Seeing Beyond the Visible

Doug Malchow

Manager, Industrial Business Development

Goodrich Corporation

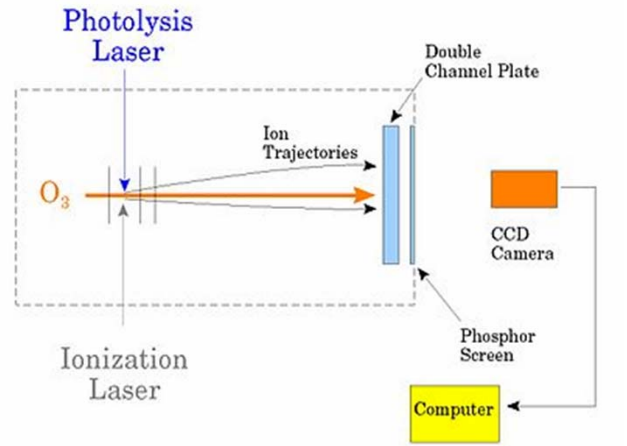
ISR Systems - Princeton

Outline

- What is imaging? (If you can't see it, does it still exist?)
- What enables imaging: The Electromagnetic spectrum
- Imaging band descriptions and examples
  - Gamma radiation
  - X-ray radiation
  - Ultraviolet radiation
  - Visible radiation
  - Infrared radiation and sub-bands of NIR, SWIR, MWIR and LWIR
- SWIR Imaging
  - Why use?
  - Where used?
    - Application examples
- Summary

What is Imaging in any Band?

- Making a visual representation of an *object* by scanning it with detector(s) or electromagnetic beam(s), or by passing an object between detector(s) and beam(s).
- It is a function of the *object* modifying the energy by passing, absorbing, reflecting or scattering the beam(s) resulting in creating a difference map for display for a human to view or for a computer to analyze
- The recorded differences are relative and influenced by everything in the beam path
  - The energy source,
  - The medium it passes through to get to *object*,
  - The *object* being imaged, which effects the beam.
  - The medium the energy passes to get to the detector,
  - The elements used to collect or focus
  - The detector



- These influences can be calibrated to take out non-uniformities or to measure the energy in absolute units

http://en.m.wikipedia.org/wiki/Photofragment-ion_imaging

Energy Source Emits

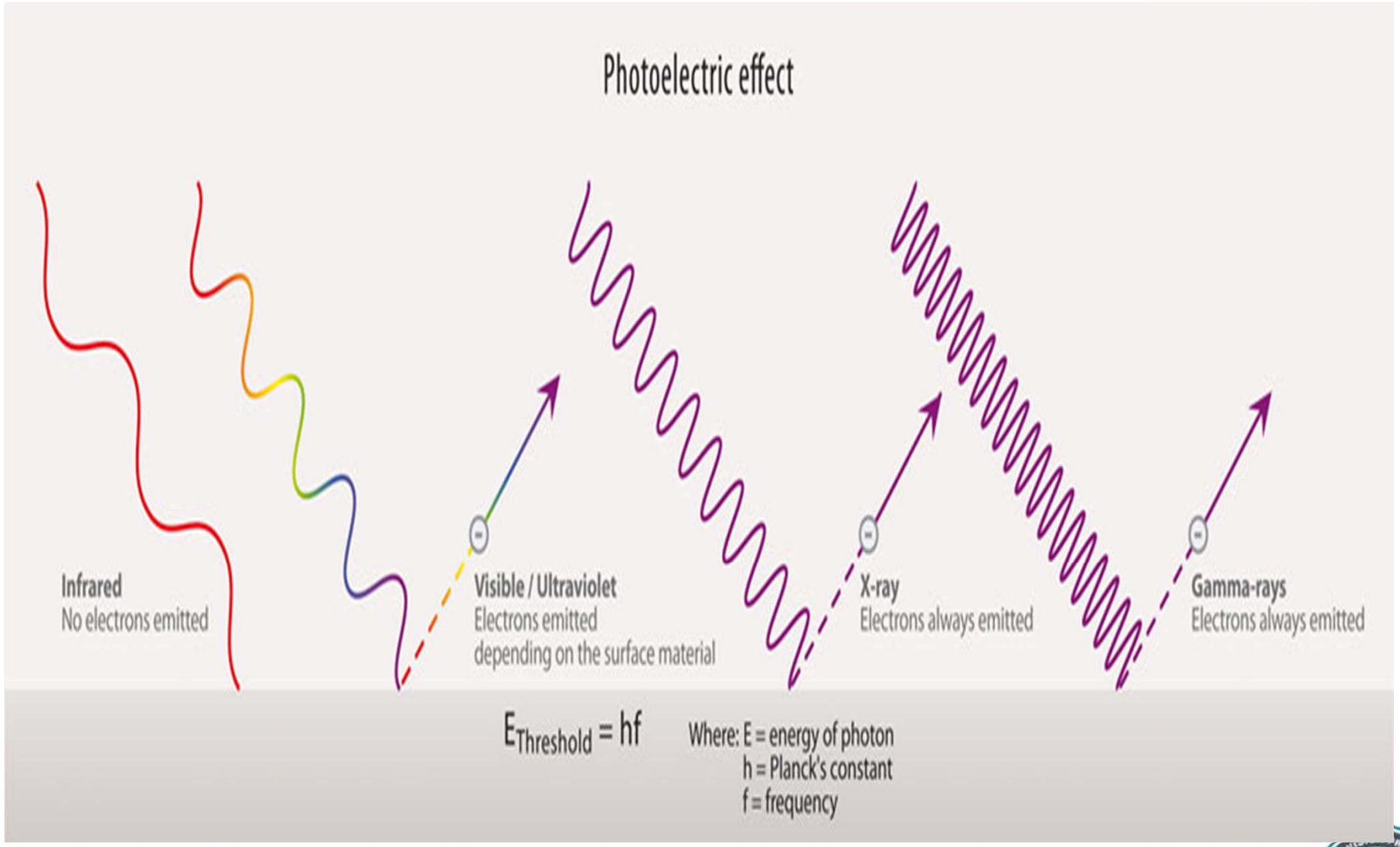


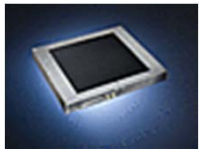
Image courtesy of ESA / AOES Mediala
Microsoft clip art

