TSBB09 Image Sensors

Infrared and Multispectral Sensors

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Contents

But first: A movie!

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Part 1

Introductory examples

Thermal imagery, what does it look like?

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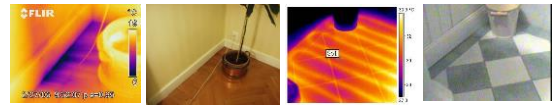
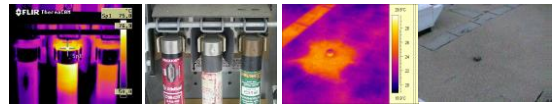
Introductory examples



Incoming cold air

Floor heating



Fuses

Moisture in flat roofs

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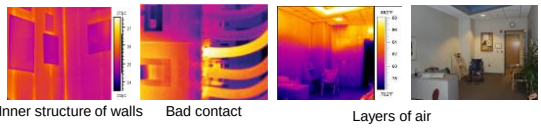
Introductory examples



Inner structure of walls Bad contact Layers of air

Storage tanks Another bad contact

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Introductory examples

Mechanics Electronics

Electric power transmission

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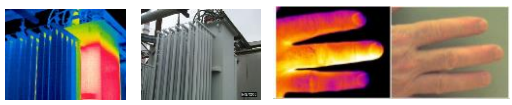
Introductory examples



Transformer Inflammation

Water leak District heating

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Part 2

Infrared and other ”light”

What does the camera see, and why?

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From where comes the radiation?

- Emitted
- Transmitted
- Reflected

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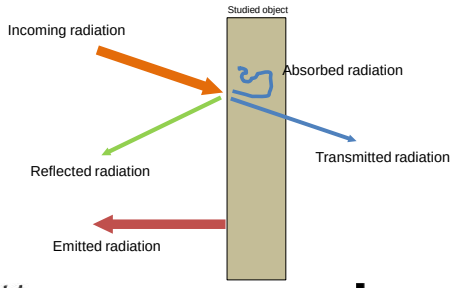
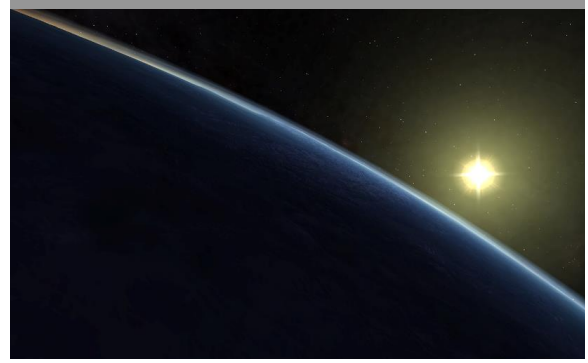
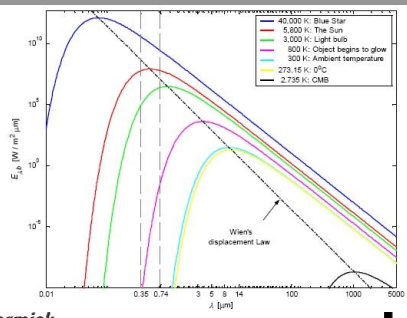
Components of the radiation



So why does it shine?

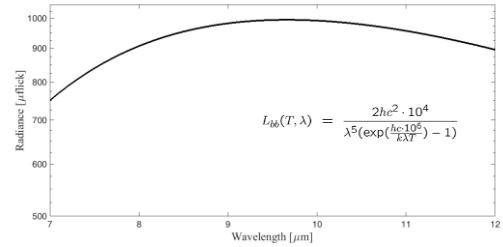


Emitted (thermal) radiation



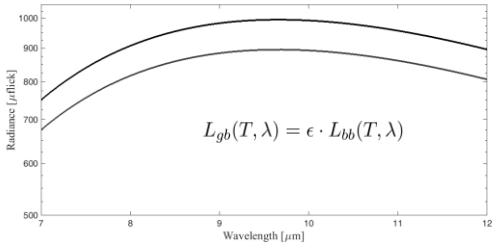
http://www.theses.ulaval.ca/2005/23016/apb.html

