Non-visible Imaging

An Overview of Infrared (IR) Concepts, Cameras, and Applications

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Allied Vision Technologies

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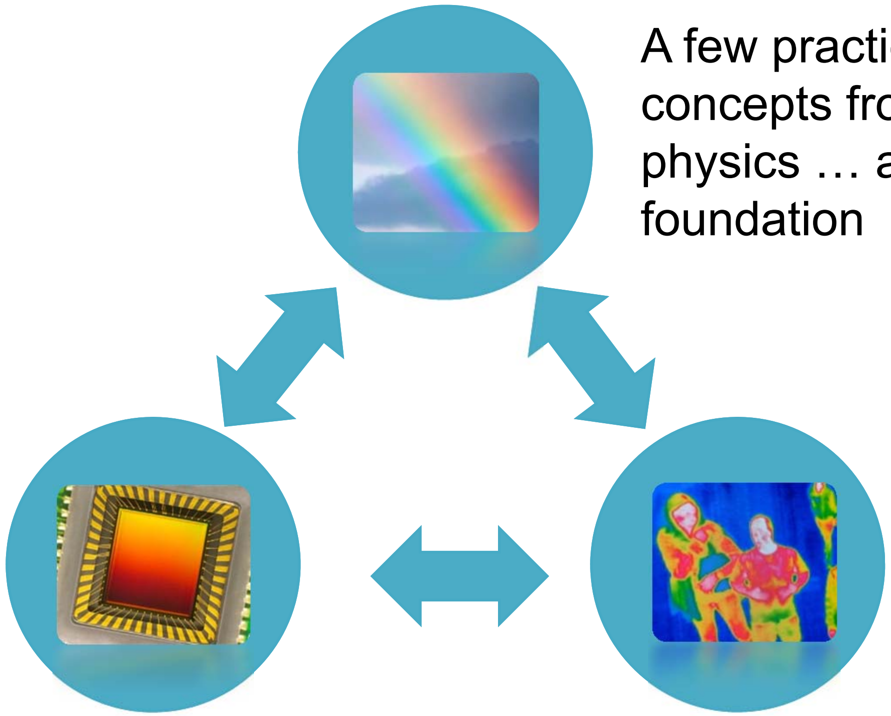
What Can You See In These Images?

Visible | **NIR / SWIR** | **LWIR**

How to Approach IR Imaging?

Physics

A few practical concepts from physics … as a foundation



Sensor characteristics determine the types of cameras that can be designed

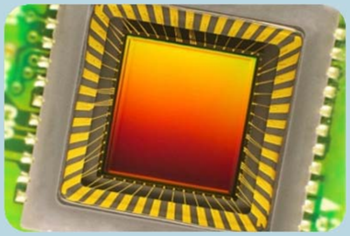
Most natural for user with an application in mind… *if all in room had same exact goal*

