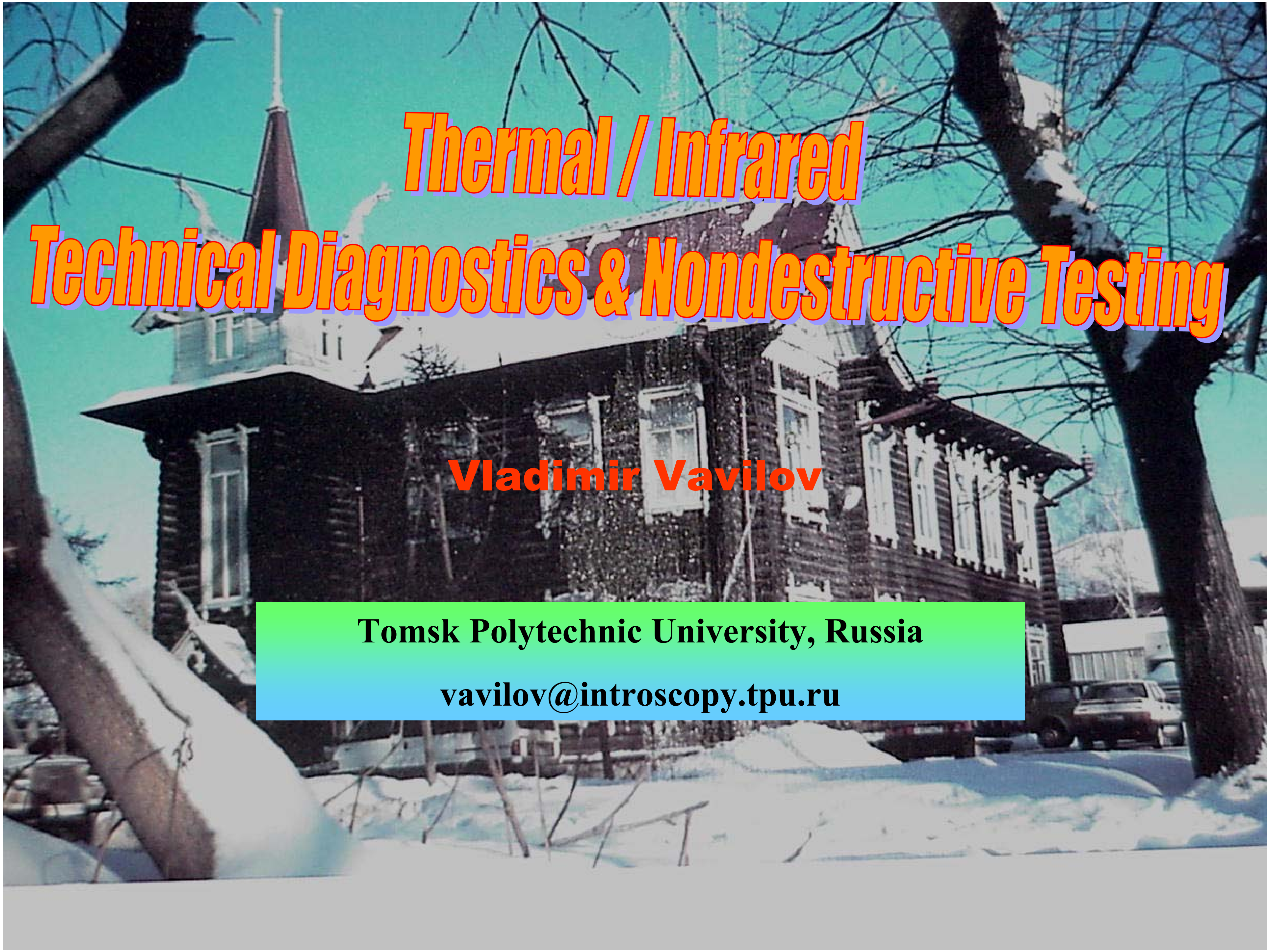

Thermal / Infrared Technical Diagnostics & Nondestructive Testing

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Course Content

- Day 1-Part 1:Basics of IR Thermography
- Day 2-Part 2: Infrared Imagers & Surveying Tricks
- Day 3-Part 3: Modeling & Data Processing
- Day 4-Part 4: Applications
- Day 5 (1/2): Practice
- Day 5 (1/2): Exams (ASNT conformed)

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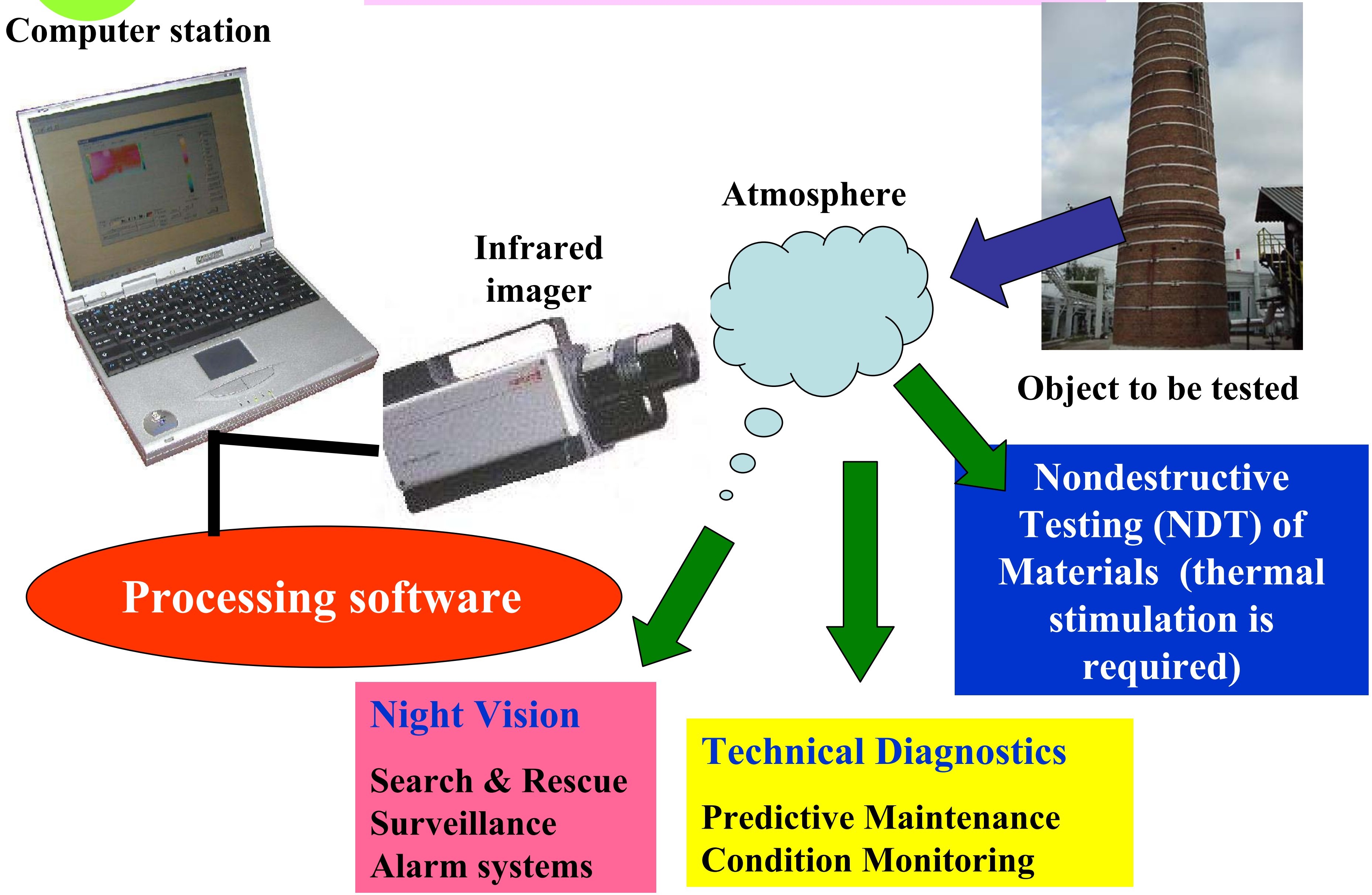
Infrared System Presentation