Emitted radiation



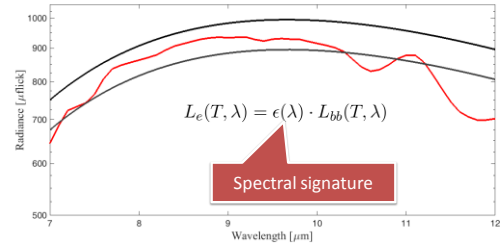
$$L_{bb}(T,\lambda) = \frac{2hc^2 \cdot 10^4}{\lambda^5(\exp(\frac{hc \cdot 10^6}{k\lambda T}) - 1)}$$

Emitted radiation



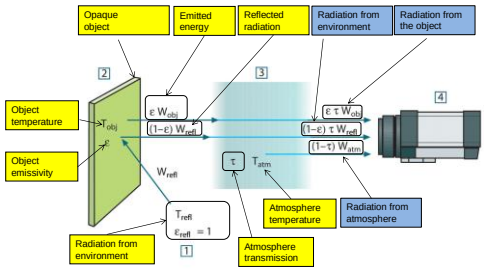
$$L_{gb}(T,\lambda) = \epsilon \cdot L_{bb}(T,\lambda)$$

Emitted radiation



$$L_e(T,\lambda) = \epsilon(\lambda) \cdot L_{bb}(T,\lambda)$$

What does the camera see?



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Some fundamental units

- Emissivity ε
- Absorptivitiy $\alpha = \varepsilon$
- Transmittance τ
- Reflectance r

- $\tau + \varepsilon + r = 1$
- For many materials, r or τ are close to zero.

- Radiance L [W m^{-2} sr^{-1}]
- Irradiance E [W m^{-2}]

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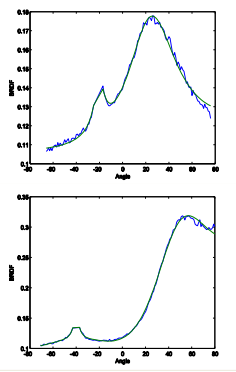
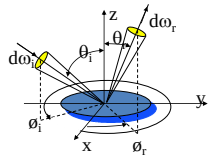


Angle dependence - BRDF



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Domains and wavelengths

Reflective vs emissive, visual vs infrared, …

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Domains

- Light is originally emitted and then commonly reflected.
- Light sources emit light. Per definition.
- In the **reflective domain**, light behaves as we are used to.
  - Dominated by reflected light.
  - Many materials have high and varying reflectance (ie, colour).
- The **emissive domain** is dominated by emitted light.

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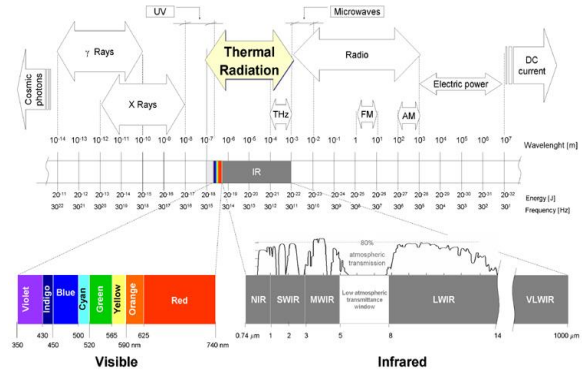

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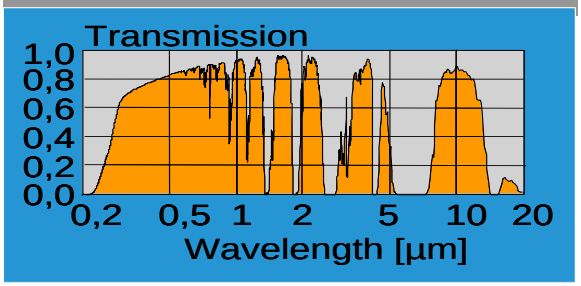
http://www.theses.ulaval.ca/2005/23016/apb.html

Atmospheric transmission



Infrared, and other, ”light”

- UV: Ultra violet
- VIS: Visual
- NIR: Near infrared
- VNIR: VIS+NIR
- SWIR: Shortwave IR
- MWIR: Midwave IR
- LWIR: Longwave IR
- FIR: Far infrared
- TIR: Thermal IR

Almost visual, you just can’t see it. Your cellphone can.