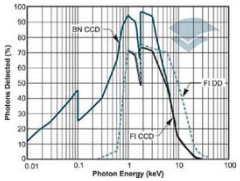
Interacts with Stuff

http://missionscience.nasa.gov/ems/03_behaviors.html
http:// marketplace.secondlife.com
http://www.flickr.com/groups/strobist/discuss/72157600866439843/page2/

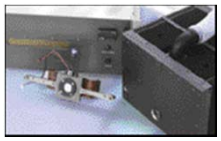
Is Detected

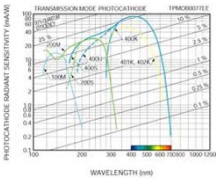
Gamma and X-ray



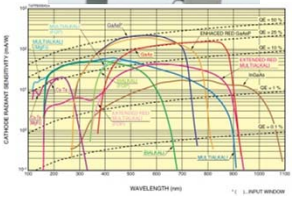


Deep UV



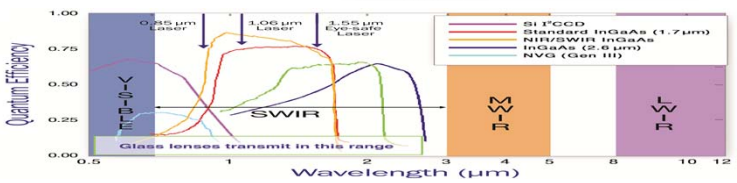


UV - Visible - NIR



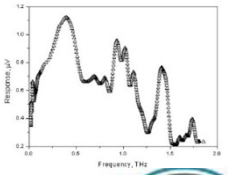
SWIR

MWIR



LWIR

TeraHertz



Is Displayed

Gamma and X-ray

Deep UV

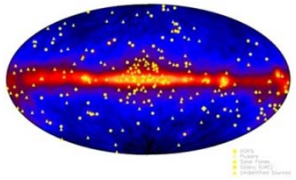
UV - Visible - NIR

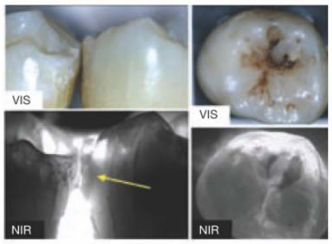
SWIR

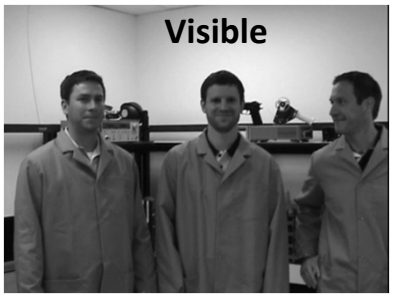
MWIR

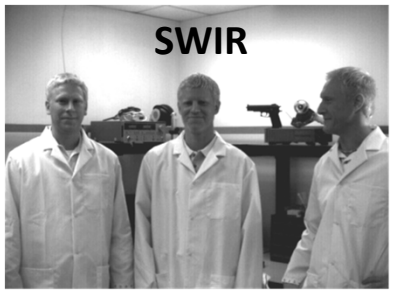
LWIR

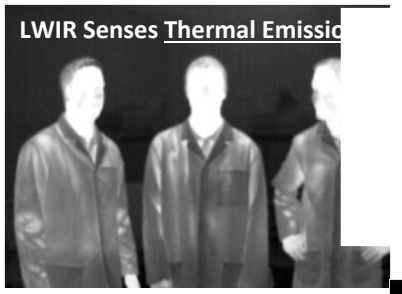
TeraHertz

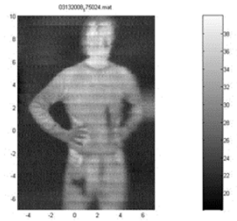