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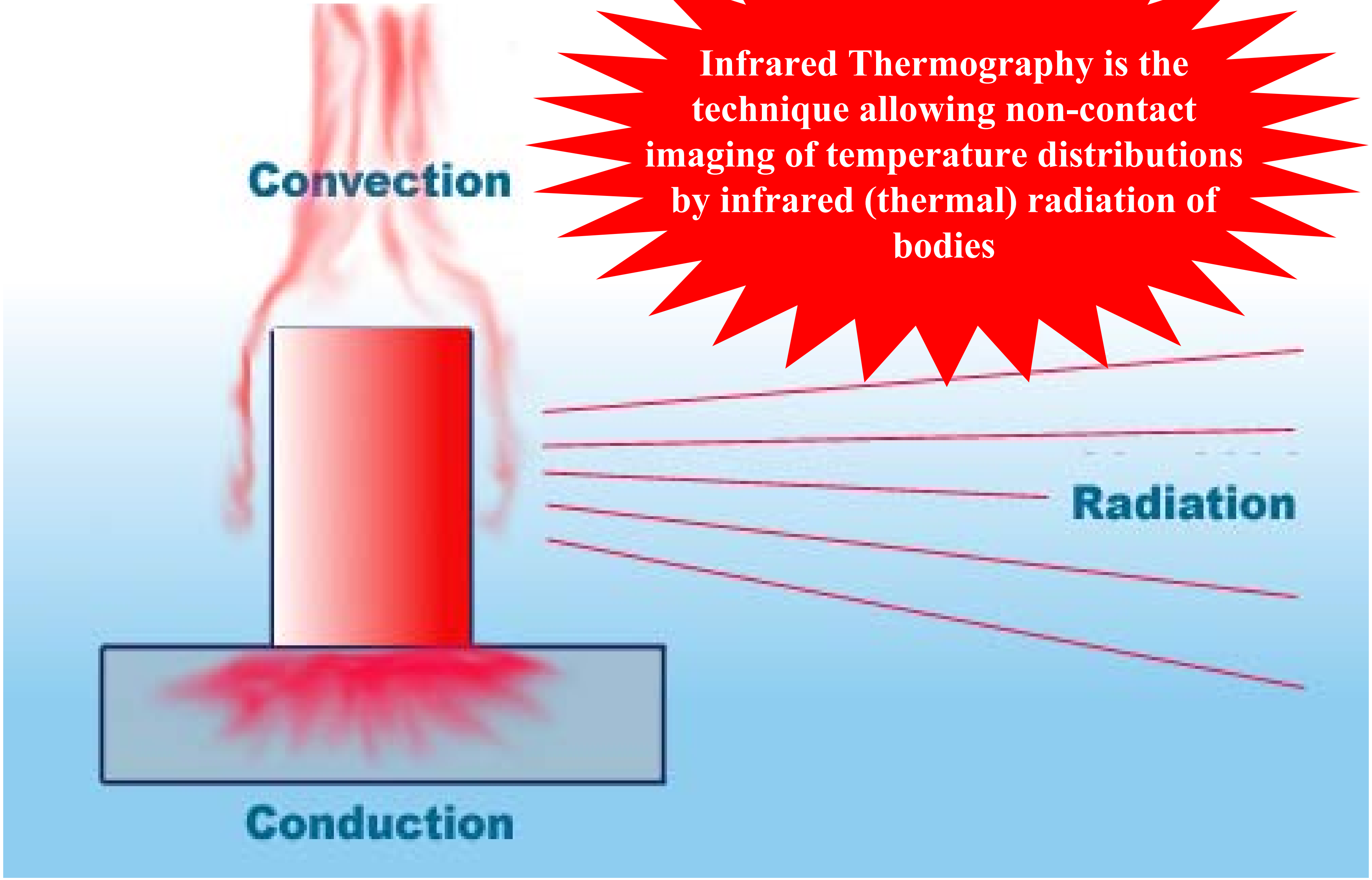
Part 1: Basics of IR Thermography

- The Electromagnetic Spectrum
- Radiation Laws
- Emissivity Problem
- Reflection, Absorption and Transmission of Incident Radiation
- IR Thermography Scheme and IR Camera Output Signal
- Infrared Thermography: ‘Passive’ vs. ‘Active’
- IR Thermographic NDT: Advantages and Limitations
- Basic Inspection Procedure

Heat Transfer Mechanisms



Infrared Thermography is the technique allowing non-contact imaging of temperature distributions by infrared (thermal) radiation of bodies

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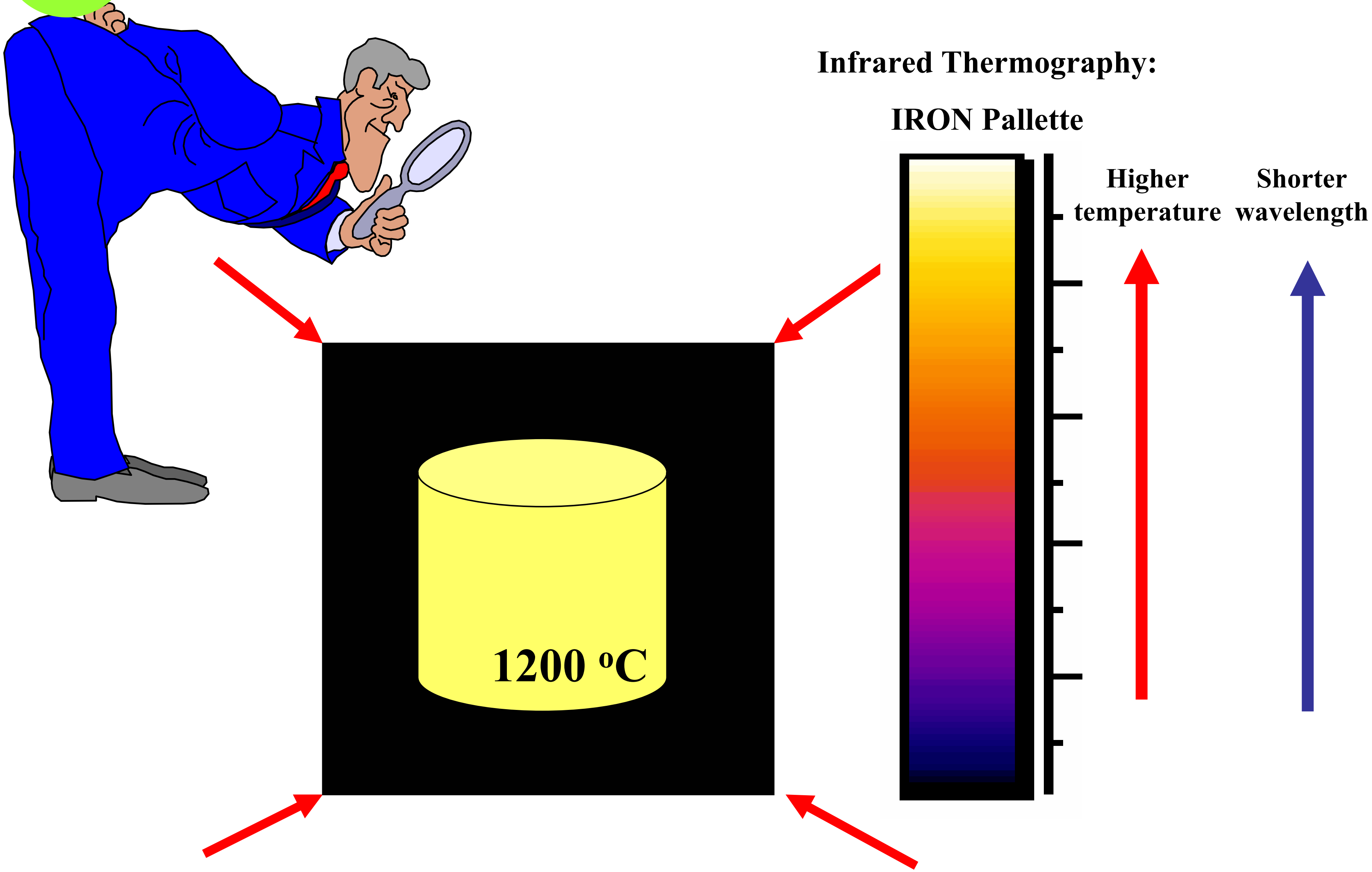
Some Basic Statements