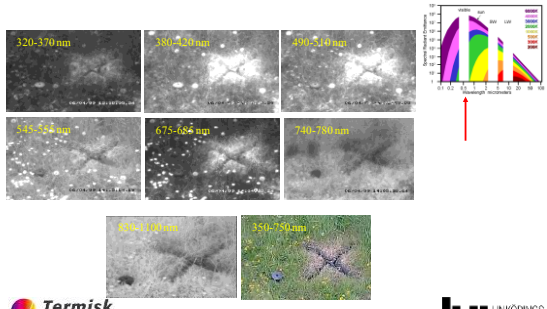
Mostly reflected light.

Mostly emitted light.

Often the same as LWIR.

Yeah, this one too. Can include MWIR as well.

Example: Reflected radiation

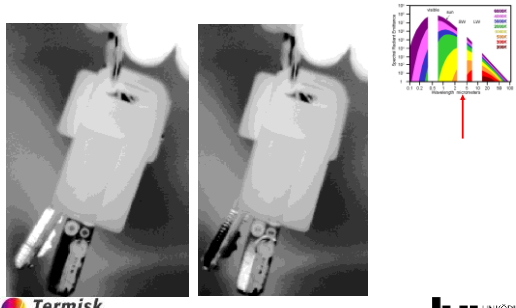


Example: Emitted radiation

Visible image
(0,3-0,7 micrometer)

Longwave image (8-12 micrometer)

Example: Reflected and emitted



From object to sensor

- A sensor integrates the incoming energy over a *certain bandwidth*.
- The radiation appearing at the sensor is (typically) the sum of
  1. The emitted object radiation transmitted through the atmosphere
  2. The emitted atmosphere radiation
  3. The reflected radiation transmitted through the atmosphere
- This does not equal the temperature of the object!

And remember, the radiation is…

Emitted

Transmitted

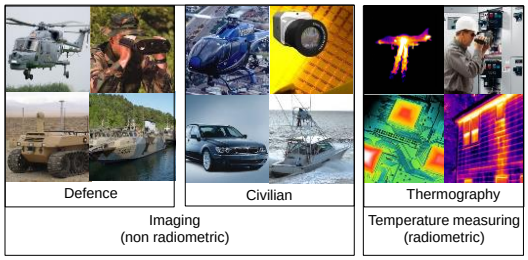
Reflected

Part 3

Thermal cameras

Cooled vs uncooled – Performance measures – Image formation

IR cameras



Temperature measuring cameras

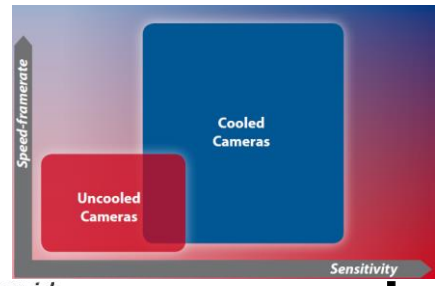
IR cameras

Sensitivity: 20 mK – 150 mK.
Precision: ± 1 K to ± 2 K / ± 1% to ± 2 %
Frame rate up to:

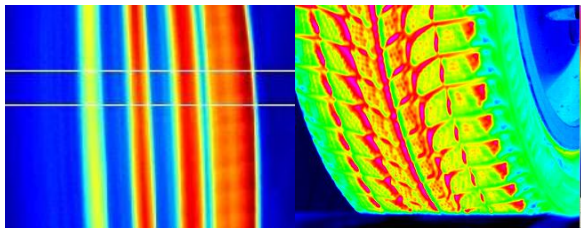
- Hundreds / thousands fps (cooled)
- 62 fps (uncooled)

Resolution: 60 x 60 to 1920 x 1280

Cooled vs uncooled cameras



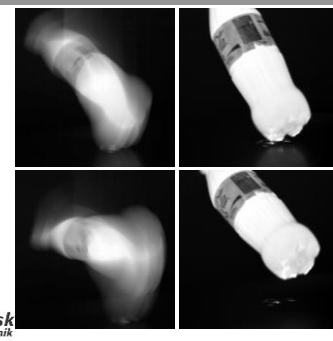
Cooled vs uncooled cameras



Uncooled camera 320 x240 pixels

Titanium 520M, integration time = 170µs

Cooled vs uncooled cameras



Cooled

Cooled detectors

- Previous lecture
- Semiconductors whose bandgap energy is less than the photon energy we want to detect.
  - 0,25 eV for 3-5 µm
  - 0,1 eV for 8-13 µm
  - 1,1 eV for silicon detectors (visual cameras etc.)
- Incoming photons give a change in resistance, voltage or current (depending on detector).
- Requires cooling!
  - Stirling engine cryometer
  - Liquid nitrogen