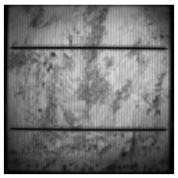


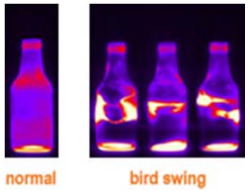


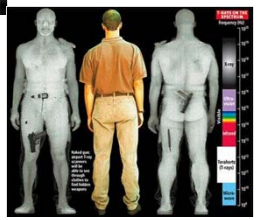


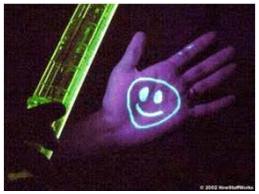


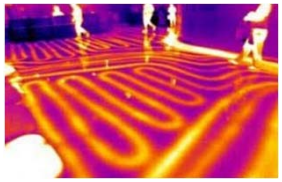
Car paint
Bruises
Fingerprints

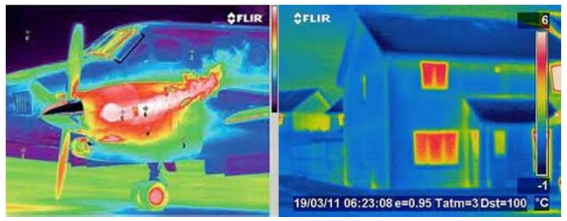




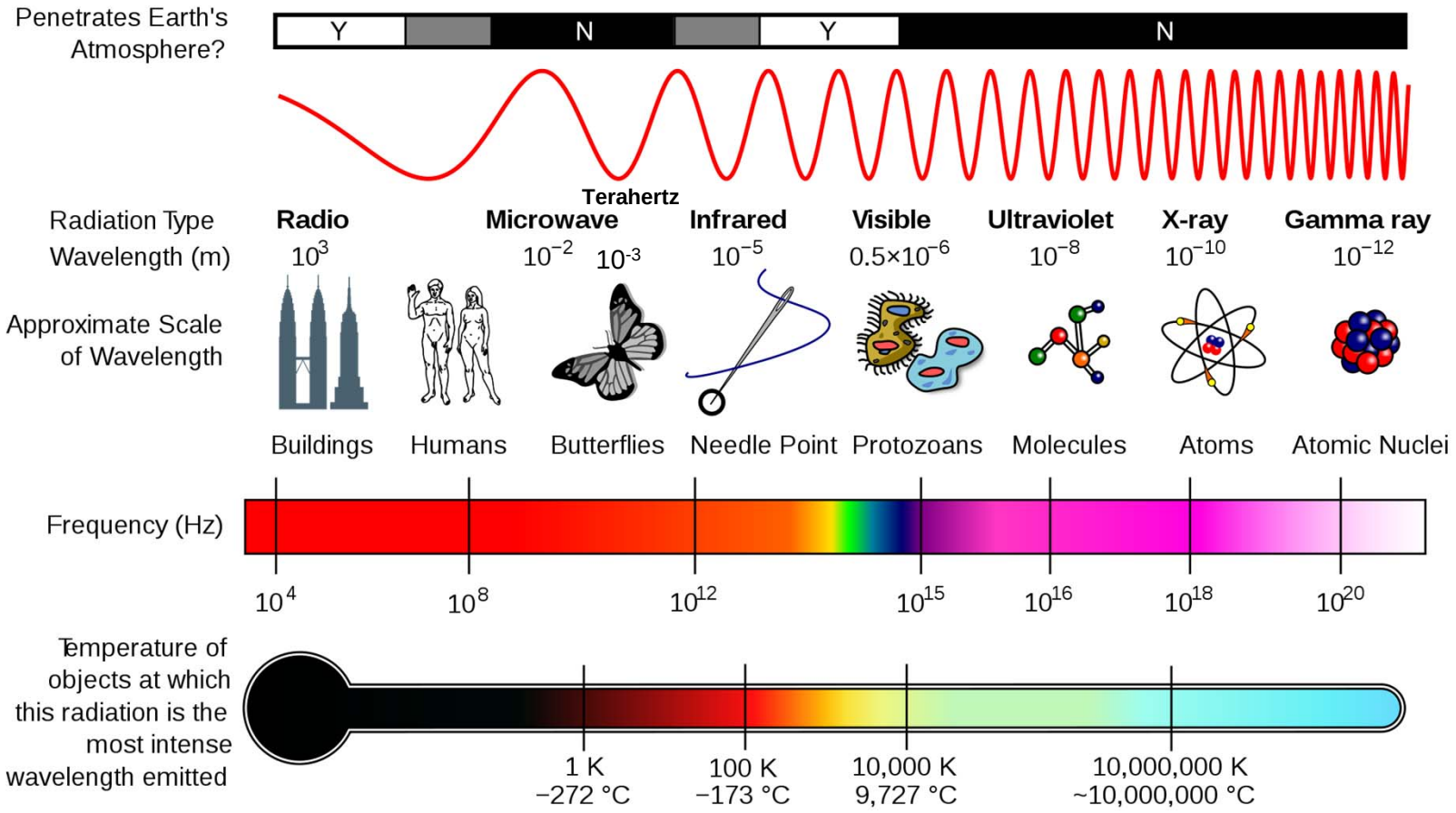








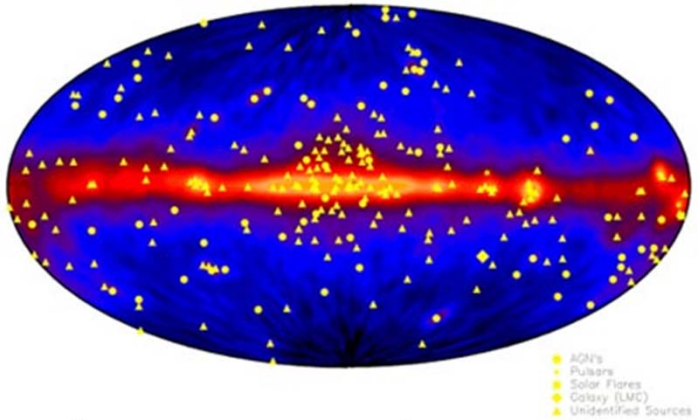
Electromagnetic Spectrum

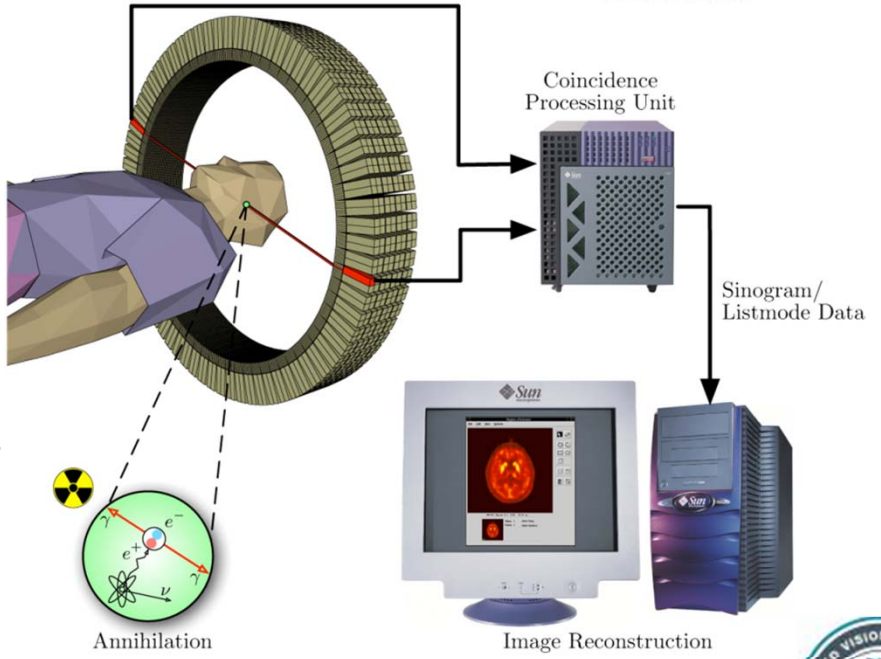


Source: http://en.wikipedia.org/wiki/Electromagnetic_spectrum

Gamma Rays

- The most energetic photons,
- Produced by radioisotopes
- No defined lower wavelength limit
- Use for imaging by:
  - Astronomers to study high-energy objects or regions
  - Physicists due to the penetrative ability
  - Doctors for PET scans
    - Isotope inside person emits gamma ray
    - Scintillator converts to visible for CCD