- Infared thermography has been an acknowledged technique in military, technical diagnostics (condition monitoring & predictive maintenance). This technique has been also becoming an important tool of nondestructive testing of materials with subsurface defects.
- Passive mode of Thermal NDT requires using only an infrared camera (IR imager). There are non-radiometric (imaging) and radiometric (temperature measuring) IR cameras commercially available on the market.
- Recently, a new generation of IR imagers appeared, particularly, those based on Focal Plane Array (FPA) detectors, including Quantum Well IR Photodetectors (QWIP).
- Active mode of Thermal NDT requires additional thermal stimulation of objects under test. Several types of heaters (coolers) are used in combination with IR cameras and computer stations.

1-6 *Heating a piece of metal in a dark room*



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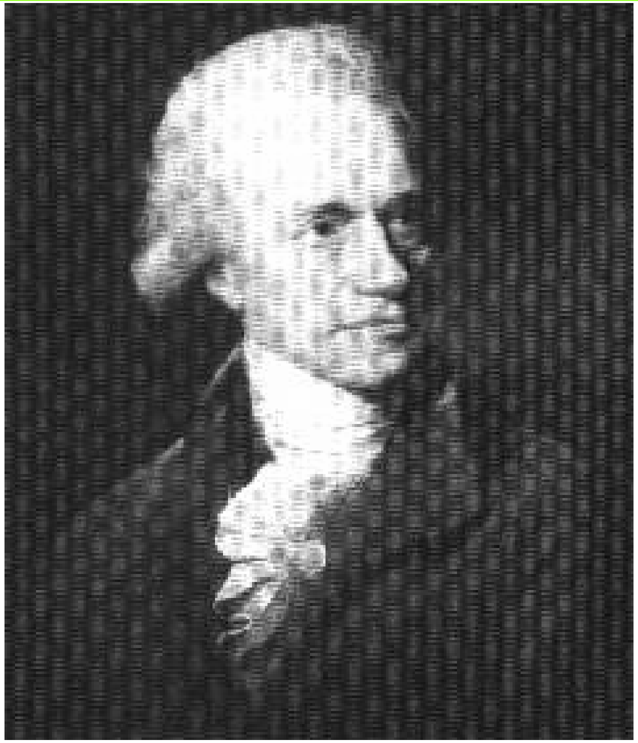
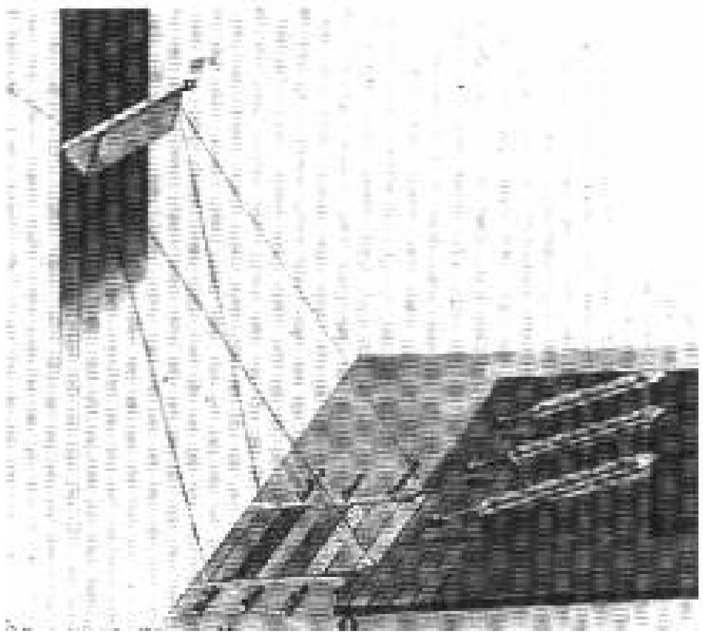
How IR Radiation Was Discovered

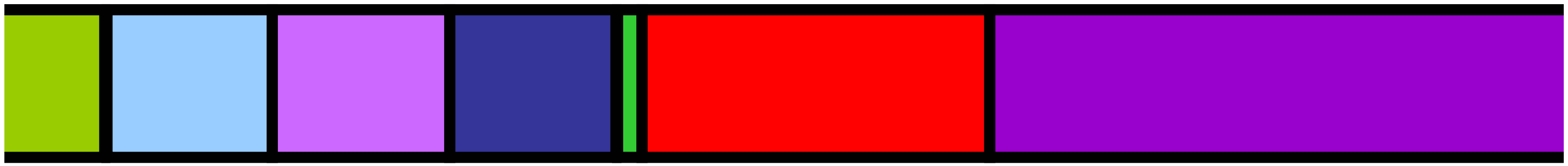
In 1800, the royal astronomer for King George III of England, sir William Herschel revealed the existence of the infrared radiation.

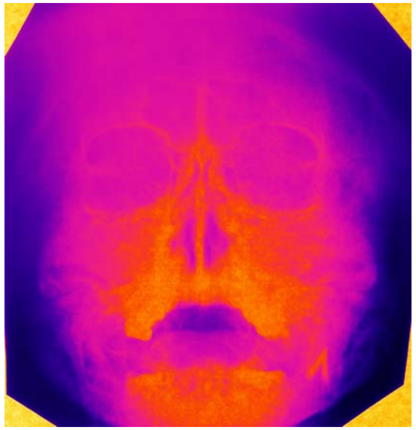


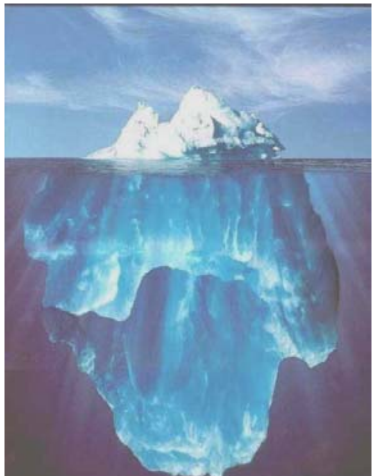
Using a mercury thermometer, Herschel noted that the maximum elevation of temperature occurred beyond the red band where no radiation was visible