Camera Technology

Applications

Contents

Physics

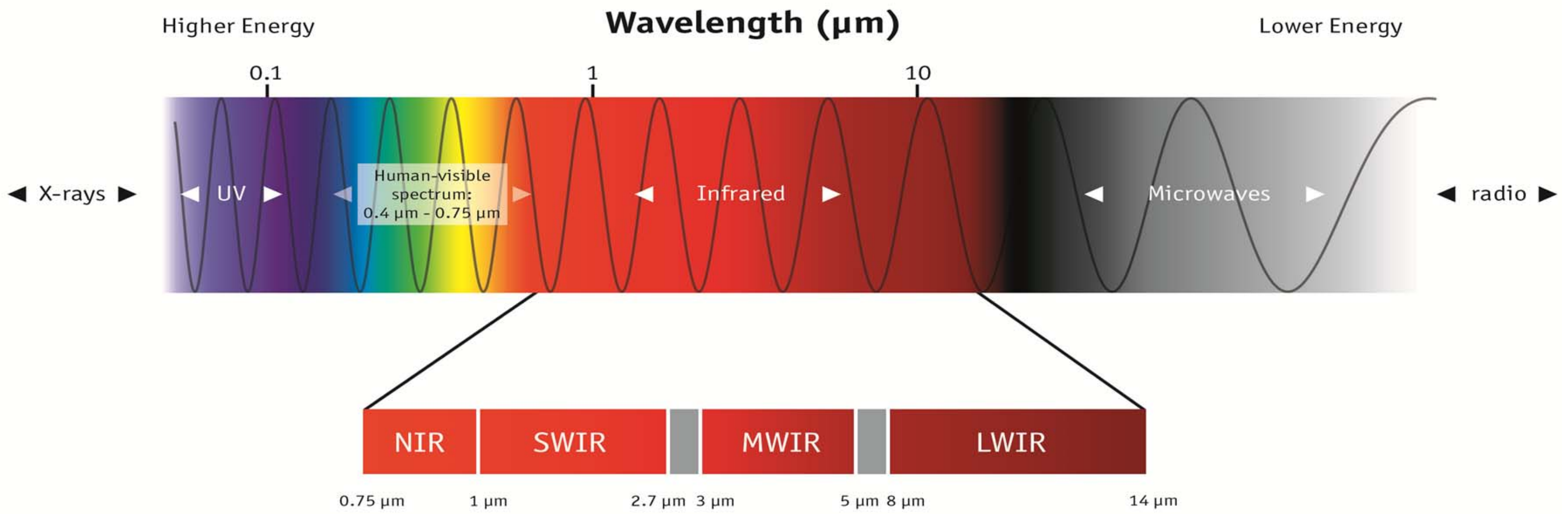


Camera Technology

- Optics and filters
- Sensor Technology
- Image (pre-) processing

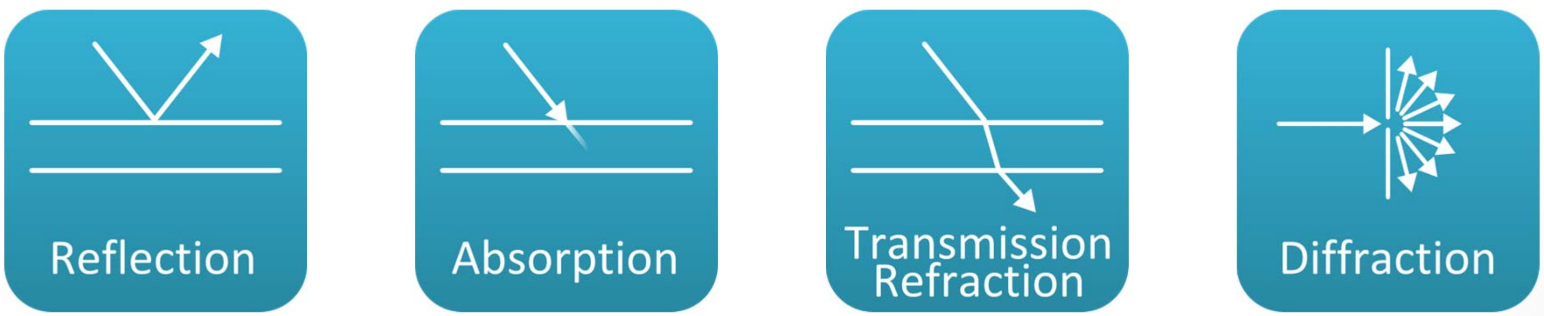
Typical Applications

Electromagnetic Spectrum: A Helpful Taxonomy …

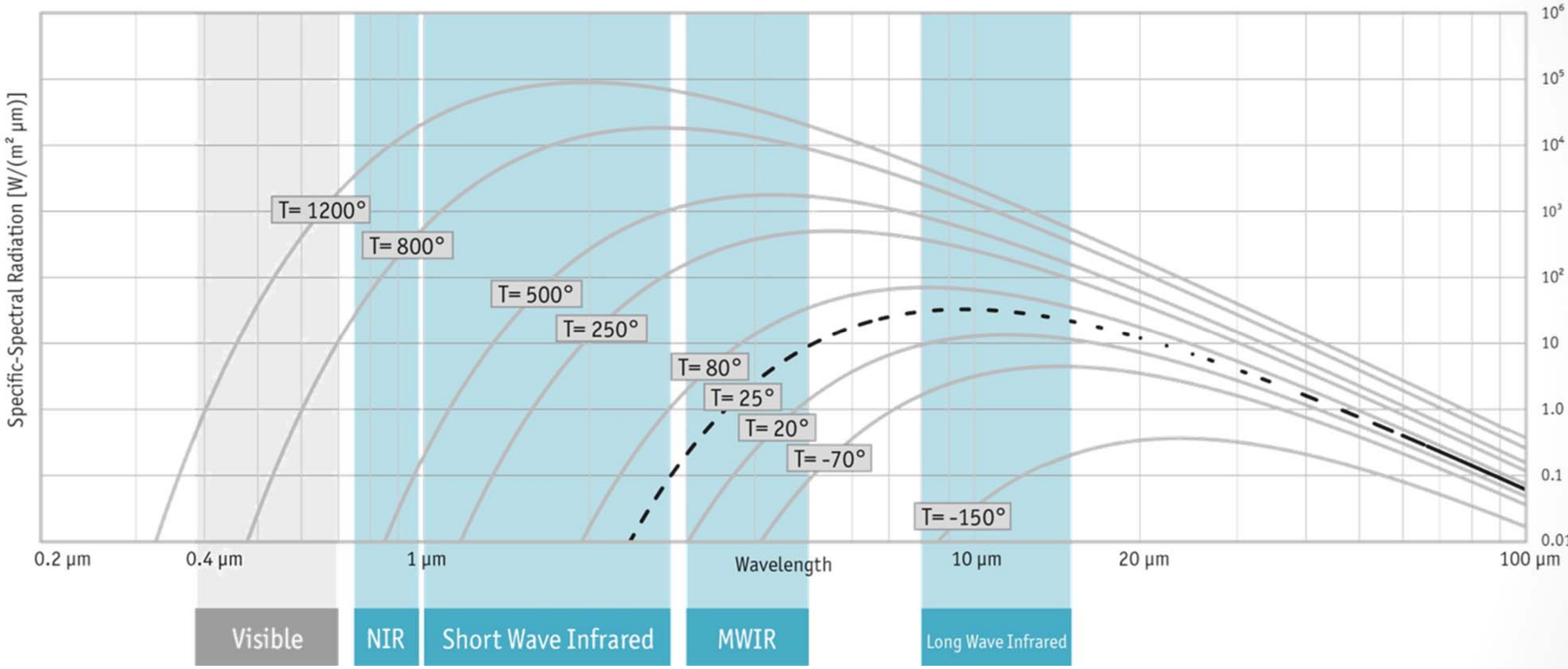


IR Radiation – Characteristics:

- **Invisible** to the human eye … but not to certain sensors
- **Caused by** the vibration and rotation of atoms and molecules
- **Emitted from all objects** with a temperature above 0 K (-273 °C)
- **Interacts** like other electromagnetic radiation, including:



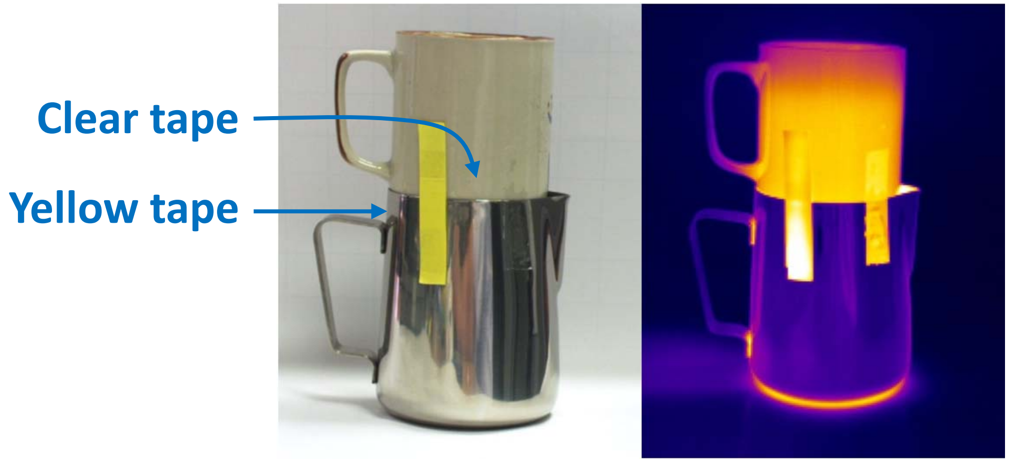
IR Energy vs. Object Temperature



Reference temps:
White hot steel ~1200 °C
Melting point of aluminum 660 °C
Water boils at 100 °C
Uncooled camera at 38 °C
Human body at 37 °C, radiates at ~ 10 µm
Water freezes at 0 °C

Measuring Temperatures

Emissivity

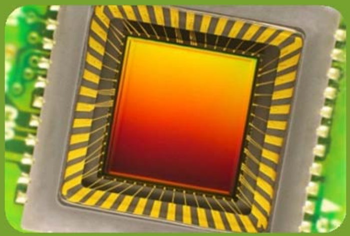


$$\varepsilon = \frac{\text{Energy emitted by an object}}{\text{Energy radiated by a black body at same temperature}}$$

- Black body by definition $\varepsilon = 1$
- In general the duller and blacker, the closer to $\varepsilon = 1$
- The more reflective, the less emissive
- Knowing emissivity permits absolute temperature measurement

You are here. ;-)

Physics



Camera Technology

- Optics and filters
- Sensor Technology
- Image (pre-) processing

Typical Applications

Structure of an IR Camera

Optics & Filters

Sensor
incl. digitization

Sensor Cooling
(optional)

Firmware
- Feature Control
- Image Correction
- Temperature Calibration

Interface and I/O Control

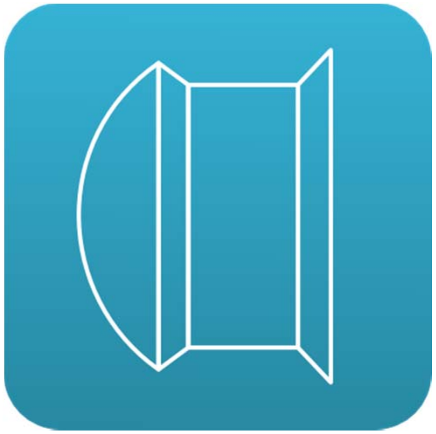
Background Correction

Gain/Offset Correction (NUC)

Defect Pixel Correction

Temp. Calibration via LUT

Drift Compen-sation

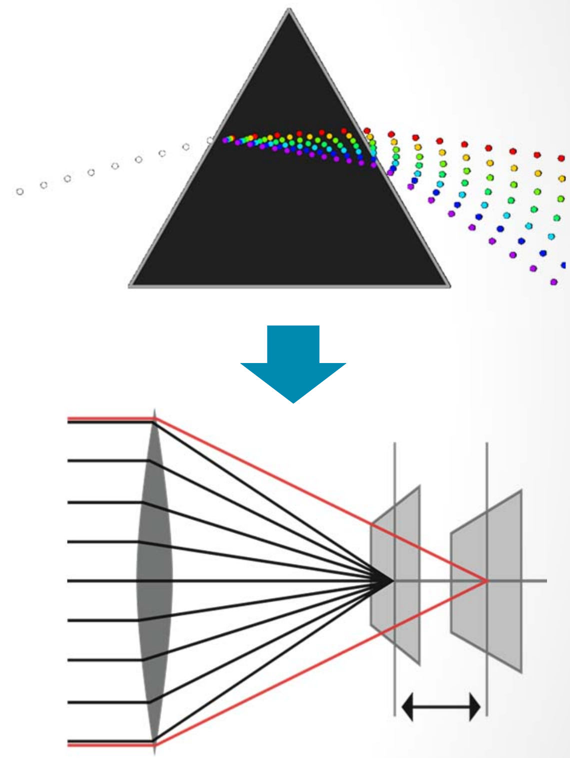


OPTICS & FILTERS

SWIR Optics

- **<u>Standard (visual) lenses</u> could theoretically work for wavelengths up to 2.5 µm. <u>But</u>:**
    1. **Dispersion** causes image blur due to different focal planes for different wavelengths
    2. **AR-coating** on standard lens <u>not</u> optimized for SWIR causes much lower light transmission
    3. **Coating inside (visual) lens** barrel may actually <u>cause</u> reflections in SWIR.