Cooled

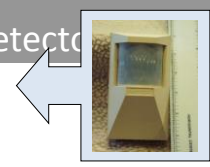
Common cooled detector materials

- MCT – Mercury Cadmium Telluride (HgCdTe)
  - SWIR, MWIR, LWIR: Broad spectral range
- InSb – Indium Antimonide
  - SWIR, MWIR
- GaAs – Gallium Arsenide
  - QWIP – Quantum Well IR Photodetector
  - Shot noise, but almost no thermal noise
  - MWIR, LWIR

Uncooled

Thermal detecto

- Pyro-electric detectors
- Microbolometer



The common detector in handheld and industrial IR cameras.

Uncooled

Internal radiation

- Much of the radiation hitting the sensor is emitted by the camera.
  - 90% is a realistic value.
- One or more internal thermometers.
- On-board processing.

3 thermometers in this one!

Uncooled IR (vs. cooled)

Cooled

Uncooled

Pros
- No cooling
- Robust
- Low weight
- Low power
- Small
- Inexpensive
- Quiet

Cons
- Angular resolution
- Temperature resolution
- Slow

Optics for IR cameras

- Glass transparent in VNIR. Inexpensive optics.
- Germanium (sometimes with diamond coating) transparent in IR. Expensive optics.

Performance measures

NETD – MRTD – NEP – D*

Performance measures (1)

- Temperature resolution = the smallest temperature difference that can be measured
  - NETD (Noise Equivalent Temperature Difference)

$$NETD = \frac{\sigma_N}{\Delta S / \Delta T} \quad [\mathrm{mK}]$$

  - MRTD (Minimum Resolvable Temperature Difference): Minimum temperature difference between a "4-bar" and the background for enabling an operator to count the bars. Typical value: 0,3 K.

Performance measures (2)

- NEP (Noise Equivalent Power): The incoming radiation S giving a signal-to-noise-ratio equal to one (S/N=1).
- Normalised detectivity D*: Performance measure independent of detector size A_d and bandwidth Δf.

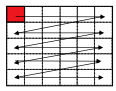
$$D^* = \frac{\sqrt{A_d \Delta f}}{NEP} \quad [\mathrm{cm}\sqrt{\mathrm{Hz}}/\mathrm{W}]$$

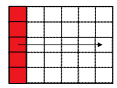
Image formation

Scanning vs. staring

Detector to image (1)

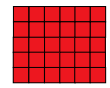
- One pixel (detector) or a line of pixels scan the image mecanically/optically using moving mirror(s).


Serial scanning


Parallell scanning

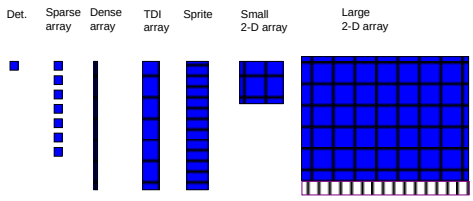
Detector to image (2)

- Two dimensional ”staring” array of pixels generating the image directly.


Focal plane array

FPA development

Generalised Focal Plane Array development

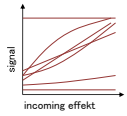


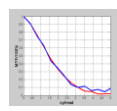
Limitations

Blooming – Noise – Uniformity – MTF

Sensor limitations

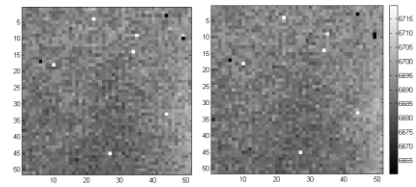
- Blooming: Leakage between pixels.
- Noise: Background, detector, electronics.
- MTF: Modular Transfer Function.
- Uniformity (next slide).





Uniformity (example)

Two acquisitions, Δt=0.04s, surface with flat temperature ~ 22.5 °C.
Measurement in 4.5–5 µm (MWIR).



Operability [%] – Percentage useful (= non-defect) detector elements in an FPA.

NUC: Non-uniformity correction.