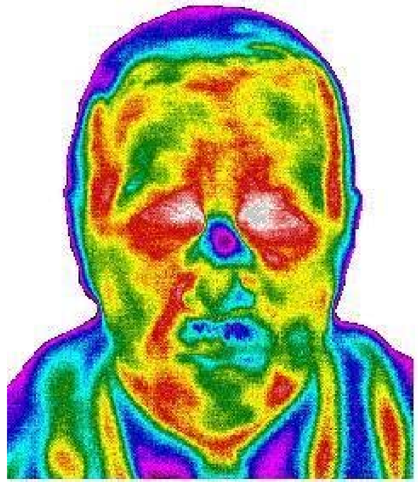


Infrared Thermography: Electromagnetic Spectrum









3-5 μm (Short Wave) and 7-13 μm (Long Wave) wavelength bands are typically used in IR thermography

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Infrared Thermography: Definitions & Units

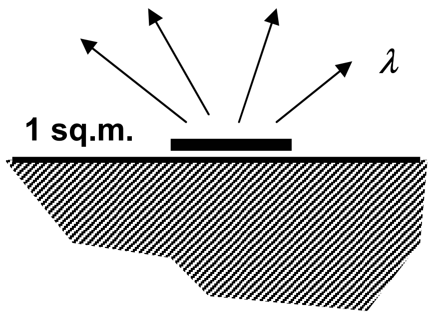
Term	Definition	Unit
Radiant power, radiant flux	$\Phi = \int_0^\infty \Phi_\lambda d\lambda$	W
Radiant energy	$W = \int_0^\tau \Phi(\tau) d\tau$	J
Radiant intensity	$I = d\Phi / d\Omega$	W/sr
Radiant exitance	$R = d\Phi / dF$	W/m²
Irradiance, dose-rate	$E = d\Phi / dF$	W/m²
Radiance	$L = \frac{I}{dF \cos\Theta}$	W/(m² ·sr)

Ω - Spatial angle (sr)

F - Surface (m²)

Radiation Laws: Spectral Radiant Exitance & Planck Law

The Planck law defines radiation power emitted by 1 sq. m. of a surface at a particular wavelength in all directions

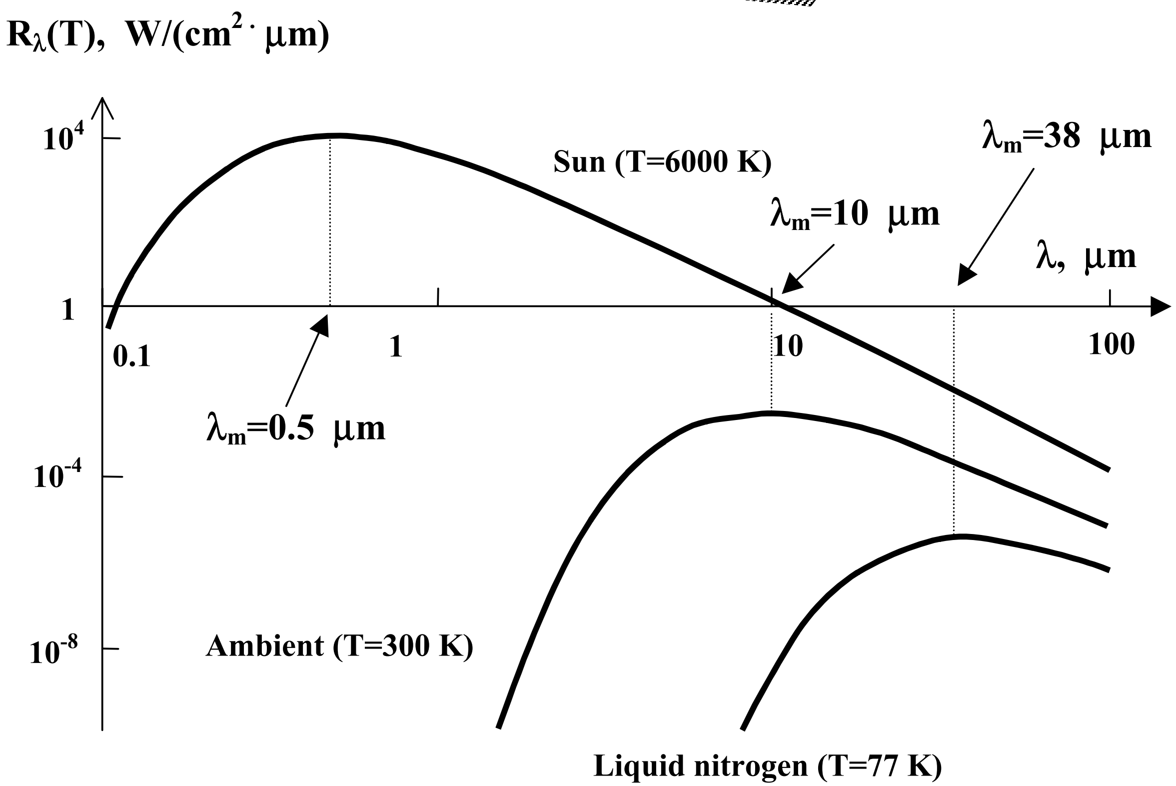


$$R_\lambda = \frac{C_1}{\lambda^5 \cdot (e^{C_2/\lambda T} - 1)},$$

$$[R_\lambda] = W \cdot cm^{-2} \cdot \mu m^{-1},$$

$$C_1 = 3.7418 \cdot 10^4 \quad W \cdot cm^{-2} \cdot \mu m^4,$$

$$C_2 = 1.4388 \cdot 10^4 \quad \mu m \cdot K.$$



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Radiation Laws: Radiant Exitance in Particular Spectral Bands

Radiant Exitance in the λ_1-λ_2 Wavelength Band

$$\Phi(\lambda_1 \div \lambda_2,\ T) = \int_{\lambda_1}^{\lambda_2} R_\lambda(\lambda,\ T)\ d\lambda$$

Radiant Exitance in the Total Spectrum ($\lambda_1 \div \lambda_2 = 0 \div \infty$): Stephan-Boltzmann Law

$$\Phi = \sigma\left(\frac{T}{100}\right)^4; \quad \sigma = 5.67\ W/(m^2 \cdot K^4)$$

Radiation Laws: Wien Law & Lambert Law

The Wien law determines a wavelength at which maximum radiant exitance is emitted. The orange Sun ($T=6000^0C$) emits maximum energy at $\sim\lambda=0.5$ mm (orange wavelength).

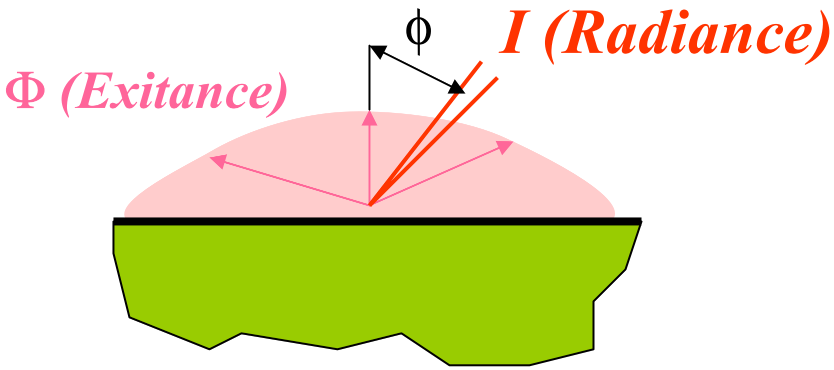
Wien Displacement Law

$$\lambda_m [\mu m] = 2898 \;/ T(K)$$

Lambert Cosine Law:

$$I\,[W\,m^{-2}\,sr^{-1}]=(\Phi/\pi)\cos\phi$$

Total energy R [*W/m²*] is emitted in a semi-infinite space by all directions. The Lambert law determines how much energy is emitted in a particular direction (under a particular angle). Valid for diffusive emitters (rough metals and most non-metals, except reflective surfaces). For example, window glass reveals considerable reflection.