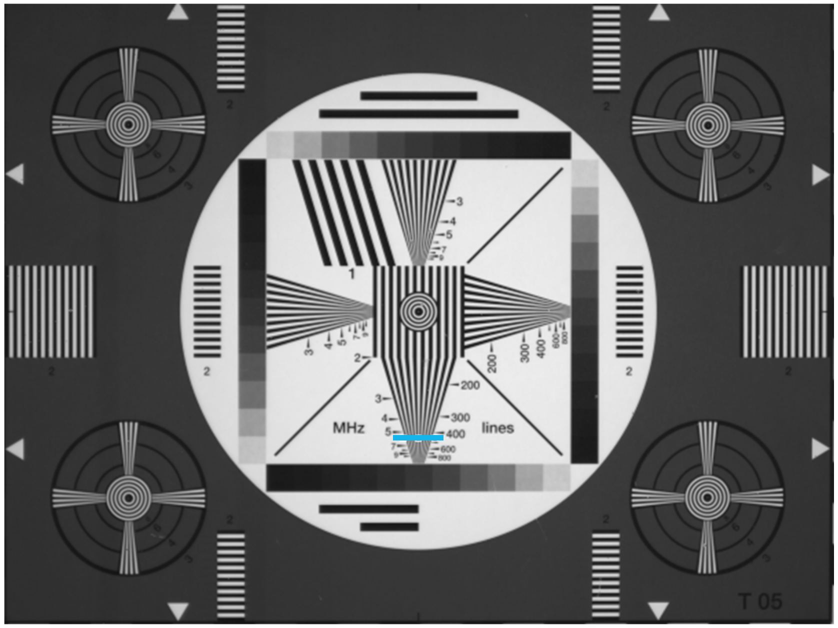
- **An <u>optimized SWIR lens</u> design enables sharp, reflection-free imaging with high spectral transmission and contrast**

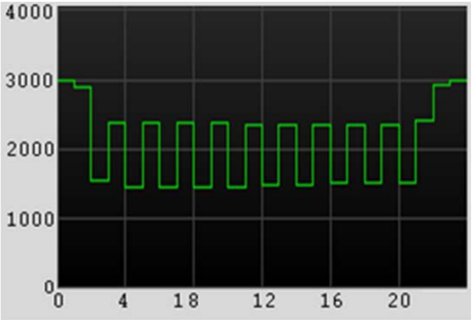


Position of focal plane depends on wavelength

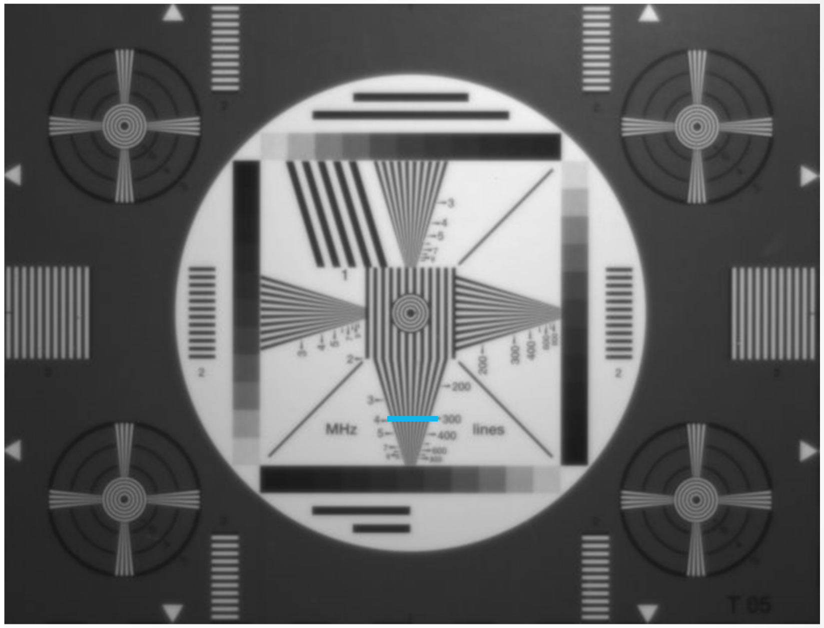
Comparing SWIR Optimized and Standard Lens

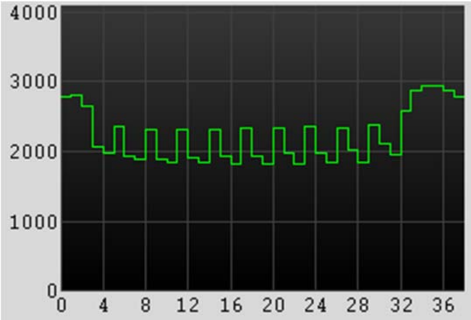
SWIR optimized lens





Non-optimized lens





Filters for SWIR Wavelengths

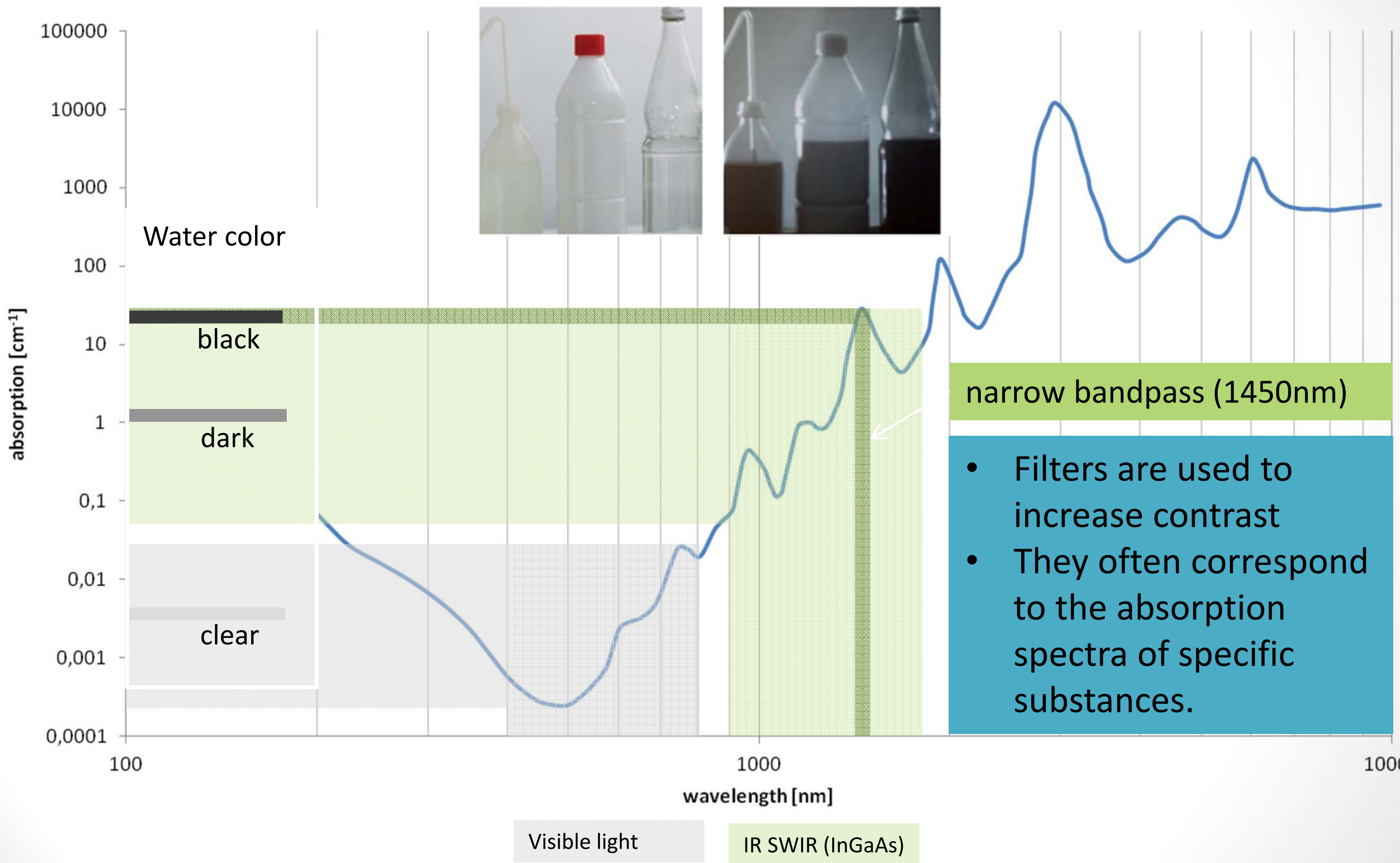
- **Filters** are used to **increase image contrast**
- **Filter selection** corresponds to the absorption or transmission spectra of a specific substances **to emphasize special features**
- Very popular example:

