRAPHY

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INFRARED BASICS

• Infrared: The portion of the electromagnetic spectrum between 700 nm and 1 mm

• Infrared ≡ “Below Red”

http://earthobservatory.nasa.gov/Experiments/ICE/panama/Images/em_spectrum.gif
INFRARED HISTORY: SIR WILLIAM HERSCHEL

• British/German astronomer and composer

• Two experiments led to the theory of Infrared radiation in 1800

• Red filters to observe sun spots

• Prism and thermometer to observe the temperature of different colors.

• On 11 February 1800, Herschel was testing filters for the sun so he could observe sun spots. When using a red filter he found there was a lot of heat produced. Herschel discovered infrared radiation in sunlight by passing it through a prism and holding a thermometer just beyond the red end of the visible spectrum. This thermometer was meant to be a control to measure the ambient air temperature in the room. He was shocked when it showed a higher temperature than the visible spectrum. Further experimentation led to Herschel’s conclusion that there must be an invisible form of light beyond the visible spectrum.
INFRARED PHYSICS

- Emission of infrared photons caused by the vibration of molecules
- Molecules can have many different normal vibration modes
VIBRATION MODES OF A BENT MOLECULE
GOVERNING LAWS

• Kirchhoff’s Law of Thermal Radiation
• Wien’s Displacement Law
• Planck’s Law of radiative emission
• Stefan-Boltzmann Law
KIRCHHOFF’S LAW OF THERMAL RADIATION

• At thermodynamic equilibrium, a perfect blackbody absorbs all incident radiation and emits the same total energy.

• The radiation emitted by the blackbody depends only on its temperature and the emitted wavelength.
WIEN’S DISPLACEMENT LAW

- The wavelength at which maximum energy is emitted is inversely proportional to temperature.
- \( \lambda_{\text{max}} = \frac{b}{T} \)
- \( b = 2.8977729 \times 10^{-3} \text{ mK} \)

http://m.teachastronomy.com/astropediaimages/wiens_law_high.jpg
FIGURE 2.6 Spectral radiance of a blackbody (Planck’s law; could be plotted with Matlab script: Planck.m).

\[ L_{\lambda, b}(\lambda, T) = \frac{c_1}{\lambda^5 \left[ \exp(c_2/\lambda T) - 1 \right]} \quad \text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1} \quad (2.15) \]
PLANCK’S LAW

- $W_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \left( \frac{W}{\text{Sr m}^3} \right)$

- $E = \frac{hc}{\lambda}$ (J/photon)

- Completely describes irradiation as a function of temperature and wavelength/frequency
STEFAN-BOLTZMANN LAW

- $E = \sigma T^4$
- $\sigma = 5.6703 \times 10^{-8} \text{ W/m}^2\text{K}^4$
- Valid for blackbodies
- Across all wavelengths
- Modified to include emissivity: $E = \varepsilon \sigma T^4$
• Fraction of total emitted energy at a particular temperature from 0 to a certain wavelength can be determined

• Very little of the total emitted energy at room temperature is below infrared

<table>
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<tr>
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<th>$F_{\text{tot}}$</th>
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<td>0.403607</td>
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<tr>
<td>3,800</td>
<td>0.443382</td>
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1. Values from Table 12.1, Incropera and DeWitt, 1999.
2. Constants used to generate these blackbody functions are: $C_1 = 3.7420 \times 10^8 \mu$m/m2 and $C_2 = 1.4388 \times 10^4 \mu$m-K.
GOVERNING LAWS AND THERMOGRAPHY

• Temperature guns (Pyrometers) use the Stefan Boltzmann Law to calculate the temperature of an object.

\[ E = \varepsilon \sigma T^4 \]

• A series of lenses focus the incoming radiation on a sensor.

• The sensor converts the infrared energy to a voltage signal.
THE IMPORTANCE OF EMISSIVITY

• The emissivity of the surface of a material is its effectiveness in emitting energy as thermal radiation. Quantitatively, emissivity is the ratio of the thermal radiation from a surface to the radiation from an ideal black surface at the same temperature as given by the Stefan–Boltzmann law.

\[ E = \varepsilon \sigma T^4 \]

• No objects are perfect blackbodies
• Emissivity can vary from near 1 to near 0 (for very reflective materials such as silver and aluminum)
• Emissivity must be accounted for when using temperature guns or thermal cameras or significant errors can occur
THERMAL IMAGING CAMERAS