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Radiation Laws: Exitance vs. Temperature

$R_\lambda(\lambda_m) \to T^5$ - at the maximum wavelength

$\Phi(\lambda = 0 \div \infty) \to T^4$ -through the total spectrum

$R_\lambda(T) \to T^n$ - at any wavelength (*n* is the function of the wavelength)

$n = 5/\beta$ **if** $\beta \le 2.5$

$n = 1 + 2.5/\beta$ **if** $\beta \ge 2.5$

$\beta = \lambda / \lambda_m$

$\Phi(T, \lambda_1 \div \lambda_2) \to T^m$ - in any wavelength band

<u>Exercise # 1.</u> Let the temperature be T=27°C (300 K). Hence, λ_m=3000/T=10 μm. At the λ=4 μm R_λ~$T^{12.5}$ (3-5 μm band) and at the λ=10 μm R_λ~T^5 (7-13 μm band).

<u>Conclusion:</u> the SW band is more sensitive to temperature variations, however, the LW band collects more energy from objects at the ambient temperature.

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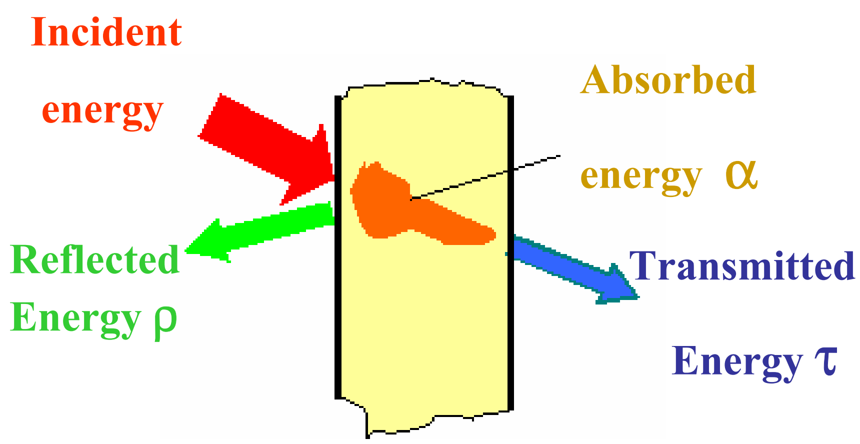
Radiation Laws: Reflection, Absorption & Transmission of Incident Radiation. Energy Conservation Law



$\alpha + \rho + \tau = 1$ **Energy conservation law**

Note #1

In temperature measurement, the reflected and transmitted components of thermal radiation should be diminished

Note #2

Maximum power is emitted at a particular wavelength (Wien's law)

Note #3

High-reflective and semi-transparent bodies are 'bad' objects for IR thermographic NDT

Note #4

The contribution of reflected radiation can be determined by using the ASTM Standard E 1862-97

Note #5

The contribution of transmitted radiation can be determined by using the ASTM Standard E 1897-97

Note #6

The radiation of real bodies can be enhanced by applying 'black' coatings

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Radiation Laws: Emission of Real Bodies & Kirchhoff Law

The formulas discussed before are valid for 'black bodies' which emit maximum energy. Real bodies are characterized with the emissivity ε that ranges from 0 to 1 being the function of the type of material and its surface finish. Emissivity is the coefficient in all radiation law expressions .

$$\varepsilon_\lambda(T) = R_\lambda^{real}(T) / R_\lambda^{BB}(T)$$

$$R_\lambda^{real} = \frac{\varepsilon_\lambda(T) \cdot C_1}{\lambda^5 \cdot (e^{C_2/\lambda T} - 1)}$$

$$\Phi^{real}(\lambda = 0 - \infty, T) = \varepsilon\sigma(T/100)^4$$

Emissivity Values for Common Materials

Graphite	0.98
Skin, human	0.98
Lacquer, matte black	0.97
Water	0.96
Paint, oil based	0.94
Brick, red	0.93
Cast Iron oxidized polished	 0.64 0.21
Aluminum, polished	0.05

The bodies that absorb well optical radiation also emit optical radiaton well

$\alpha_\lambda = \varepsilon_\lambda$ **Kirchhoff law**

α_λ - **absorptivity**

ε_λ **_emissivity**

$\rho_\lambda = 1 - \varepsilon_\lambda$ **For opaque bodies**

ρ_λ - **reflectivity**

The Kirchhoff law is also valid in narrow spectral intervals, e.g. in SW

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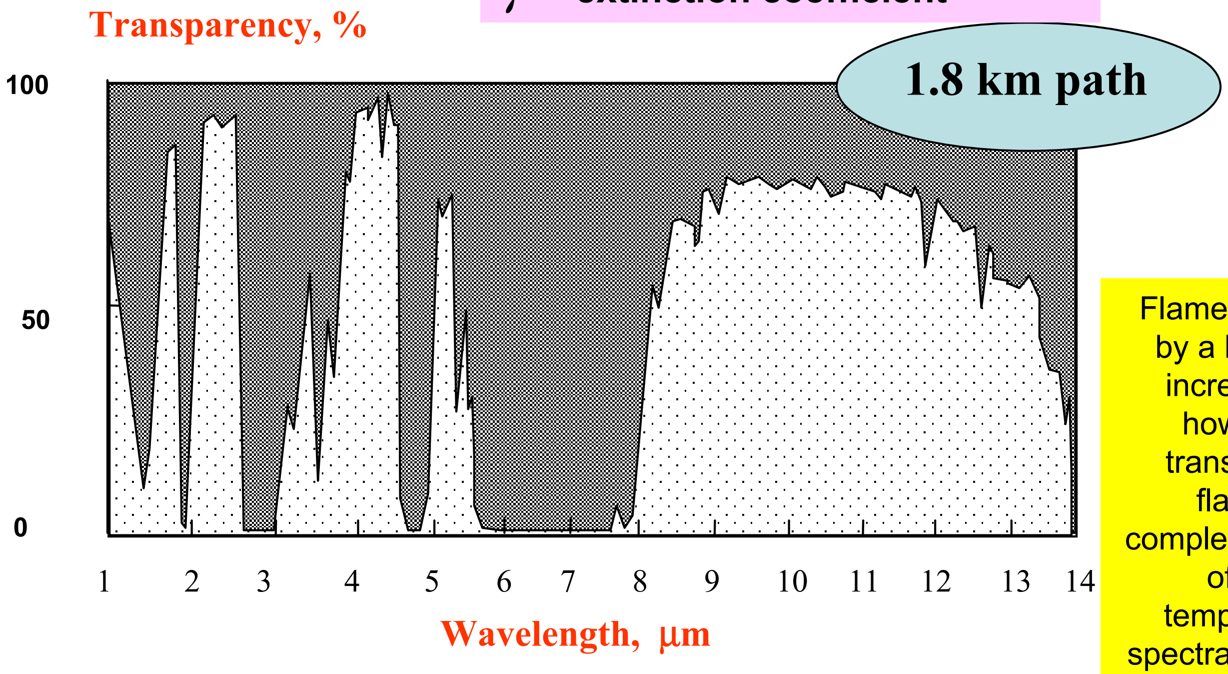
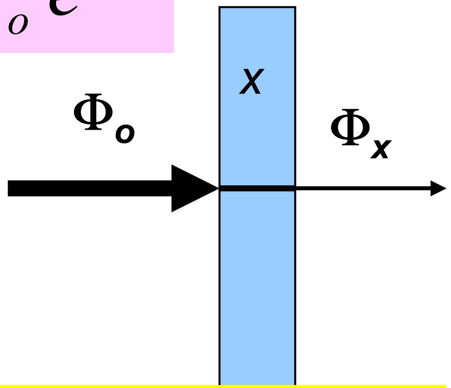
How Does IR Radiation Propagate Through the Atmosphere ?