  1450nm Band-pass filter (water filter) to detect moisture

C-Mount
with
Filter

Easy and flexible filter mounting is a plus!

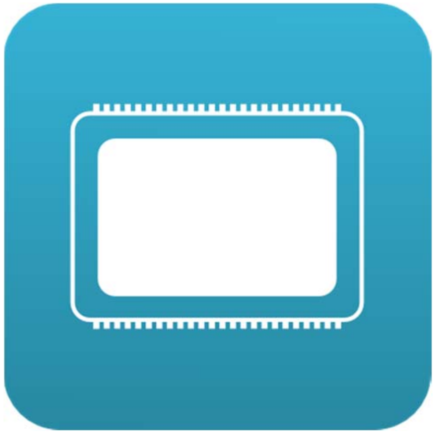
How the water filter works



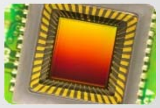
- Filters are used to increase contrast
- They often correspond to the absorption spectra of specific substances.

MWIR & LWIR Optics

- Wavelengths > 2.5 µm would be blocked by glass
- Special and costly optics needed: germanium and silicon
- Further materials available for high transmittance
- No standard mounts defined



SENSOR TECHNOLOGY



Quantum vs. Thermal Detectors

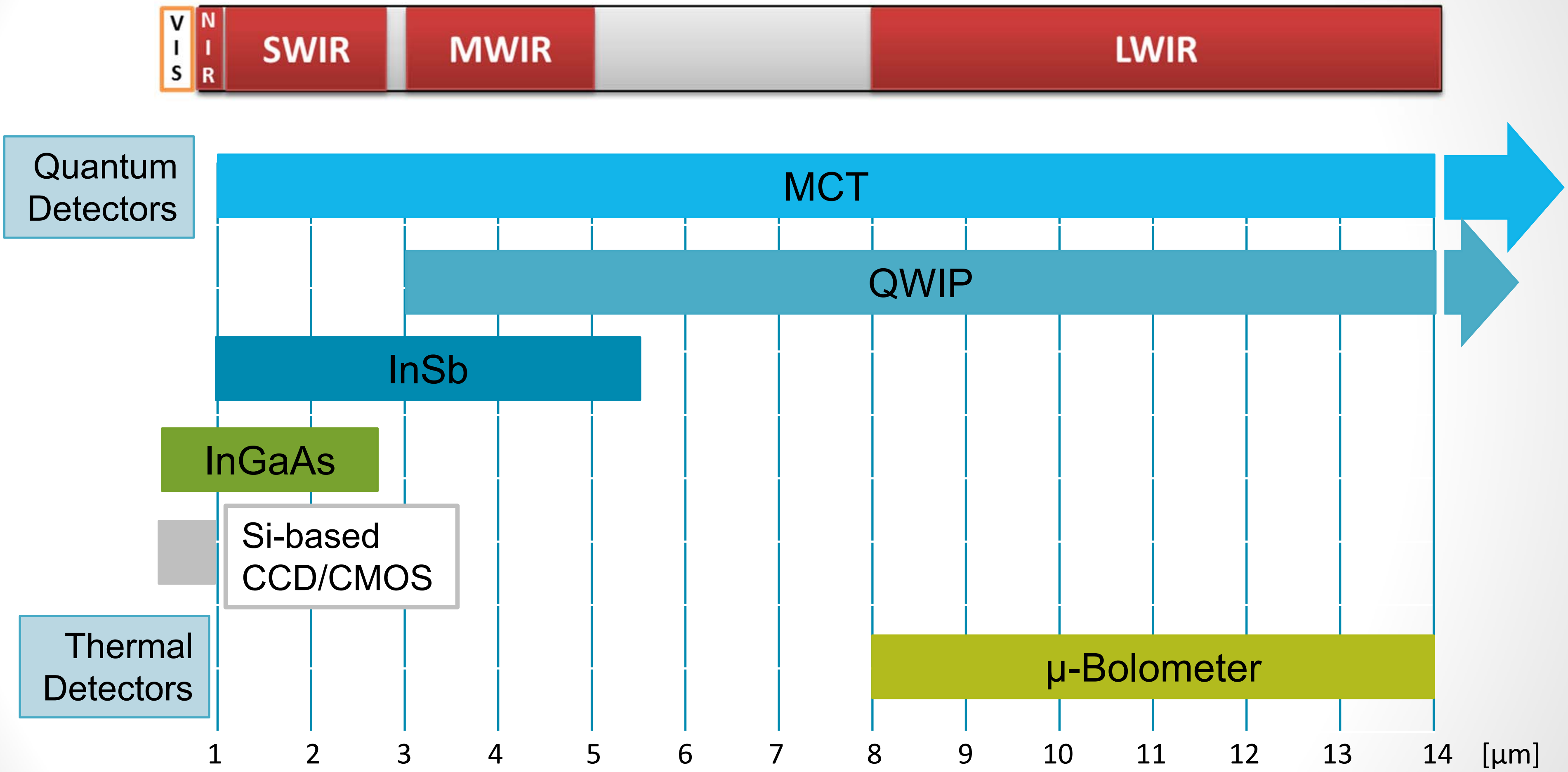
Quantum Detectors

- Sensitivity dependent on wavelength
- Require **cooling** to improve S/N ratio especially for wavelengths beyond 1µm
- High detection performance and fast response

Thermal Detectors

- Detect IR energy as heat
- In general do not require cooling
- Have a slow response time and detection capability

Spectral Sensitivity for typical IR Detector Types



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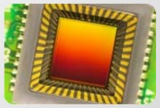
Infrared Detector Selection

Min. Object Temperature (self-emissive)	**Sensor Type**	**Sensor wavelength** [µm]	**Sensor Operating Temperature**
800°C	CCD/CMOS [Si]	< 1	300 K (27 °C)
250 °C	SWIR [InGaAs]	< 1.7	< 300 K (27 °C)
0 °C	MWIR [InSb]	< 6	77 K (-196 °C)
-70 °C	LWIR [µBolometer]	< 14	300 K (27 °C)
-150 °C	LWIR [MCT]	< 20	77 K (-196 °C)

Reference temps:
White hot steel ~1200 °C
Melting point of aluminum 660 °C
Water boils at 100 °C
Uncooled camera at 38 °C
Human body at 37 °C, radiates at ~ 10 µm
Water freezes at 0 °C



Cooling Methods

- **Cryogenic Cooling**
  - Dry ice or liquid nitrogen
  - Mechanical cooling using Stirling elements
- **Thermoelectric Cooling (TEC) using Peltier elements**
  - Lower cost
  - Solid state – no vibration