- Operation is based on the same principle as temperature guns
- Camera creates a 2D image using an array of sensors
- Behaves similar to a modern digital camera

http://www.flir.ca/uploadedImages/Thermography_USA/Products/E-Series/Exx-Series-WiFi.png
PASSIVE THERMOGRAPHY

Uses infrared imaging to capture the natural temperature variations or mappings in materials and structures like buildings. It is used in the predictive maintenance community where temperature distributions of operating machinery or electrical systems are imaged to locate hot spots indicative of operating problems. This is a very important technological field and does not involve the use of an external heating source.
INFRARED CAMERAS


http://www.flir.ca/uploadedImages/Thermography_USA/Products/E-Series/Exx-Series-WiFi.png

http://www.flir.ca/uploadedImages/Thermography_USA/Products/E-Series/Exx-Series-WiFi.png
THERMAL IMAGING CAMERA USE

- Software interface shows a colored image representing the temperature gradient of the camera’s field of view.
- Calibrated targets can be placed on the image to determine the exact temperature.
- A laser guide can be used to help aim the camera.
- “Trigger” used for capturing and saving image.
- Should be pointed straight at desired object if it is not a diffuse emitter.

INSTRUMENTATION

- Minimal: Thermal Imaging Camera
- Common brands: FLIR, Fluke, Seek Thermal, Micro-Epsilon
- Optional additions: computer software, multi-meter, moisture meter, active heating source
THERMAL IMAGING CAMERA USE

• Save pictures and/or videos (with viewing mode)
• Picture in picture mode (infrared image with visual image)
• Accuracy/sensitivity
• Temperature range
• Resolution
• Alarm mode (indicating if a temperature is measured above a desired limit)
• Multiple temperature spots
• Image editing and annotations
• GPS & compass
• Adjustable lens
• Wifi
• Camera Design
• Touch Screen
• Smartphone app
THERMOGRAPHY ALTERNATIVES

- Thermal Cameras are emerging in the fields of NDT and NDI as they are non-contact methods of temperature measurement.
- Thermometers and thermocouples require contact.
- Thermocouples are easy to use and do not require auxiliary power, but require contact and can be inaccurate.
THERMAL IMAGING ADVANTAGES

• Large area and moving objects can be measured
• “Big Picture”
• Non-contact. Useful for hard to reach or hazardous objects
• Easy to use
• Does not require complicated setup
THERMAL IMAGING LIMITATIONS

- Other nearby objects can result in mis-measurement
- Emissivity of the material must be known
- Surface finish can affect uniformity of emissivity
- Very dependent on the environment
- Needs to be calibrated
- Results in some inaccuracy
- Expensive
APPLICATIONS

- Building inspection
- Electrical and mechanical maintenance
- Optical gas imaging
- Night Vision
- Military and police
- Firefighting
- Medicine
- Astronomy
BUILDING INSPECTION

- Heating and cooling require the most energy compared to other home energy uses
- Insufficient insulation and/or moisture can lead to heat loss
WHY USE THERMAL IMAGING?

• Non-Destructive: Alternatives require opening walls to inspect insulation
• Big Picture: Can scan large areas at once, making it easy to find leaks
• Safe: Does not emit any harmful rays
• Simple to understand
RESIDENTIAL HEAT LOSS

http://www.iranalyzers.com/images/homebldngenvelope.jpg
CAUSES OF INSULATION DEFECTS

• Insulation effectiveness is defined by its R value; \( R = \frac{\text{thickness of the component}}{\text{apparent thermal conductivity}} \). Larger R values mean better insulation

• Often issues arise in attics and roofs

• Missing or compressed insulation affects R value

• Poor vapor barriers can introduce moisture

BENEFITS OF DETECTING HEAT LOSS

• Climate control
• Energy savings
• Energy bill reduction
• Environmental benefits

THERMAL IMAGING AND HEAT LOSS

- Infrared cameras create a visual image of the temperature distribution of the façade of a house (or interior room)
- Exterior: The warmest portion of the outer walls indicates heat losses
- Interior: The coldest portion of an inner wall indicates where heat is lost
THERMAL IMAGING AND OTHER BUILDING APPLICATIONS

- Locate moisture to avoid heat loss and health concerns
- Analyze HVAC flow
- Determine the location of inner wall components prior to construction