In semi-transparent media, thermal radiation is attenuated according to the exponential law

$$\Phi_x = \Phi_o \, e^{-\gamma x}$$

γ - extinction coefficient





Flame is a specific test object characterized by a linear spectrum. Emissivity of flames increases with more non-burnt particles, however, in general, flames are semi-transparent. Therefore, while monitoring flames thermographically, there is a complemented signal conditioned by radiation of a 'back wall'. To measure flame temperature, one should use convenient spectral bands or place a thin solid target into the flame of which temperature is to be measured with an IR camera.

This chart explains why most night vision and IR surveillance systems utilize two wavelength bands:

Short Wavelength Band 3-5 µm **Long Wavelength Band 7-14 µm**

In thermal NDT, atmosphere influence is negligible. In technical diagnostics, it can be neglected in most cases, if distance is under 30-50 m

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Infrared Thermography: Summarizing Remarks

Power of radiation increases with temperature depending on a wavelength band ($\sim T^4 - T^9$) **1**

Maximum power is emitted at a particular wavelength: the higher is the temperature, the shorter is the wavelength of maximum radiation **2**

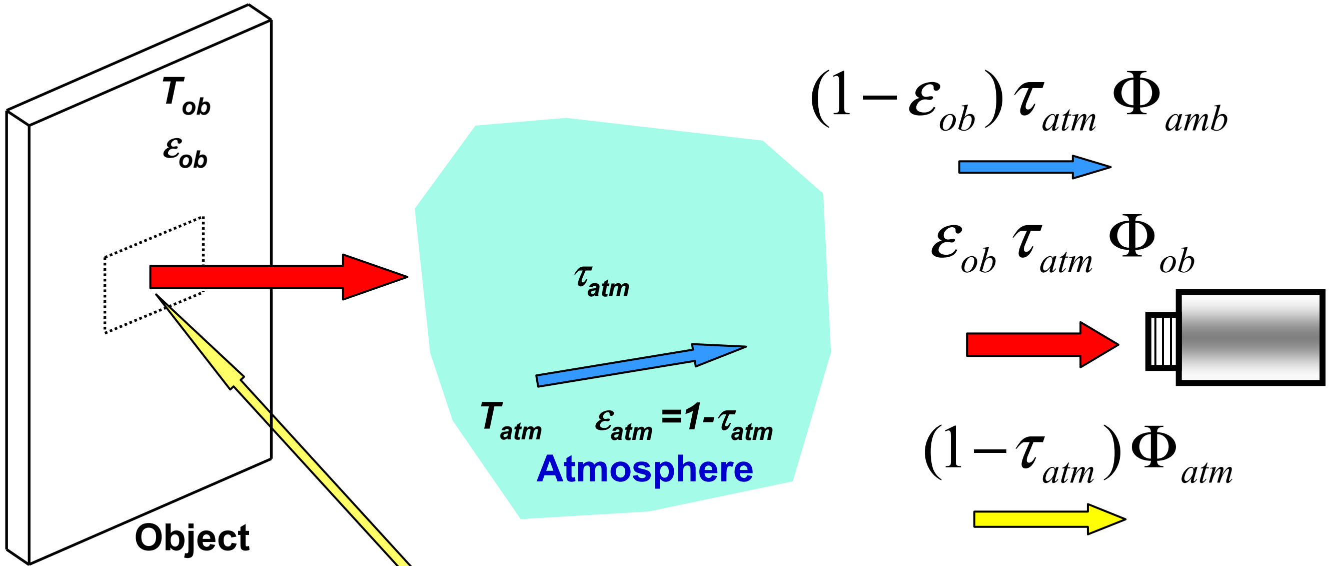
IR thermography typically uses two wavelength bands: 3 – 5.5 µm and 7 – 14 µm **3**

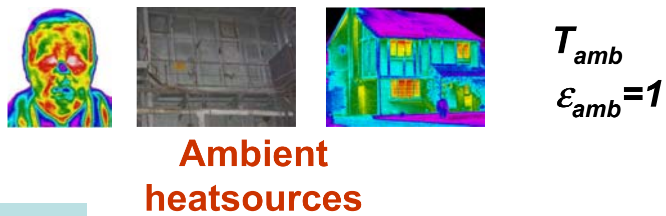
In IR thermography, the preference of a wavelength band is not unanimous. Typically, LW imagers have better integral sensitivity, but SW imagers are more sensitive to small temperature variations (in particular, on a noisy background) **4**

High-reflective and semi-transparent bodies are 'bad' objects for IR thermographic NDT. In temperature measurements, the reflected and transmitted components of thermal radiation should be diminished. **5**

Infrared Thermography Scheme

An IR camera output electrical signal is proportional to the thermal flux received by an IR detector. This thermal flux includes three components: flux emitted by the object, flux from ambient sources reflected by the object, flux emitted by the atmosphere.





In technical diagnostics, atmosphere transparency τ_{atm}=1. Therefore, the thermal flux emitted by the atmosphere can be neglected.

Γ **-geometrical factor (constant coefficient)**

Output signal

$$\Phi=\Phi_{ob}+\Phi_{refl}=\Gamma\int_{\lambda_1}^{\lambda_2}\varepsilon_{\lambda ob}\tau_{\lambda atm}R_{\lambda}^{BB}(T_{ob})+\Gamma\int_{\lambda_1}^{\lambda_2}\rho_{\lambda ob}\tau_{\lambda atm}\varepsilon_{\lambda amb}R_{\lambda}^{BB}(T_{amb})$$

$$\rho_{\lambda ob}=1-\varepsilon_{\lambda ob}$$

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Simplified equation of IR thermography (I)

Typically, the ambient emits as a black body, i.e. ε_{amb}=1, then the equation from the previous slide can be written as:

$$\Phi = \Gamma \int_{\lambda_1}^{\lambda_2} \varepsilon_{\lambda ob} \tau_{\lambda atm} R_{\lambda}^{BB}(T_{ob}) + \Gamma \int_{\lambda_1}^{\lambda_2} (1-\varepsilon_{\lambda ob}) \tau_{\lambda atm} R_{\lambda}^{BB}(T_{amb})$$

In relatively narrow spectral bands, it can be assumed that object emissivity and atmosphere transmittance are independent on wavelength, i.e. $\varepsilon_{\lambda ob}=\varepsilon$ and $\tau_{\lambda atm}=\tau_{atm.}$ By neglecting the geometrical factor in the previous formula, we obtain:

$$\Phi \sim \varepsilon \tau_{atm} \int_{\lambda_1}^{\lambda_2} R_{\lambda}^{BB}(T_{ob}) + (1-\varepsilon) \tau_{atm} \int_{\lambda_1}^{\lambda_2} R_{\lambda}^{BB}(T_{amb})$$

In particular spectral bands, the integral by the Planck function can be replaced with $R_{\lambda}(T)=KT^{n}$, as introduced in ***Slide 1-13***. Then the last equation acquires the following form:

Typical IR wavelength bands:

n=10.11 in 3-5.5 μm

n=4.83 in 7-14 μm

$$\Phi \sim \varepsilon \tau_{atm} T_{ob}^{n} + (1-\varepsilon) \tau_{atm} T_{amb}^{n}$$

Simplified equation of IR thermography (II)

It is obvious that, when monitoring real bodies, an IR radiometer calibrated by a blackbody reference, will show the so-called ***apparent***, or ***radiation***, temperature $T_{ob\,ap}$ according to the following equation:

$$T_{ob\,ap}^{n} = \varepsilon \tau_{atm} T_{ob}^{n} + (1-\varepsilon)\, \tau_{atm} T_{amb}^{n}$$

The last equation is used in modern IR radiometers for correcting temperature readings if a thermographer has introduced the following parameters (IR radiometer settings): 1) **object emissivity** ε, 2) **ambient temperature** T_{amb}, 3) **distance to the tested object**, and 4) **atmosphere humidity**. The two last parameters stand for compensating atmosphere transmittance τ_{atm} according to the exponential law discussed in ***Slide 1-16***.