Sensor development

Summary

- Thermal cameras are cooled or uncooled
  - Cooled: Noisy, cumbersome, expensive, fast, sensitive.
- Most cameras you will see are uncooled bolometer cameras operating in LWIR.
- Optics for VNIR: Glass.
  Optics for thermal: Germanium (expensive).
- Sensor development is fast.

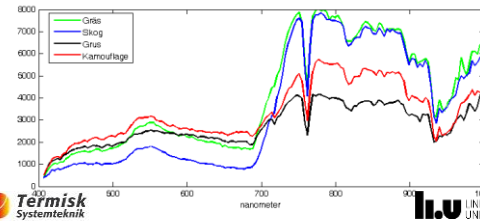
Part 4

Multispectral cameras

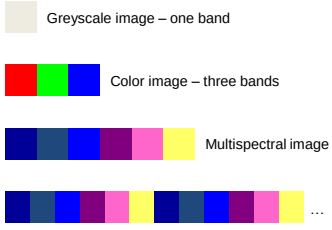
What, how, and why?

Multispectral sensors

- Sensors for multiple wavelengths.
- Each pixel gives a spectral signature.



Spectral images



Hyperspectral image processing

- Why?
  - Each pixel gives information about the material!
  - See the difference between ”tank pixels” and ”tree pixels”!
- Hyperspectral information is not that easy to ”watch”
  - Each pixel is a multidimensional vector.

Five ways of making a multi/hyperspectral sensor

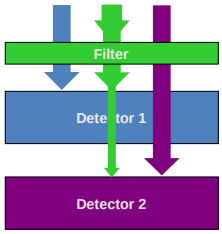
Mosaic – Multilayer – Filter wheel – Scanning – Interferometer

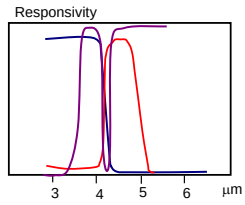
Principle 1 - Mosaic

R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B

- The common digital camera
- Small filter on each sensor element
- The colours are not aligned!
- OK, Klas already told you in a previous lecture, right? So let's move on.

Principle 2 – Multilayer

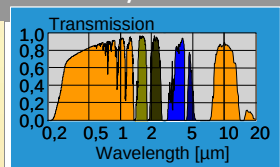


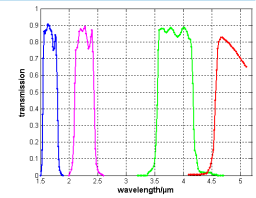


Principle 3 – Filter wheel

- Broad band sensor.
- Rotating filter wheel with N filters between the sensor and the optics.
- Each N:th image from band k.
- In a static world, the pixels are registered (aligned).

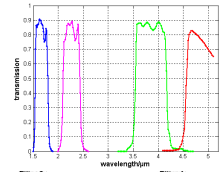
MultimIR: 4-band SWIR/MWIR

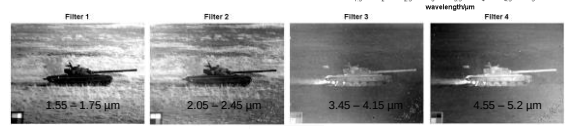




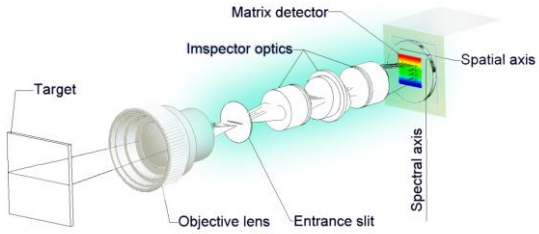
Sensor example - MultimIR

- 2 bands in SWIR
  - Much reflected radiation
- 2 bands in MWIR
  - Much emitted radiation