SWIR Sensor Technology

- **Quantum detector**

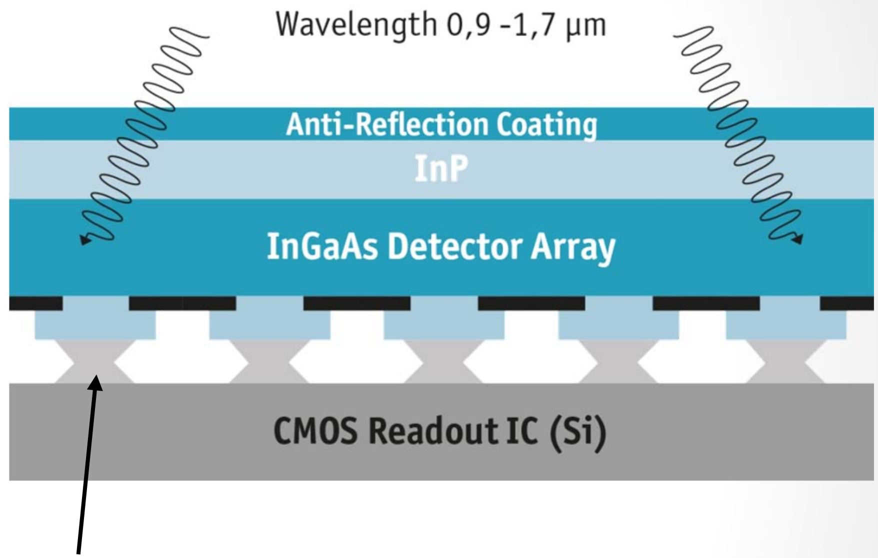
  Working principle:
  Absorption of photons that elevate the material's electrons to a higher energy level, so that they can be counted

- **Hybrid array**

  IR detector, Si readout

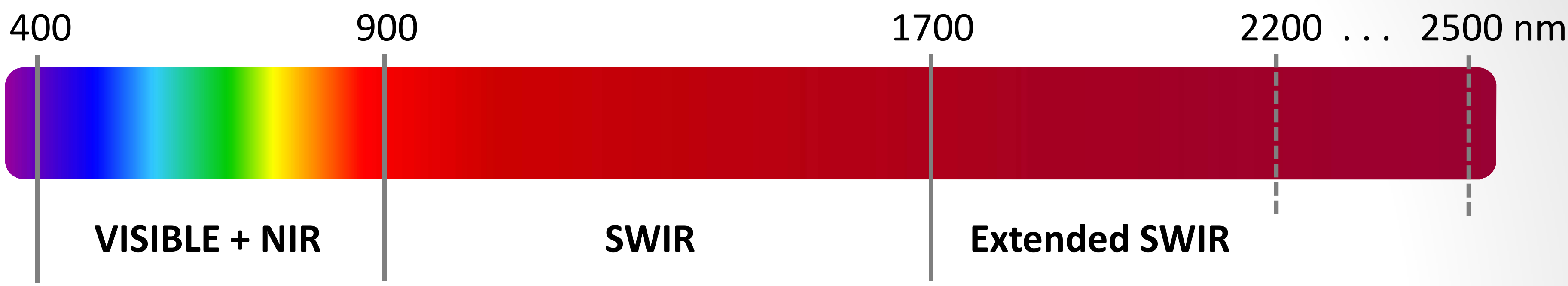
- **InGaAs sensors have higher dark** current than pure SI-based CCDs or CMOS sensors

  → For exposure times > 40 ms sensor cooling with Peltier elements (TEC) needed

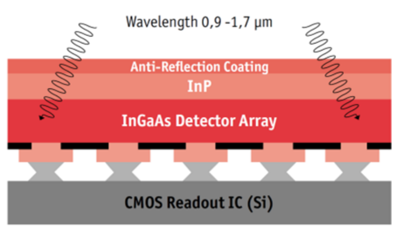


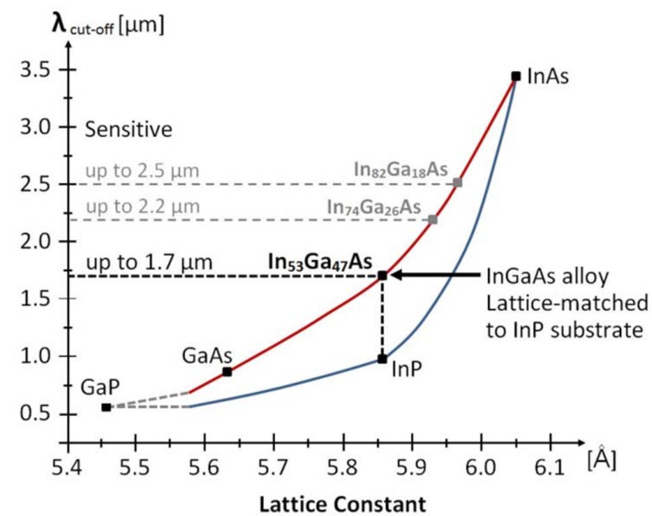
Indium bumps on each pixel of array and readout IC

Spectral Range Extension of InGaAs Sensors



Thinning InP-Layer

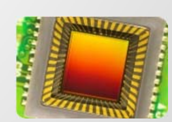




Changing Lattice-Constant

Influenced by ratio between InAs and GaAs

Sensors require stronger cooling, because of extended dark current



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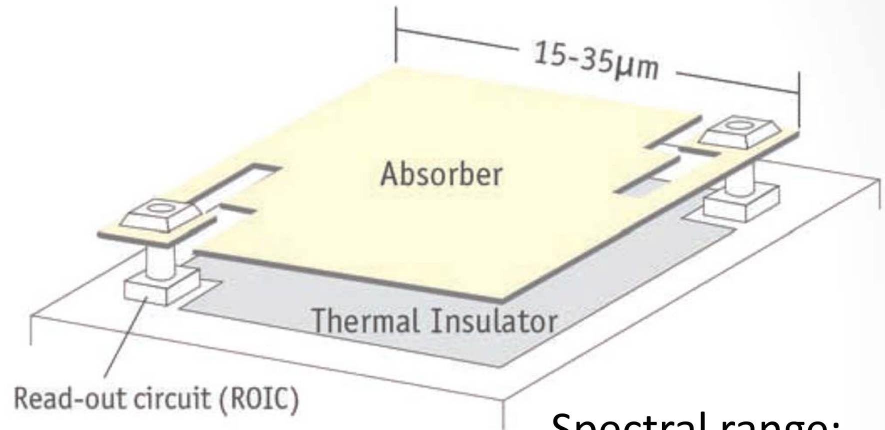
µBolometer Sensor Technology

- **Thermal detector**

  Working principle:
  Detection of electrical resistance changes in a thermally insulated absorber material

- **Hybrid array**

  IR detector, Si readout



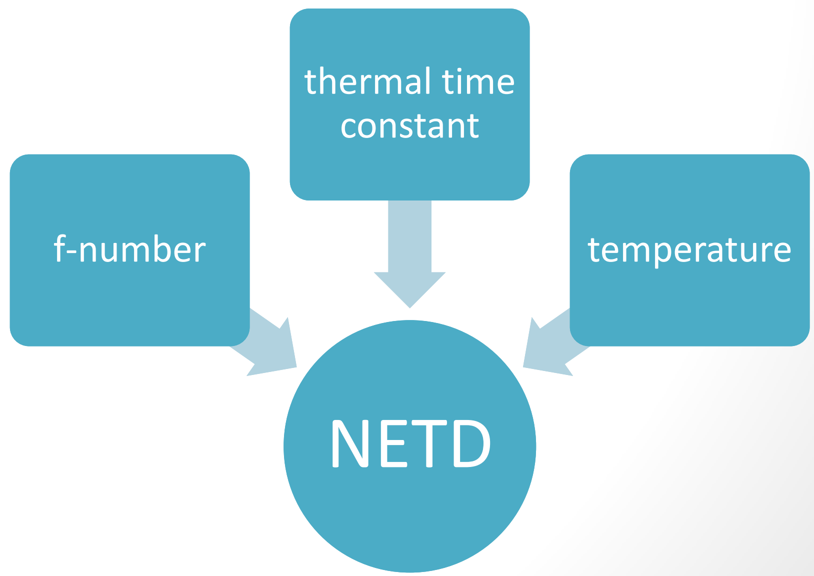
Spectral range:
8 ..14 µm i.e. for LWIR

Comparing camera performance

Noise Equivalent Temperature Difference [NETD]