In the 'still' atmosphere at distances less than 30-50 m, it can be assumed that τ_{atm}=1. Then, a simple equation of a thermography test can be written in the following form to demonstrate the relationship between two important parameters: object emissivity and temperature of the ambient (or hot neighbor objects):

$$T_{ob\,ap}^{n} = \varepsilon T_{ob}^{n} + (1-\varepsilon)\, T_{amb}^{n}$$

Emissivity Problem

Thermal NDT
Serious Problem

$$T^n_{ob\,ap} = \varepsilon T^n_{ob} + (1-\varepsilon)\, T^n_{amb}$$

IR thermographic temperature measurements are accompanied by inaccuracies related to ε и T_{amb}.

Important! Level I, II Exam programs (ASNT, ITC etc.) often contain questions regarding inaccurate setting of emissivity and compensating ambient radiation reflected from the object surface.

If the ambient temperature is close to the object temperature, ***overestimating*** ε leads to ***underestimating*** true temperature T_{ob}, and vice versa.

!

The case when the ambient (or neighbor objects) temperature is higher than the tested object temperature, deserves special treatment related to the analysis of reflected ambient radiation.

Note#1

In thermal NDT, emissivity variations represent a strong source of signals that can be misinterpreted as defect signals. The statistics of these variations on the surface of solids is scarcely studied (2% for black coatings and up to 100% for rusty metals)

Note#2

Body radiation can be enhanced by applying 'black' coatings.

Relationship between true and apparent (radiation) temperatures

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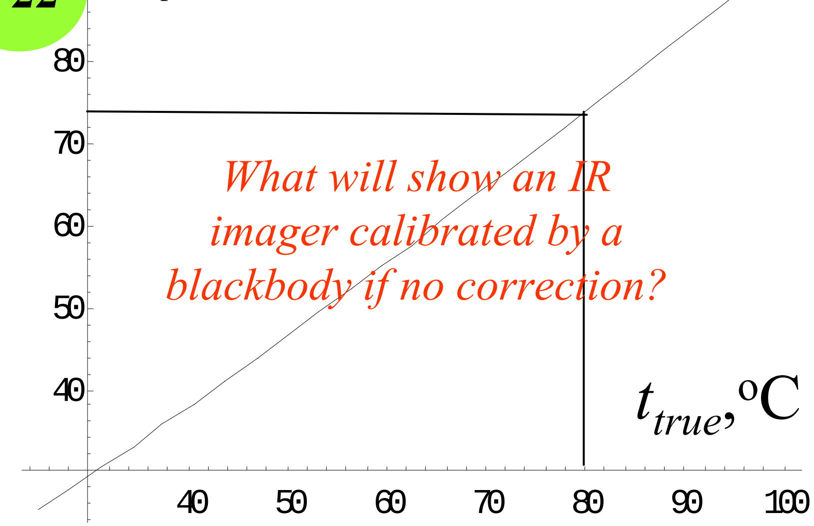
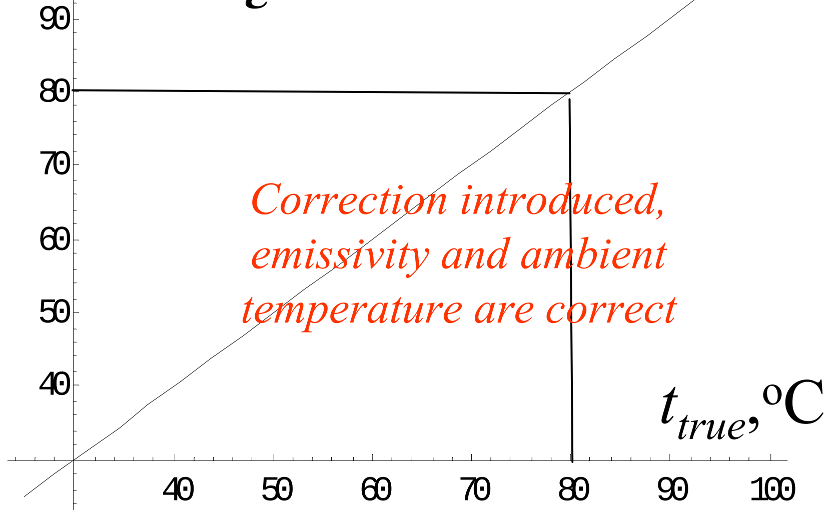
$$T_{ap}^n = \varepsilon \; T^n + (1-\varepsilon) \; T_{amb}^n$$

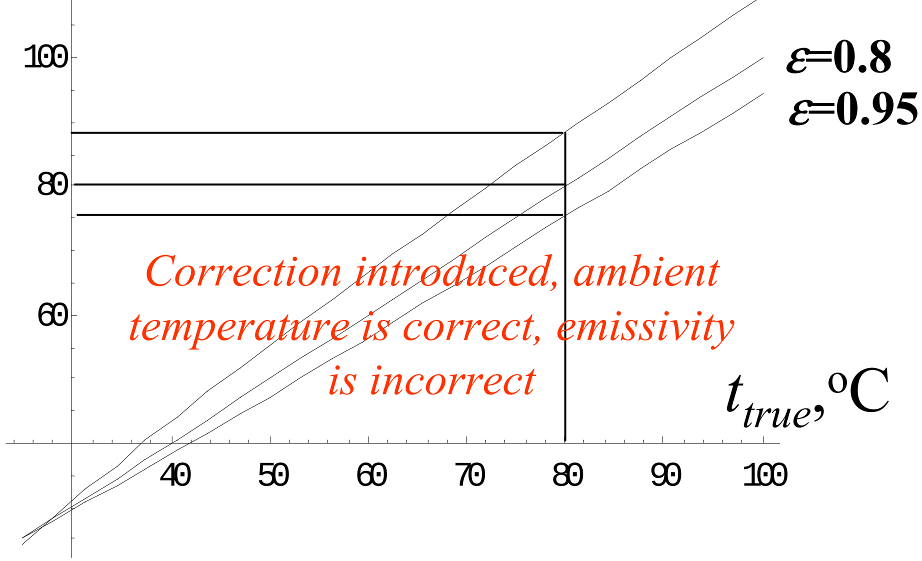


$$T_{cor} = \{\frac{1}{\varepsilon} \; [T_{ap}^n - (1-\varepsilon) \; T_{amb}^n]\}^{1/n}$$



t_{amb}=27°C; ε=0.8; 3-5.5 µm, i.e. n=10.11

In an IR imager with a built-in emissivity correction, exaggerated emissivity values will cause temperature underestimates, and vice versa