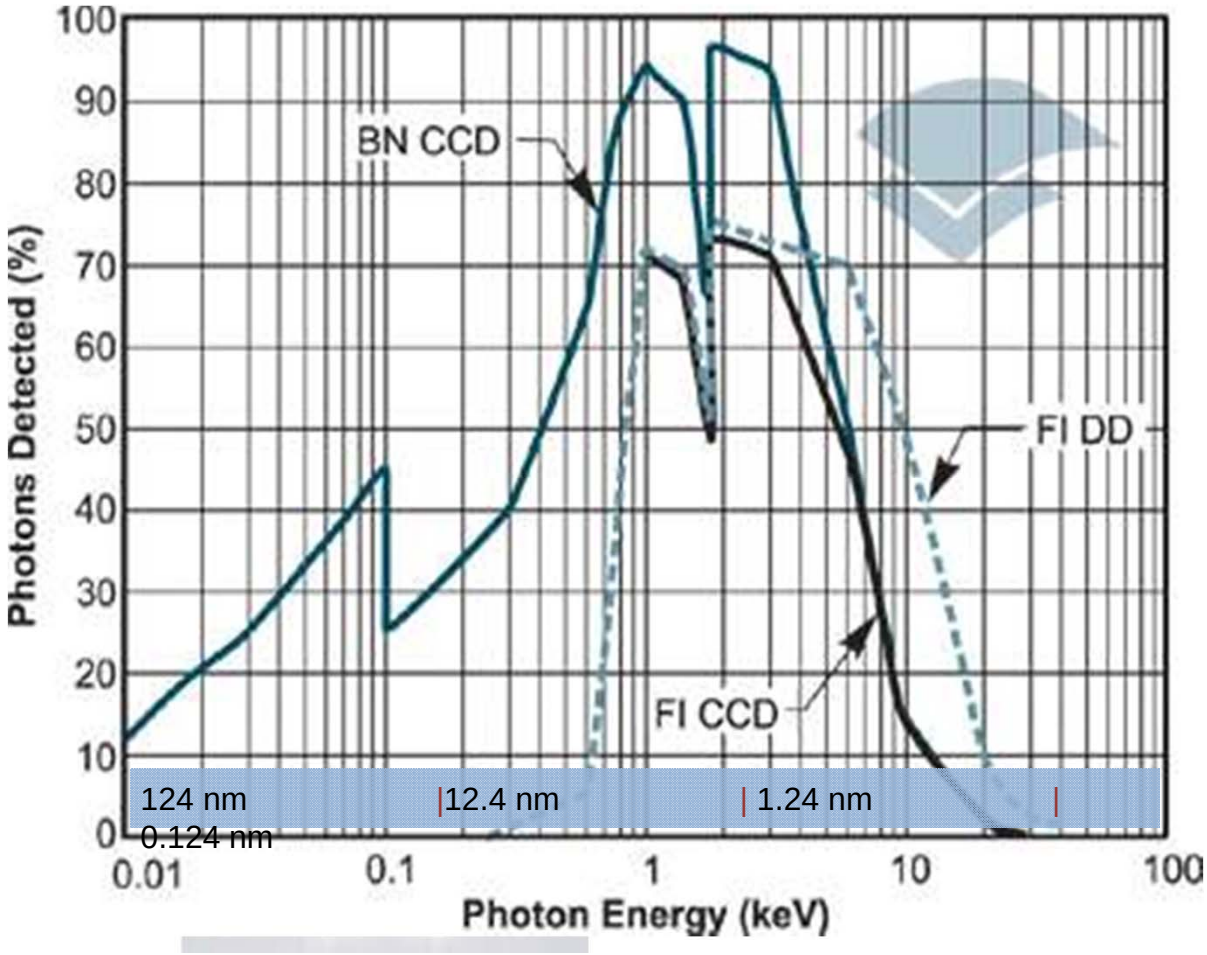




http://science.hq.nasa.gov/kids/imagers/ems/gamma_ray_sky.jpg
http://en.wikipedia.org/wiki/Positron_emission_tomography

X-rays

- Lower energy, but longer wavelengths than Gamma
- Also ionizing.
- Hard X-rays have shorter wavelengths than soft X-rays.
- Used to ‘see through' objects:
  - Radiography for diagnostic images in medicine
  - Homeland security
- Imaging high-energy sources in physics and astronomy:
  - Neutron stars
  - Black holes
  - Some types of nebulae