FIGURE T10: On top is an infrared image of a metal cup holding a very hot drink. Notice the rings of color showing heat traveling from the liquid through the metal cup. You can see this in the metal spoon as well. On bottom is an infrared image of a melting ice cube. Notice the rings of color showing how the melt water warms as it travels away from the cube. Although the ice cube is cold, it still puts out heat, as you can see by matching the color of the ice cube with its temperature.
FIGURE T11: A visible light picture (top) and an infrared picture (bottom) of two cups. One cup contains cold water, while the other contains hot water. In the visible light picture we cannot tell, just by looking, which cup is holding cold water and which is holding hot water. In the infrared image, we can clearly “see” the glow from the hot water in the cup to the left and the dark, colder water in the cup to the right. If we had infrared eyes, we could tell if an object was hot or cold without having to touch it.
FIGURE T12: By using special infrared cameras, we can get a view of the infrared world. These cameras are very useful and have even helped save people's lives. In the infrared, you can "see" in the dark. Even if the Sun is down and the lights are off, the world around us still puts out some heat. The infrared picture shows deer in a forest during a dark night. Notice how we can clearly see the heat from the deer, especially from areas not covered with thick fur like the ears, face and legs. The trees and the ground put out less heat than the deer, but can still be seen through an infrared camera.
FIGURE T13: Infrared images of a warm-blooded dog (top) and of a warm-blooded human holding a cold-blooded caterpillar (bottom).
FIGURE T14: Above is a visible (top) and infrared (bottom) view of a person's hand inside a black plastic bag. In the visible image, the hand cannot be seen. In the infrared image, however, the heat from the hand can travel through the bag and can be seen by an infrared camera. Infrared light can pass through many materials which visible light cannot pass through.
FIGURE T15: **Top:** An infrared map of sea surface temperatures, with red being the warmest and purple the coldest. **Bottom:** two images taken by telescopes of a thick area of gas and dust in space where stars are born. Since infrared can travel through thick dust, astronomers can see through thick clouds of dust and gas in space by using infrared telescopes. **On the left** is a space cloud as seen by a visible light telescope. Notice that we cannot see what lies behind the cloud. In the infrared view **(right)** we can see through the cloud and find bright, young stars which have just been formed.
ACTIVE THERMOGRAPHY

Active (or dynamic) thermography integrates infrared imaging with time variant external heating to assess subsurface structures via the thermal-wave response of the sample. Here camera use is more complicated than in passive thermography. The most important variant to-date is “lock-in thermography (LIT)” and advanced variants like the thermal-wave radar (TWR).
FIGURE T16: A typical experimental setup for active thermography.
FIGURE T18. The function $dW_\lambda/dT$ as a function of wavelength.
CAMERA OPTIONS

- Most basic model: FLIR E4
- $\pm 2^\circ C$ degrees accuracy
- 80 x 60 pixels
- $0.15^\circ C$ sensitivity
- $(-20^\circ C) - (250^\circ C)$ temperature range
- Higher end models have better sensitivities, temperature ranges, resolution and include more features
## METHODS FOR SPECIMEN HEATING

<table>
<thead>
<tr>
<th>Method</th>
<th>Wavelength</th>
<th>Onset Time</th>
<th>Periodic Modulation Possible?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>0.5–10 μm</td>
<td>psec–sec</td>
<td>✓</td>
</tr>
<tr>
<td>Flashlamps</td>
<td>IR</td>
<td>&lt; msec</td>
<td>x</td>
</tr>
<tr>
<td>Quartz lamps</td>
<td>IR</td>
<td>&gt; sec</td>
<td>✓</td>
</tr>
<tr>
<td>Microwaves</td>
<td>1 mm–10 cm</td>
<td>&gt; nsec</td>
<td>✓</td>
</tr>
<tr>
<td>Induction heating</td>
<td>10 cm–1 m</td>
<td>&gt; msec</td>
<td>✓</td>
</tr>
<tr>
<td>Resistive heating</td>
<td>N/A</td>
<td>&gt; msec</td>
<td>✓</td>
</tr>
<tr>
<td>Hot air blower</td>
<td>N/A</td>
<td>≫ sec</td>
<td>x</td>
</tr>
</tbody>
</table>
NON-CAMERA MID-IR DETECTORS
LOCK-IN THERMOGRAPHY

- Another name for lock-in thermography is modulated thermography
- The signal resolution can be improved considerably by using the lock-in principle
- Lock-in Thermography allows better contrast for inspection
- Less sensitive to environmental conditions
- Phase is less sensitive/insensitive to surface emissivity
IMPROVED RESOLUTION

• Microscopic IR thermography has resolution on the order of 40 mK

• AGEMA Thermovision 900 mirror scanner, showed a noise level of 15 mK
EXPERIMENTAL SET-UP FOR LOCK-IN THERMOGRAPHY (LIT)
PHYSICAL PRINCIPLE OF LOCK-IN THERMOGRAPHY
SINUSOIDAL WAVE EXCITATION