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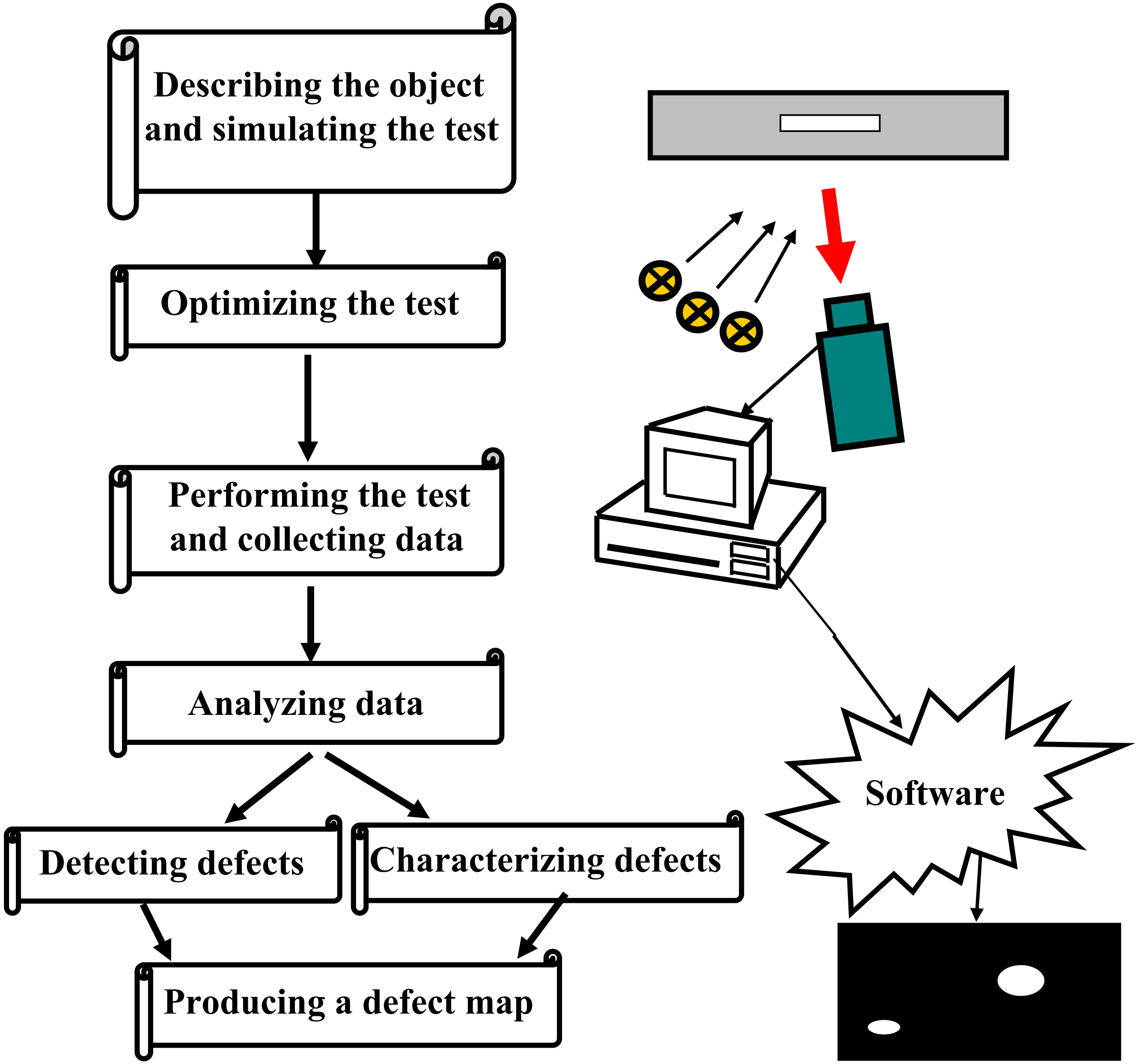
Basic Inspection Procedure (Thermal NDT)



How to Solve Emissivity Problem?

Measuring Emissivity with an IR Imaging Radiometers (by the ASTM Standard E 1933-97)

Test method #1. Point an IR radiometer at the specimen. Measure the true temperature by a contact thermometer. Use the IR radiometer measuring function to adjust an emissivity value.

Test method #2. Point an IR radiometer at the specimen. Apply the surface-modifying material with a known emissivity value to the specimen. Measure the true temperature in the area covered by the material. Use the IR radiometer measuring function to adjust an emissivity value.

Treating a sample:

- Painting the sample in black (coating, moistening)
- Using the dynamic behavior of the sample temperature
- Introducing a reference (marker, cavity, reference sample)
- Irradiating the sample with a radiant heat
- Heating uniformly the sample and producing the emissivity map

Processing radiation:

- Working in a short wavelength band
- Using a dual-band technique (producing the emissivity map and the temperature image)
- Using polarized radiation
- Mathematically treating the spectrum

'Passive' vs 'Active' IR Thermography

'Active' defects emit energy during object operation and require no external stimulation

'Passive' defects have the temperature of a host material and require external stimulation

Passive	**Active**
Features	
• A steady-state measurement • Signal variations due to temperature and emissivity variations • Detection of 'active' buried defects	• An excitation source is required • A time-dependent measurement • Signal variations due to temperature and emissivity variations • Detection of 'passive' buried defects
Applications	
• Predictive maintenance • Condition monitoring • IR reconnaissance	• Defect detection and characterization • Thermal properties measurement

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Advantages of IR Thermographic NDT

- Quantitative defect characterization
- Non-contacting process for both excitation and detection sides
- Rapid inspection rate
- Sensitive to various types of the defects which exhibit changes in local thermal properties
- Analysis of fast thermal events (i.e. inspection of thin materials) is possible
- Can be used effectively with other NDT techniques (screening tests)

Limitations of IR Thermographic NDT

- Non-trivial data analysis (specifically, the removal of noise and surface clutter)
- Signal is strongly dependent on the defect depth (in a one-sided test) and the lateral dimensions of the defects
- Defect edges blur due to heat dissipation (transverse heat conduction)

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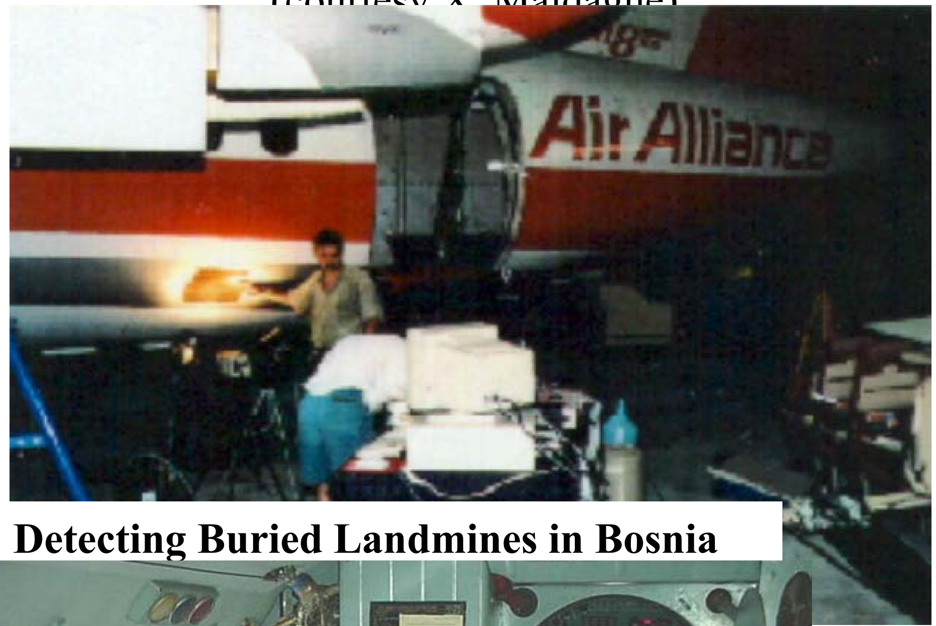
On-Site Thermal NDT

Inspecting Aircraft for HiddenCorrosion
(courtesy X. Maldague)



Inspecting Atlas Space Launch

Detecting Buried Landmines in Bosnia