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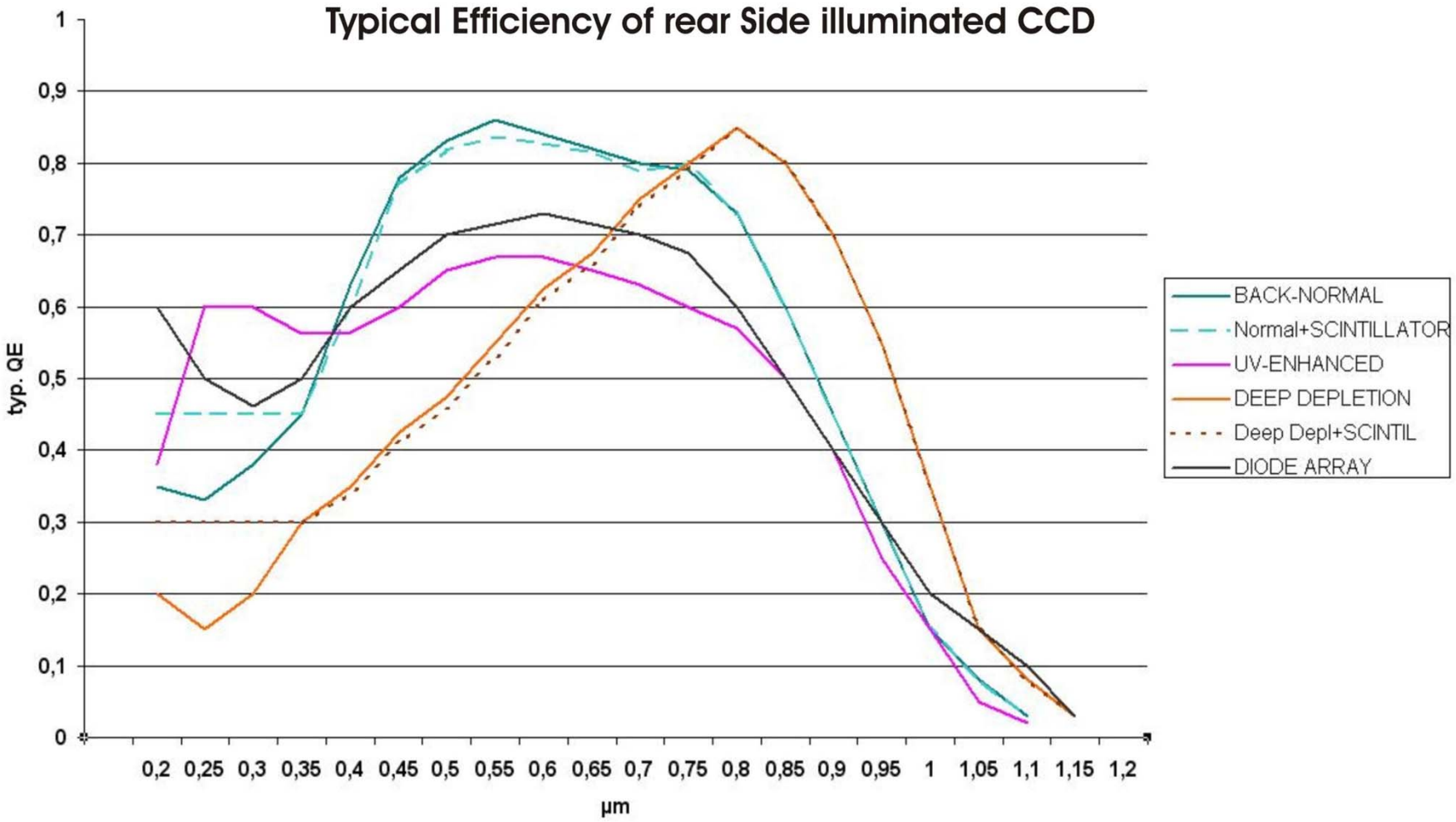
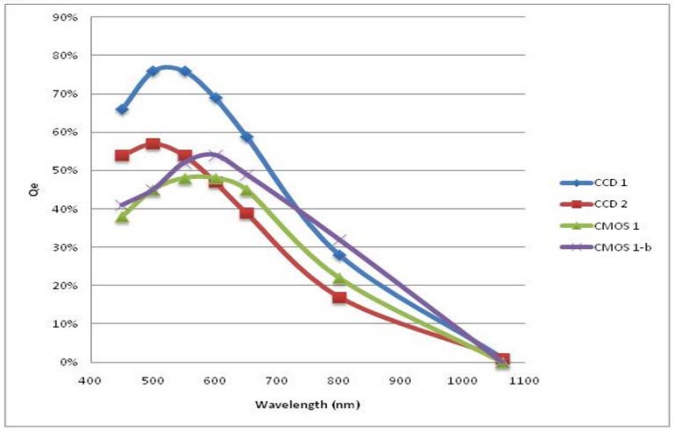
UV Imaging

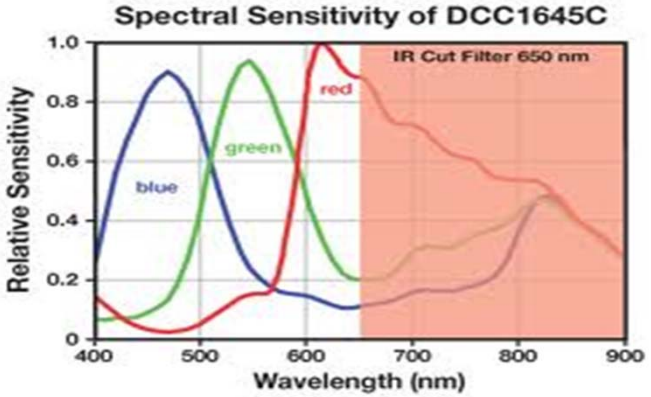


http://www.stanford.edu/group/pandegroup/folding/education/papers/nature02.html
http://www.uvcamera.com/Faraghan%20Medical%20Camera%20Systems/Welcome.html
BI CCD QE © http://www.spectra-magic.de/E-Detectors.htm