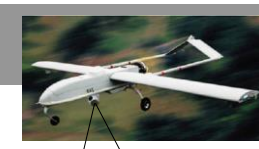


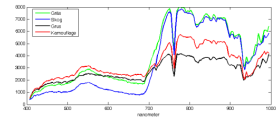
Principle 4 – Scanning

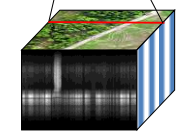


www.specim.fi

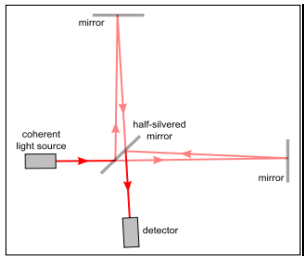
Push-broom

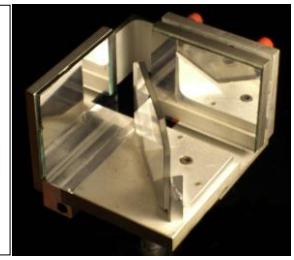




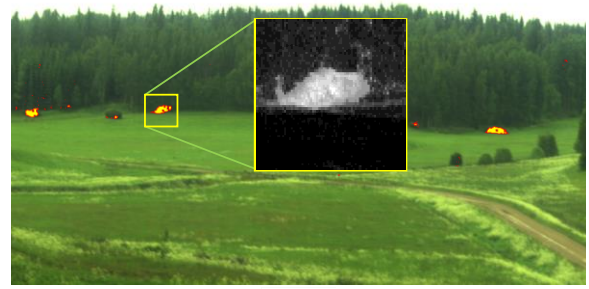


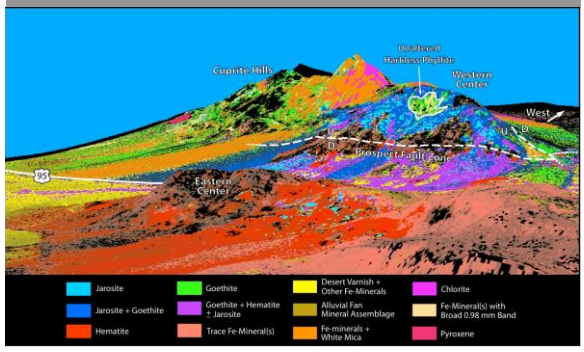
Principle 5 – Interferometer





Hyperspectral: Ground-to-ground recon





Summary

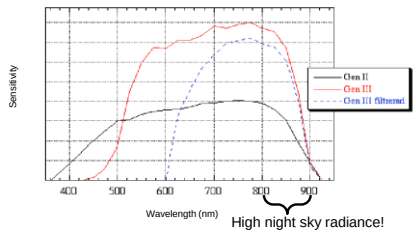
- Use multiple wavebands to see better!
- Recognize materials in one pixel!
- Five ways of making a multi/hyperspectral camera.
- Applications: Mostly remote sensing (military, environment)

Part 5

Application examples

Application example 1 Military applications

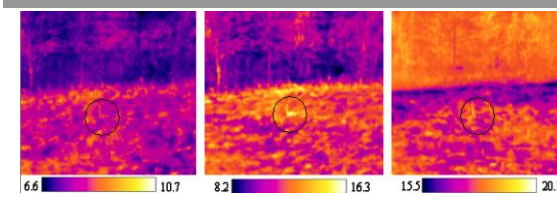
Night Vision Devices



High night sky radiance!

"Image enhancers", not thermal IR!

Mine detection

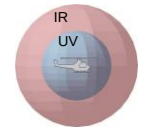


08:14 08:22 16:47

IRST – Infrared Search and Track

Missile Approach Warning

- Detects IR from rocket engine ans/or missile hull
- MWIR and/or LWIR
- Advanced signal processing
- Detection distance ~3-10 km
- Scanning systems are available commercially, staring under development.



UAV reconnaissance

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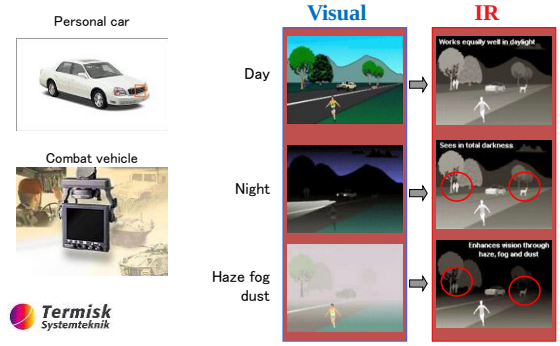
Night vision for driving



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Night vision for driving

Real-time (video rate) detection of pedestrians in thermal infrared video.

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Target detection

Robust detection of military ground vehicles in thermal infrared data.