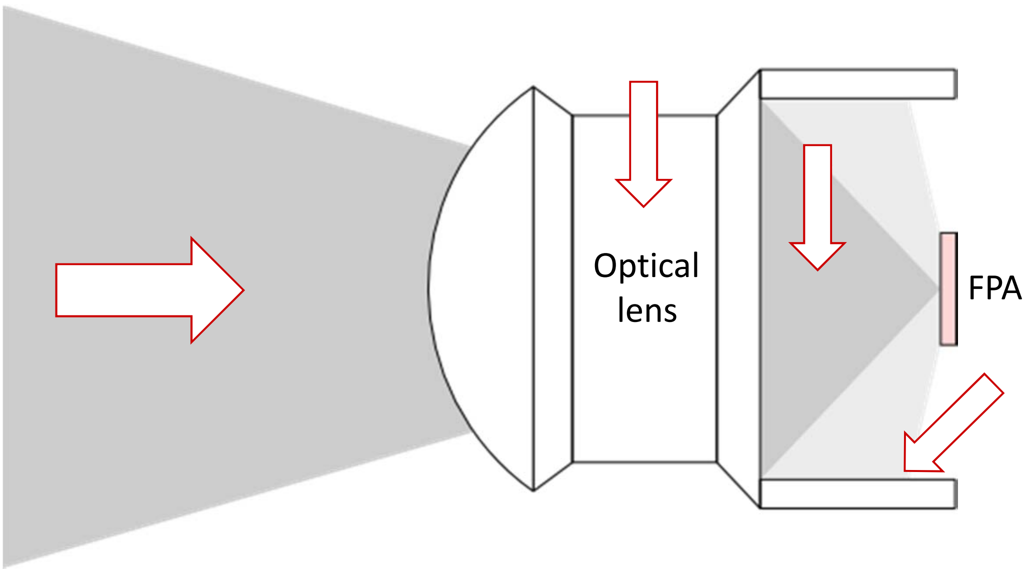
- Is equal to temperature difference which would produce given noise
- A measure of detector sensitivity; influences precision of temperature measurement
- Measured in °C or K
- 10 mK – 200 mK typical

Influencing variables



~ car shopping performance measures: horsepower, torque, gear ratios, miles per gallon, km per liter, weight, cubic displacement. … ALL are relevant, not just one alone

Various Heat Sources Cause Drift



Heat comes from:

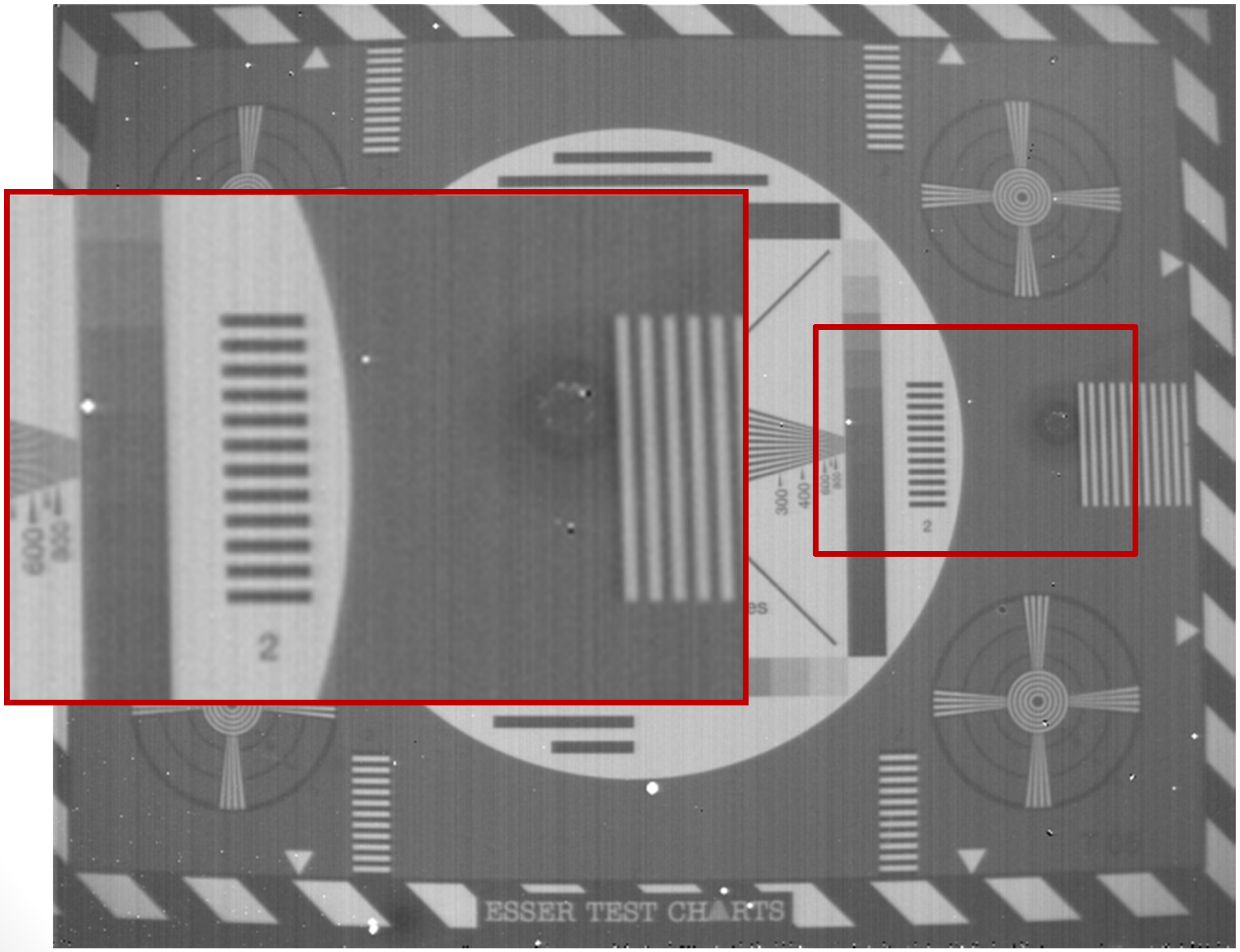
- Scene / object of interest ☺
- Lens
- Camera housing
- Sensor (FPA) ☹

Heat can´t be "blocked" like visible light

→ For exact temperature measurement, correction for the undesired heat effects is essential