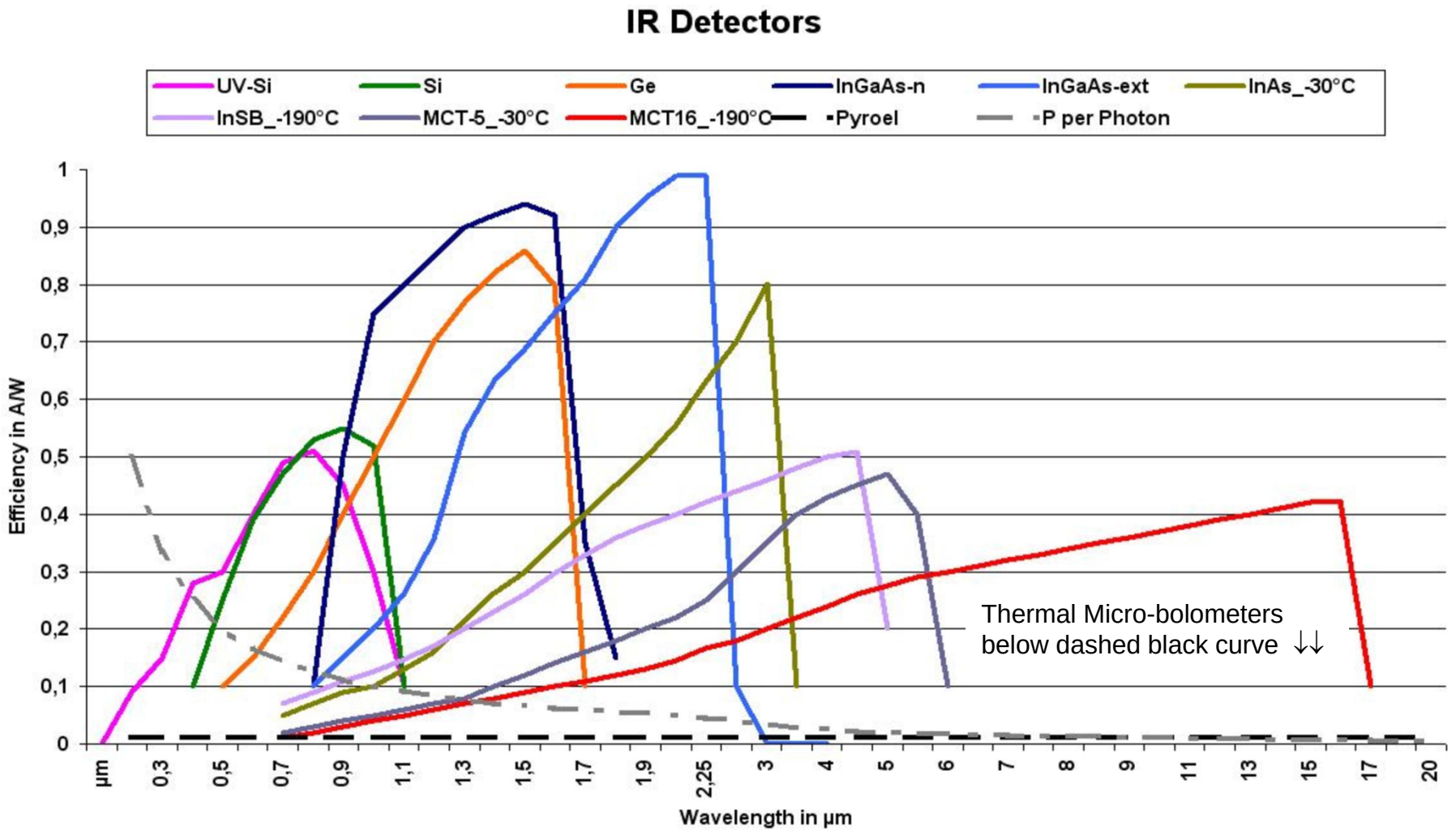
Visible

- Visible light and near-infrared light is absorbed and emitted by molecules and atoms as the electrons move from one energy level to another.
- Wavelengths between 380 nm and 760 nm (790–400 terahertz) are detected by the human eye as visible light.
- White light is a combination all the wavelengths in the visible spectrum.
- Passing white light through a prism splits it up (refracts) into the rainbow.
- Silicon detectors respond from 200 to 1100 nm; Back illuminated CCDs have highest QE, lowest noise.