FOI

Non-destructive testing

Application example 2

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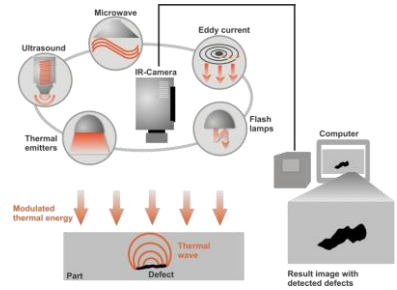
Non-destructive testing (NDT)



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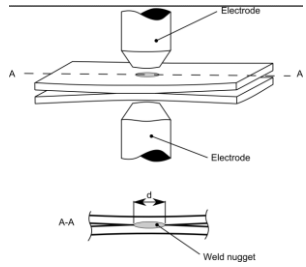
Spot weld



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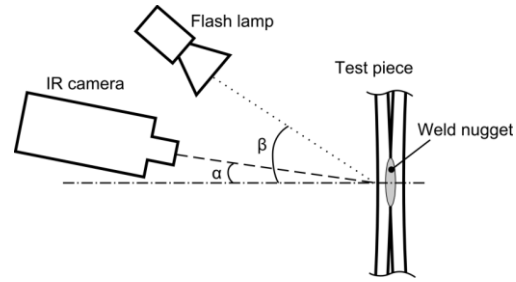
NDT: Spot weld inspection



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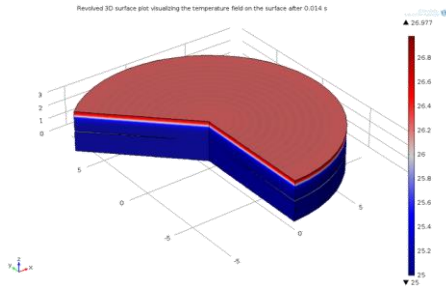
Simulation



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Message

No, you *can't* see inside solid objects with a thermal camera, *but* you might observe the effects of the inside.

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Fires!

Application example 3

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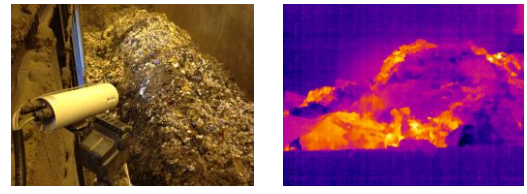
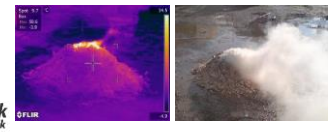
Fire in the bunker





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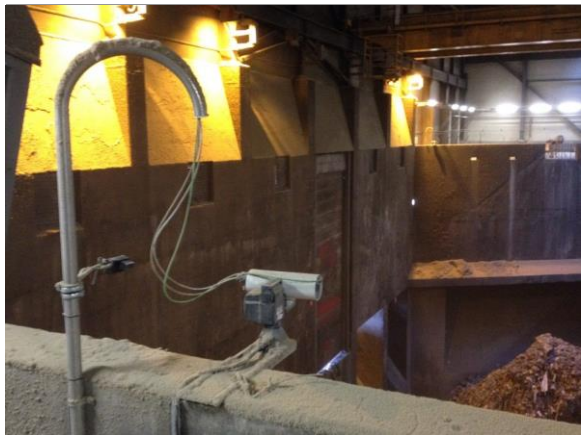
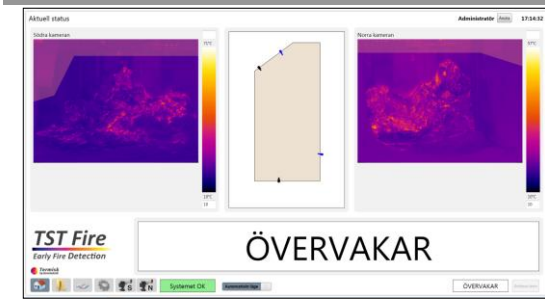


Operator view



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Cows!