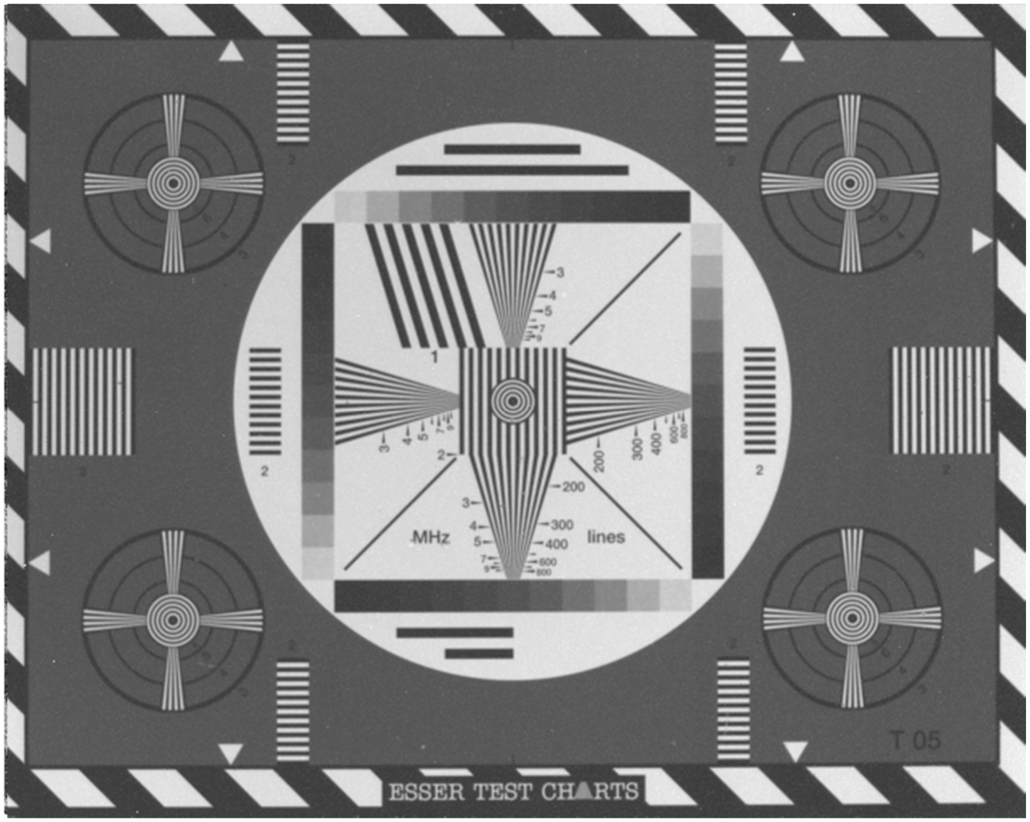
IMAGE PROCESSING

Closer Look at SWIR Sensor Image



- Non-uniformities
- Defect Pixels
- Incorrect flip-chip bonding

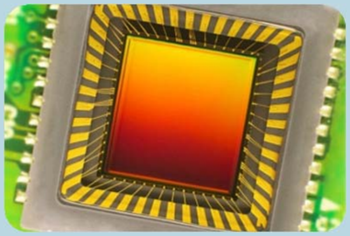
How an Image is Processed



1. **Original image** of an uncooled SWIR sensor exposed for 100ms @ **+40°C**
2. **Sensor temp. -5°C** @100ms exposure
3. **@800ms exposure**
4. **Including NUC**
5. **Including Defect Pixel Correction**

Applications!

Physics



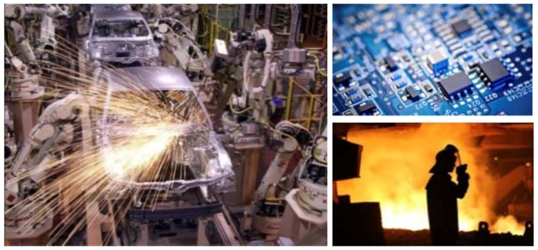
Camera Technology

- Optics and filters
- Sensor Technology
- Image (pre-) processing

Typical Applications

IR Imaging Application Fields

Industrial Machine Vision



- Electronics & Semiconductor
- Photovoltaics
- Automotive
- Chemical (gas, plastic, foil)
- Metal Production
- Paper Production
- Glass Production
- Pharmaceutical
- Agriculture
- Food
- etc.

Scientific & Medical

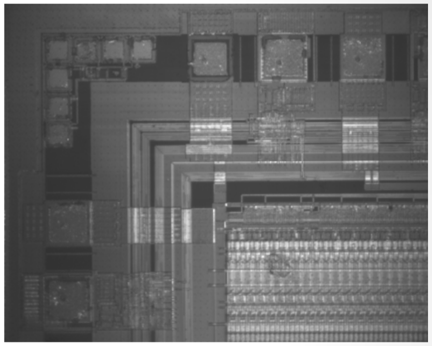
- OCT
- Microscopy
- Tissue Imaging
- Thermal Imaging
- Cancer Detection
- Veterinary
- Hyperspectral Imaging
- Laserbeam Profiling
- Airborne Remote Sensing
- etc.

Security & Traffic

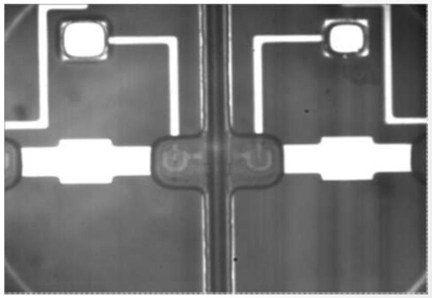
- Surveillance
- Vision Enhancement
- Night Vision
- Military
- Firefighting
- Road Tolling
- Red Light Enforcement
- Driver Assistance Systems
- etc.

Semiconductor Inspection

Application Field	**Automation & Process Control**
Spectral Range	SWIR
Functionality	Silicon is transparent at wavelengths above 1100 nm. This enables looking through: • the silicon to see underlying structures in semiconductors or • the backside of a TFT display to verify the quality of contacts
Notes	Usage of magnification lenses



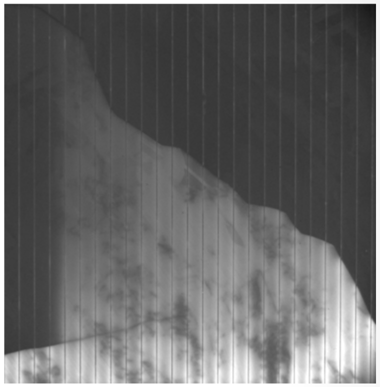
Underlying structures in a wafer

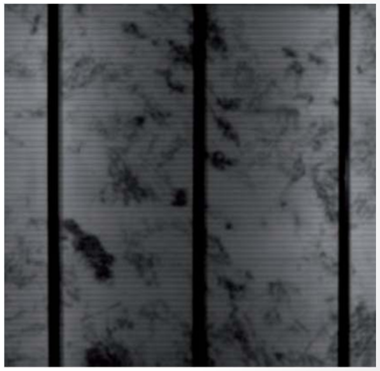


Contacts at backside of a TFT display

Solar Cell & Module Inspection

Application Field	**Automation & Process Control**
Spectral Range	NIR; SWIR
Functionality	**Luminescence imaging** helps to identify non-uniformities in the silicon wafer or solar cell by forcing it to emit light: • **Electroluminescence** (EL) A solar cell emits light / heat in response to electric current flow • **Photoluminescence** (PL) A solar cell emits light / heat in response to being exposed to light
Notes	SWIR cameras ensure a quick characterization (within ms) during the manufacturing process. Whereas, NIR enhanced CCD/CMOS cameras need longer exposure times up to 3 s.





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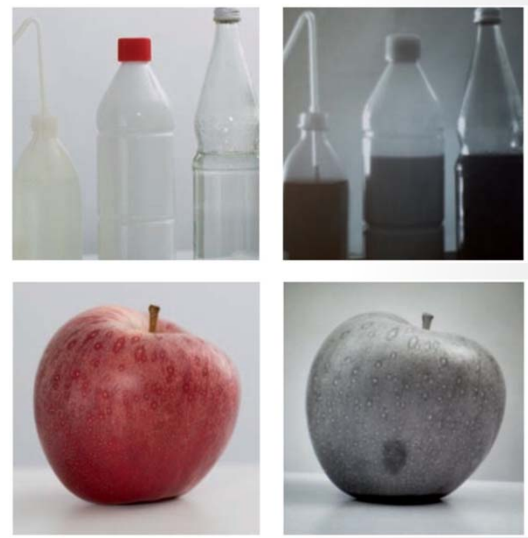
Water Detection

Application Field	**Automation & Process Control**
Spectral Range	SWIR and MWIR
Functionality	**Water absorbs strongly at specific wavelengths**, e.g.: 1.45, 1.9, 2.9, and 6 µm By using a corresponding filter or lighting, this feature can be used for various inspection tasks: ▪ Verification of coatings or dryness uniformity in bulk material ▪ Fill-level detection in bottles ▪ Inspect fruits, vegetables and legumes ▪ Gauging relative water content in plants
Notes	Use corresponding filters to emphasize features