- Sinusoidal waves are commonly used as trigger and as thermal excitation source (thermal wave generators)
- Shape and frequency of the response are preserved
- Only Amplitude and Phase change
- Optical- halogen lamps
Figure T25. (a) A schematic of the thermophotonic setup along with (b) the Lock-In signal processing algorithm.
If a function $x(t)$ contains no frequencies higher than $B$ hertz, it is completely determined by giving its ordinates at a series of points spaced $1/(2B)$ seconds apart.
Figure T26: Synchronous undersampling of a high frequency wave form using a low sampling rate. One modulation cycle is sampled out of each 12 consecutive cycles.
DISCRETE FOURIER TRANSFORM (DFT)

\[ F_n = \Delta t \sum_{k=0}^{N-1} T(k\Delta t) \exp(-j2\pi nk/N) = \text{Re}_n + \text{Im}_n \]

\[ A_n = \sqrt{\text{Re}_n^2 + \text{Im}_n^2} \]

\[ \phi_n = \tan^{-1}\left(\frac{\text{Im}_n}{\text{Re}_n}\right) \]

- Where \( j \) is the imaginary unit
- \( n \) is the frequency increment
- \( \Delta t \) is the sampling interval
- \( \text{Re and Im} \) are the real and imaginary parts of the transform
DATA FORMAT IN ACTIVE THERMOGRAPHY

FIGURE T 23: Schematic for data format used in active thermography.
LIT ADVANTAGES AND DISADVANTAGES

- High resolution
- Less sensitive to noise than dc thermography
- Requires less energy to perform LIT experiments
- Generally slower than other approaches
DETECTION OF HEAT SOURCES IN ELECTRONIC PACKAGING

Amplitude image

Phase image
• SINGLE-FREQUENCY THERMAL-WAVE RADAR: A NEXT GENERATION DYNAMIC THERMOGRAPHY
Conventional Lock-In Amplifier (LIA) signal processing.

\[ A = \sqrt{V_I^2 + V_Q^2} \quad \text{and} \quad \varphi = \tan^{-1}\left(\frac{V_Q}{V_I}\right) \]

\[
\begin{align*}
&\begin{cases}
\sin(\omega_0 t) \times A \sin(\omega_0 t + \phi) \\
\sin(\omega_0 t + 90) \times A \sin(\omega_0 t + \phi)
\end{cases} \xrightarrow{\text{Mixing}} \quad \frac{A}{2} \begin{cases}
\cos(\phi) - \cos(2\omega_0 t + \phi) \\
\sin(\phi) - \cos(2\omega_0 t + \phi + 90)
\end{cases} \\
&\begin{cases}
\frac{A}{\sqrt{2}} [\cos(\phi) - \cos(2\omega_0 t + \phi)] \\
\frac{A}{\sqrt{2}} [\cos(\phi) - \cos(2\omega_0 t + \phi + 90)]
\end{cases} \xrightarrow{\text{LPF}} \quad \begin{cases}
X = \frac{A}{\sqrt{2}} \cos(\phi) \\
Y = \frac{A}{\sqrt{2}} \sin(\phi)
\end{cases} \quad \begin{cases}
A = \sqrt{X^2 + Y^2} \\
\varphi = \arctan\left(\frac{Y}{X}\right)
\end{cases}
\end{align*}
\]

where \(\sin(\omega_0 t)\) and \(\sin(\omega_0 t + 90)\) represent the in-phase and quadrature reference signals and \(A\sin(\omega_0 t + \phi)\) is the captured infrared signal with amplitude \(A\) and phase \(\varphi\).
Using the same frequency for the start and end of a TWRI sweep allows the calculation of the amplitude and phase at that frequency and the measurement of detailed pixel frequency dependencies by scanning over a wide range of frequencies at arbitrary intervals similar to photothermal radiometry, free from critical frequency exclusion, inter-frequency interval constraints, and upper limits imposed by sampling. **Signal processing is done through CC, not through the lock-in process.**

- **Critical parameters:** single-frequency chirp duration + (max) camera frame rate are operator controlled, *not controlled by frequency requirements.*
- **Result:** The SNR is higher for SF-TWR than for LIT and the SNR difference increases with increasing frequency.
- **SF-TWR is advantageous for work requiring frequency scans (quantitative dynamic thermography)**
Comparison: LITI and SF-TWRI at 10 Hz for steel block with blind hole at 0.4 mm depth. Profiles of row 60.