Application example 4

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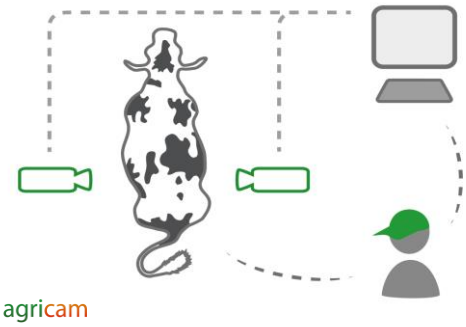
Automatic milking

agricam



agricam

Example images

agricam

Surveillance & tracking

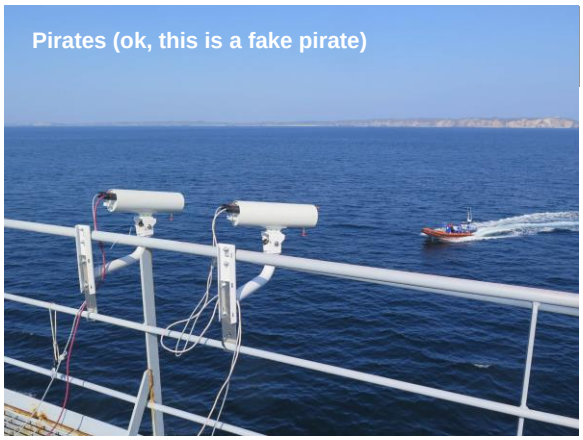
Application example 5

An image-based tracker

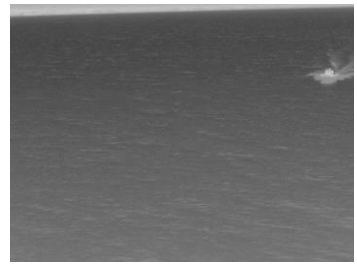
Tracking of objects

- Note that objects are not always warmer than the background.

Pirates (ok, this is a fake pirate)



Computer vision problems



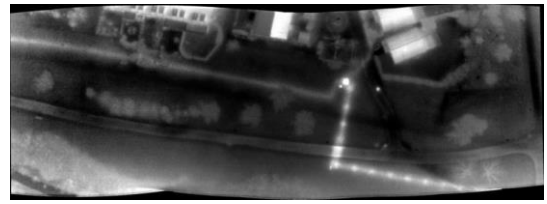
- Extreme scale variations
- Low contrast (sometimes)
- Wakes
- Occlusion (wakes, waves, …)

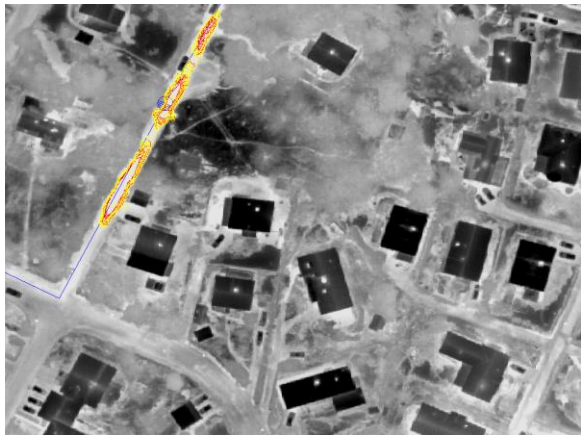
To be solved…

District heating pipes

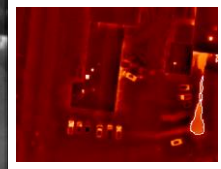
Application example 6

District Heating Pipes





District Heating Pipes



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District Heating Pipes

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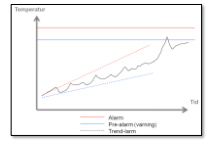
Fire detection in waste & biofuel



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Some other stuff

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”The Ultimate Handbook…”

- Read Ch. 1- 3.
- Books donated by Termisk Systemteknik AB.

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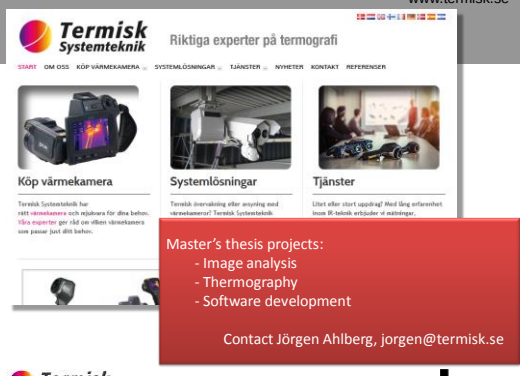

Master's thesis projects:

- Image analysis
- Thermography
- Software development

Contact Jörgen Ahlberg, jorgen@termisk.se

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