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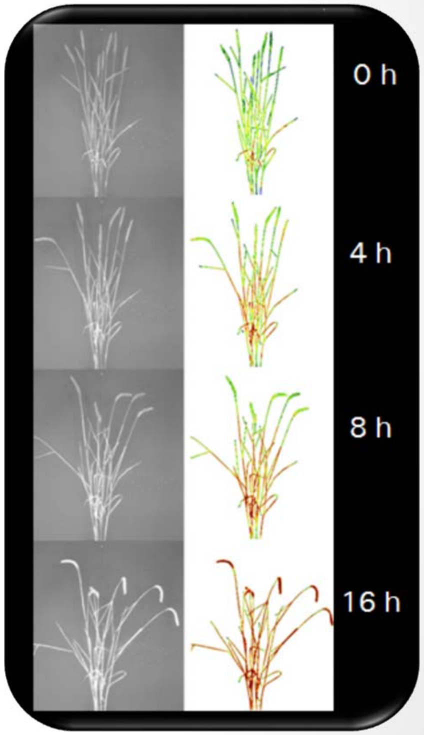
Agricultural Inspection

Application Field	**Automation & Process Control**
Spectral Range	SWIR
Functionality	Water appears darker in SWIR images due to its stronger absorption -- specially at a wavelength of approx. 1450 nm. Therefore, SWIR images show a strong increase in reflectance as the water in plants is reduced.
Notes	Recommended filter for detecting water in SWIR range: Band-pass filter with 1450 nm +/- 25 nm

A bunch of wheat dries out in warm ambient conditions over time.



The example is taken by LemnaTec GmbH

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Document Authentication

Application Field	**Automation & Process Control**
Spectral Range	Visible; NIR; SWIR
Functionality	Certain safety features disappear or become visible when exposed to infrared light. In the examples certain areas of legitimate notes are not visible in IR.
Notes	Sometimes special filters are required, e.g., $-note: 1262 nm – 1338 nm band pass filter

Art Inspection (Reflectometry)

Application Field	**Scientific Imaging**
Spectral Range	SWIR
Functionality	Artists often created sketches using infrared-absorbing materials like India ink, black chalk or charcoal. Infrared reflectography is a non-destructive and non-contact method to authenticate works of art by imaging through surface pigments to detect the presence of any underlying drawings. The higher the wavelength, the deeper it passes the upper layers of the painting.
Notes	If you find a Rembrandt hanging in your living room, please let us know…

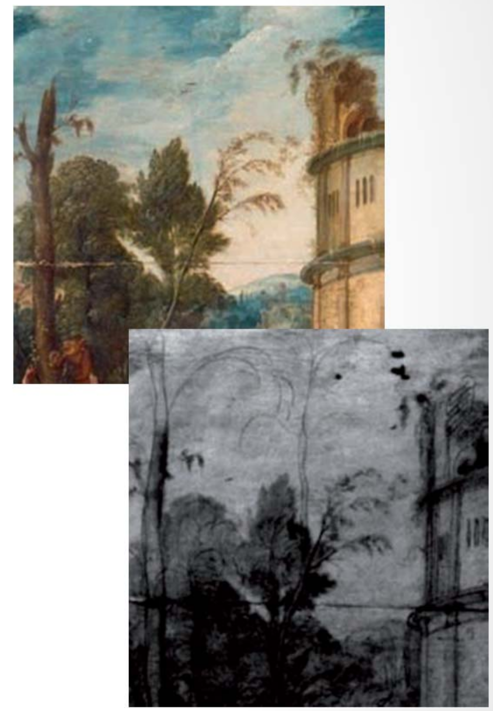
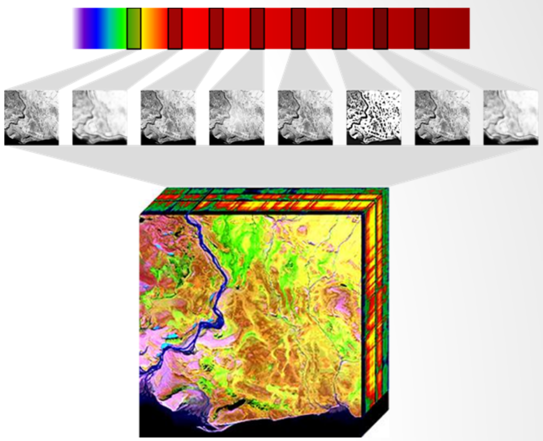


Image provided by:
Musée national d'histoire et d'art Luxembourg

(Hyper) Spectral Imaging

Application Field	**Automation & Process Control / Science & Research**
Spectral Range	VISNIR; SWIR; MWIR; LWIR
Functionality	Incoming light is split into many bands before it falls on the detector. Hyperspectral data contain both spatial and spectral information from objects within a given scene. Each image of a scene represents a specific band of the electromagnetic spectrum. With this technology materials can be identified and distinguished.
Notes	Spectrograph is necessary



Hyperspectral 'images' build three-dimensional data cube for processing and analysis.

Plastics Sorting

Application Field	**Automation & Process Control – Recycling Industry**
Spectral Range	SWIR
Functionality	Short Wave Infrared (SWIR) cameras enable sorting many type of materials. For plastics, a SWIR camera combined with a spectrometer can be applied to identify **PE-HD, PE-LD, PP, PET, PET-G, PS, PVC**, and similar plastics found in household, automotive, and electronics products.
Notes	Spectrograph needed

Quality Inspection – Imaging through Plastics

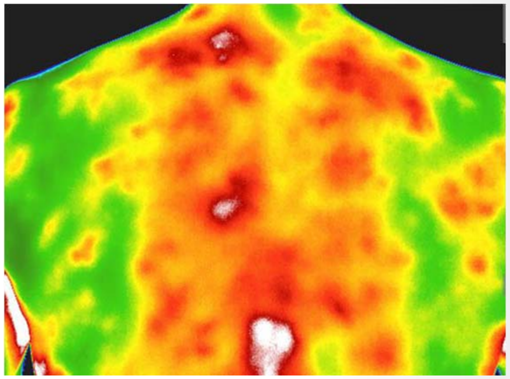
Application Field	**Automation & Process Control – Medical Device Industry**
Spectral Range	SWIR
Functionality	In the spectrum above 1000 nm one can see through plastic. The needle of a syringe can be detected and checked for defects through the cap.
Notes	Transparency of materials at specific wavelength (e.g., plastics) can also be used for other inspection tasks.

Laser Beam Profiling

Application Field	Automation & Process Control – Quality Inspection
Spectral Range	UV, Visible, NIR, SWIR, MWIR, and LWIR
Functionality	A laser beam profiler captures, displays, and records the spatial intensity profile of a laser beam at a particular plane transverse to the beam propagation path. There is an assortment of instrumentation for measuring laser beam profiles, e.g.: A beam profile, which is a 2D intensity plot of a beam at a given location along the beam path.
Notes	Typical laser beam wavelengths inspect able with SWIR cameras: 1310nm, 1480nm, 1512nm, 1550nm, 1625nm, 1654nm

Medical Thermography

Application Field	**Medical Imaging**
Spectral Range	LWIR
Functionality	The skin's surface temperature is correlated with the blood circulation in the outer millimeters of the skin. This blood flow is subject to complex regulation by the nervous system and specific local factors. This enables the ability to "see" the pathological processes such as tumors, inflammation or tissue damage etc., as these processes have an impact on the patient's skin.
Notes	Accurate temperature calibration of the camera needed to detect slight, dynamic temperature changes of 0.05 °C.



Trends

- Infrared imaging is already used successfully in many fields, and the number and range of applications is increasing steadily.
- Technologically, we see the same trends as in the visible spectrum. Future sensors will have:
  - Larger resolutions due to smaller pixel sizes (10-12 µm)
  - Higher frame rates as the Si-based Read-Out Integrated Circuits (ROIC) perform faster
  - Increased sensitivity and quality due to improving technology (materials, semiconductor manufacturing processes, etc.)

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I would like to acknowledge the many talented colleagues who contributed to this presentation but shall not attempt to name each here – Thank you!