Real issue with high frequency LIT: not having enough synchronized data points to process the lock-in method. This can be avoided with the chirp method at fixed frequencies.
Comparison: LITI and SF-TWRI at 16 Hz for steel block with blind hole at 0.4 mm depth. LITI undersampled by skipping 1 cycle.

**SF-TWRI.** \( t=1\text{s}; 360 \text{ fr/s. } t = 1 \text{ s.} \)

**LITI.** 150 fr/s. Averaging 16 images.

Statistical distributions of amplitude and phase for marked areas

- FWHM of amplitude and phase for SF-TWRI is less than for LITI.
- Depth resolution for TWRI is better than for LITI.
Quantitative SF-TWRI: Two - layer theoretical model with grouped parameters for quantitative estimation of layer thickness

\[
\Delta T_1(0, f) = \frac{P_2(1 - \gamma_{01})}{P_1(1 - \gamma_{02})} \left( \frac{1 - \gamma_{21} e^{-2(i+1)\sqrt{\pi f} Q_1}}{1 + \gamma_{21} e^{-2(i+1)\sqrt{\pi f} Q_1}} \right)
\]

Where
\[
Q_m = \frac{L_m}{\sqrt{\alpha_m}}, \quad P_m = \frac{k_m}{\sqrt{\alpha_m}}, \quad \gamma_{mn} = \frac{b_{mn-1}}{b_{mn+1}},
\]
\[
b_{mn} = \frac{P_m}{P_n},
\]
\[
k_0 = 0.026 \text{ Wm}^{-1}k^{-1}
\]
\[
\alpha_0 = 22.26 \times 10^{-6} \text{ m}^2/\text{s}
\]

Parameters: \(Q_1, P_1, P_2\)

The Q parameter is the most sensitive parameter to layer thickness and is most reliably measured through frequency-response best-fitting.
Sample for imaging of coating thickness (Al substrate)

- ~40 x 40 x 16 mm block
- Al substrate, CoP nano-coating with nominal ~250 µm thickness
SF-TWR phase images of sample with deposited layer on the Al substrate.
Normalization procedure

PHASE. 8HZ. DEPOSITED LAYER SAMPLE.

Fitted Q - parameter

Phase. 8Hz. Zr

Normalization to Zr sample

Fit to two-layer model

\[ Q_1 = \frac{L_1}{\sqrt{\alpha_1}} \]
Phase was calculated as the mean value of a 6 x 6 pixel group in regions A and B. The frequency of phase maximum $f_{max}$ is determined by parameter Q. Larger Q leads to $f_{max}$ shift to lower frequency.
Directly measured and camera evaluated deposited layer thickness profiles

![Graph showing directly measured and camera evaluated thickness profiles. The graph plots distance (mm) on the x-axis and thickness (um) on the y-axis. The blue dashed line represents directly measured data, while the red dotted line represents camera evaluated data for band C-C.]
dc image and 20 Hz SF-TWR amplitude and phase images of sample with deposited layer on polymer (Polyetherketone, PEEK) substrate.

20 Hz amplitude, arb. un.

dc image, pixel value

20 Hz phase, degrees

Phase, degrees

Normalization with Zr sample
Images of Q-parameter and thickness of deposited layer on PEEK substrate.

<table>
<thead>
<tr>
<th>Calculated ( \alpha ), m(^2)/s</th>
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<tr>
<td>Fitted ( Q, s^{1/2} ) (P64x160)</td>
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<tr>
<td>Measured thickness (P64x160, ( \mu m ))</td>
<td>200 ( \mu m )</td>
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SUMMARY

• The temperature of an object can be determined based on the amount of infrared radiation it emits

• Thermal imaging cameras create a 2D image by detecting incoming radiation

• IR Cameras have a wide array of applications in the field of non-destructive testing and imaging

• **Passive Thermography** is established in building inspection, electrical and mechanical maintenance, optical gas imaging, Night Vision, Astronomy

• **Lock-in Thermography (LIT)** allows better contrast for inspection, is less sensitive to environmental conditions and has higher spatial resolution than passive thermography.

• Phase is less sensitive/insensitive to surface emissivity

• **Single-frequency (SF-) TWRI** is a next-generation dynamic quantitative thermography modality, an improvement over conventional LIT. It can be implemented at the same set-up as LIT with only software signal generation and processing change.

• The SNR is higher for SF-TWRI than for LIT and the SNR difference increases with increasing frequency.
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➢ Canada Research Chairs Program