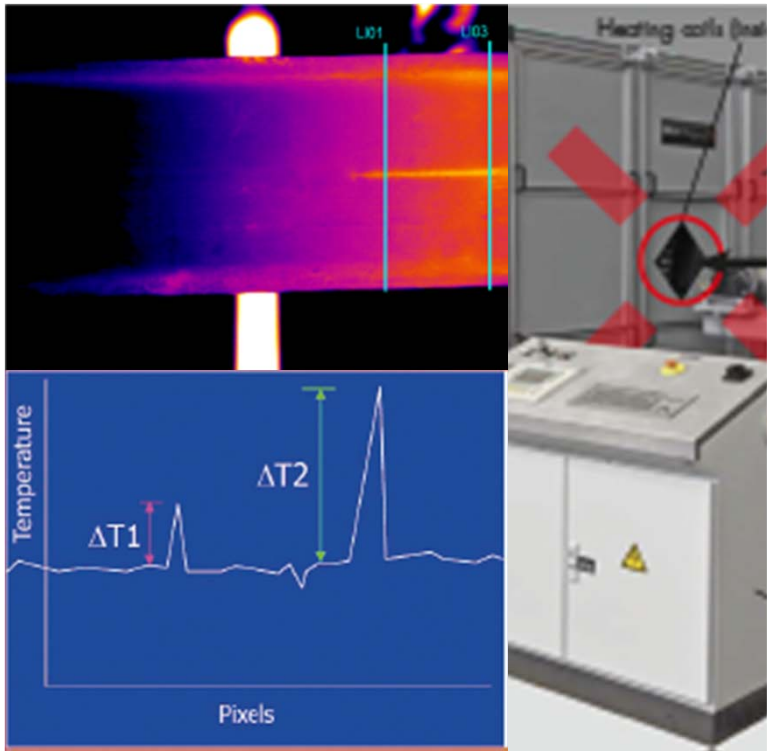


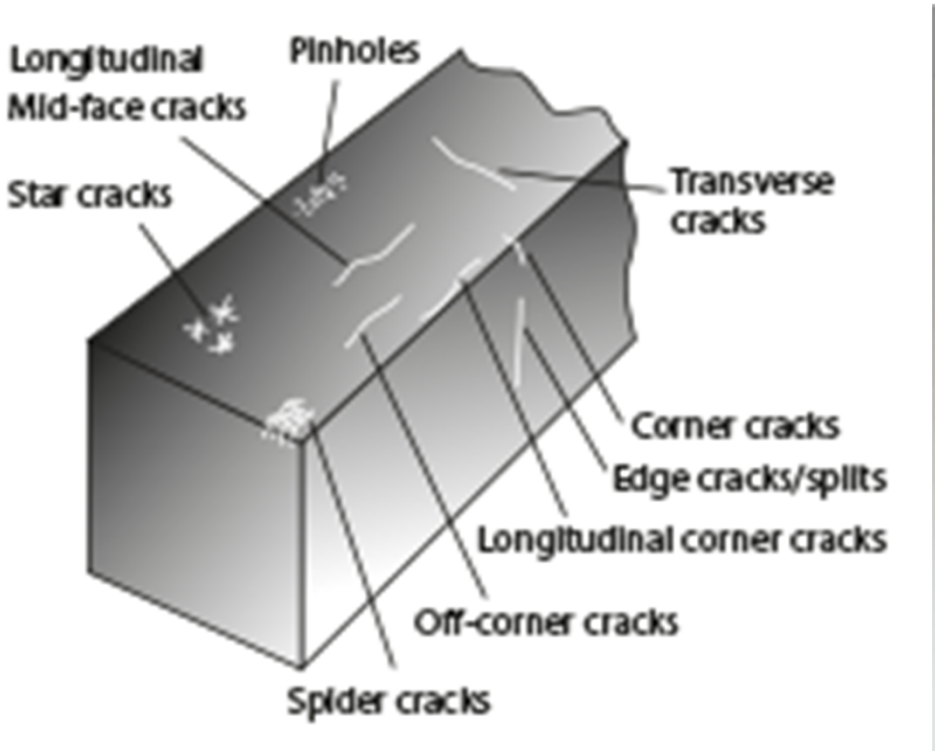
Infrared



Infrared - Thermal

Thermal MV

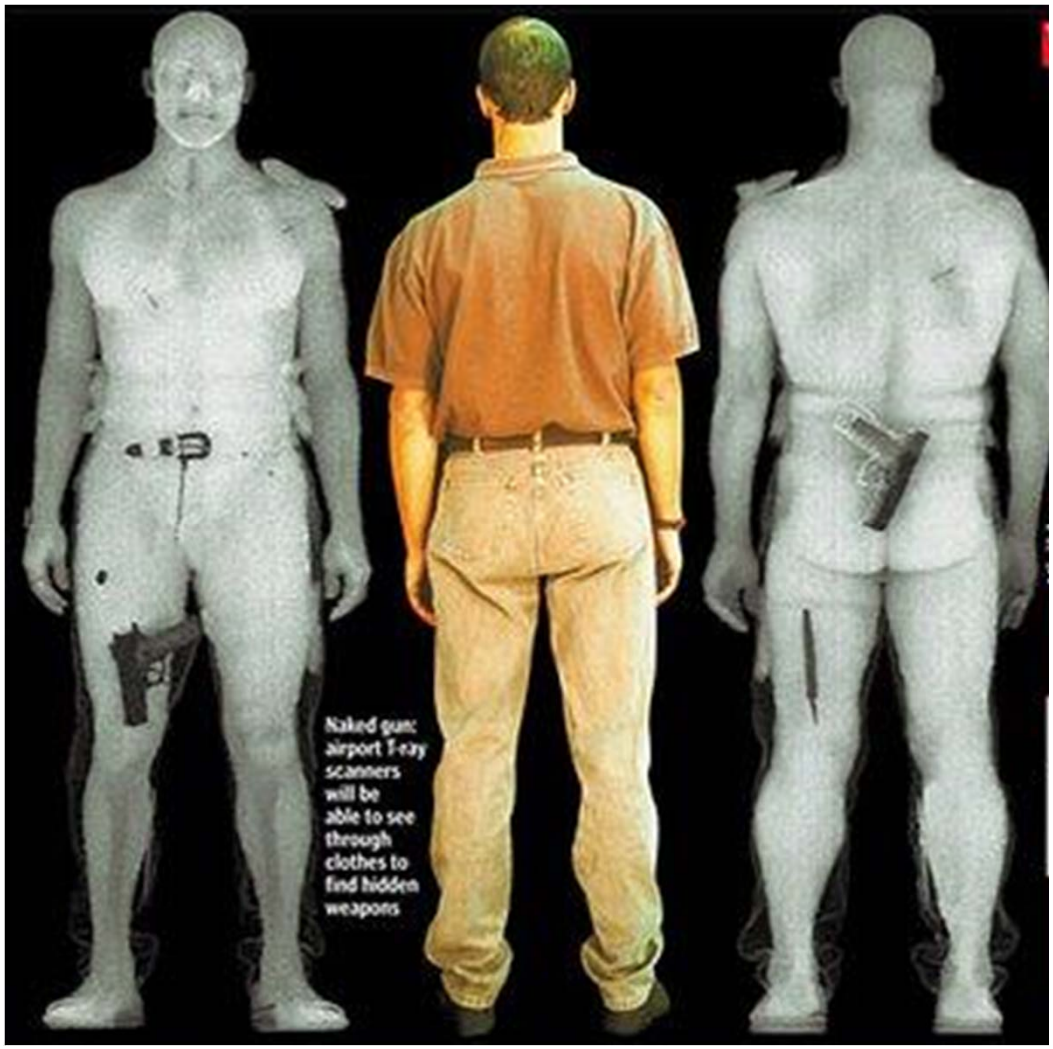




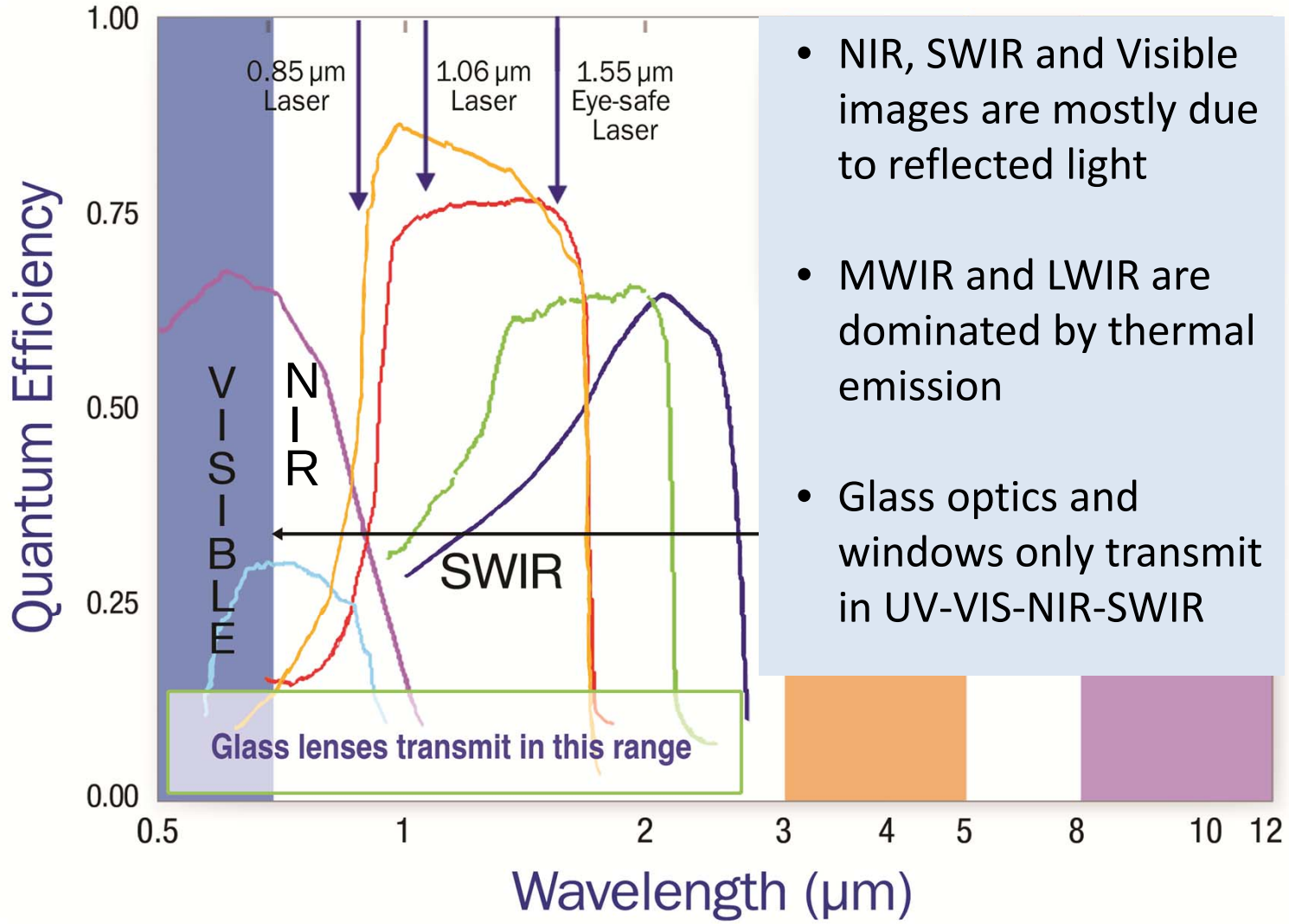
- **FLIR Application Stories – Automation**
  - **raw steel quality**
- http://www.flir.com/cs/emea/en/view/?id=42180

Terahertz

- 0.1 mm (or 100 μm) infrared to 1.0 mm microwave aka the long-wavelength edge of far-infrared light.
- From 3000 GHz (3×10^{12} Hz or 3 THz) to 300 gigahertz (3×10^{11} Hz or 0.3 THz), aka high-frequency edge of the microwave band.
- The THz band straddles region of wave-like characteristics (microwave) and particle-like characteristics (infrared).



Infrared Wavelength Bands



- NIR, SWIR and Visible images are mostly due to reflected light
- MWIR and LWIR are dominated by thermal emission
- Glass optics and windows only transmit in UV-VIS-NIR-SWIR

Why Use SWIR Wavelengths

- **Reduced Scattering** - Longer wavelengths penetrate obscuring layers (haze, fog, smoke)
  - Small particles (relative to light wavelength) scatter short wavelengths heavily (Rayleigh scattering model)
  - Medium particles scatter proportionally to wavelength (Mie scattering model)
  - Large particles scatter all wavelengths
- **For Chemical ID** - Molecular vibrations absorb light in unique wavelength bands
  - SWIR bands easily observed remotely with diffuse reflected light
  - No sample preparation
  - Lower detector cooling needs less costly, more robust
- **For SWIR MV –** Sees contrast where visible cameras do not
  - illumination is non-interfering with visible cameras
- **For Telecom** - Fiber communications use SWIR wavelengths
- **For Silicon inspection** – Silicon and GaAs detectors become transparent and/or emit in SWIR wavelengths when excited

Applications

Military & Law Enforcement

- **Target Acquisition and Tracking**
  - **Munitions**
  - **Adaptive Optics**
  - **See-spot**
  - **Free Space Communication**
- **Surveillance/Passive Imaging**
- **Sniper detection and spotting**
- **Covert Illumination**
- **Range Gated Imaging**
- **Hyperspectral Imaging**
  - **Camouflage detection**
  - **Friend/Foe ID**
  - **Chemistry of explosives**

Commercial

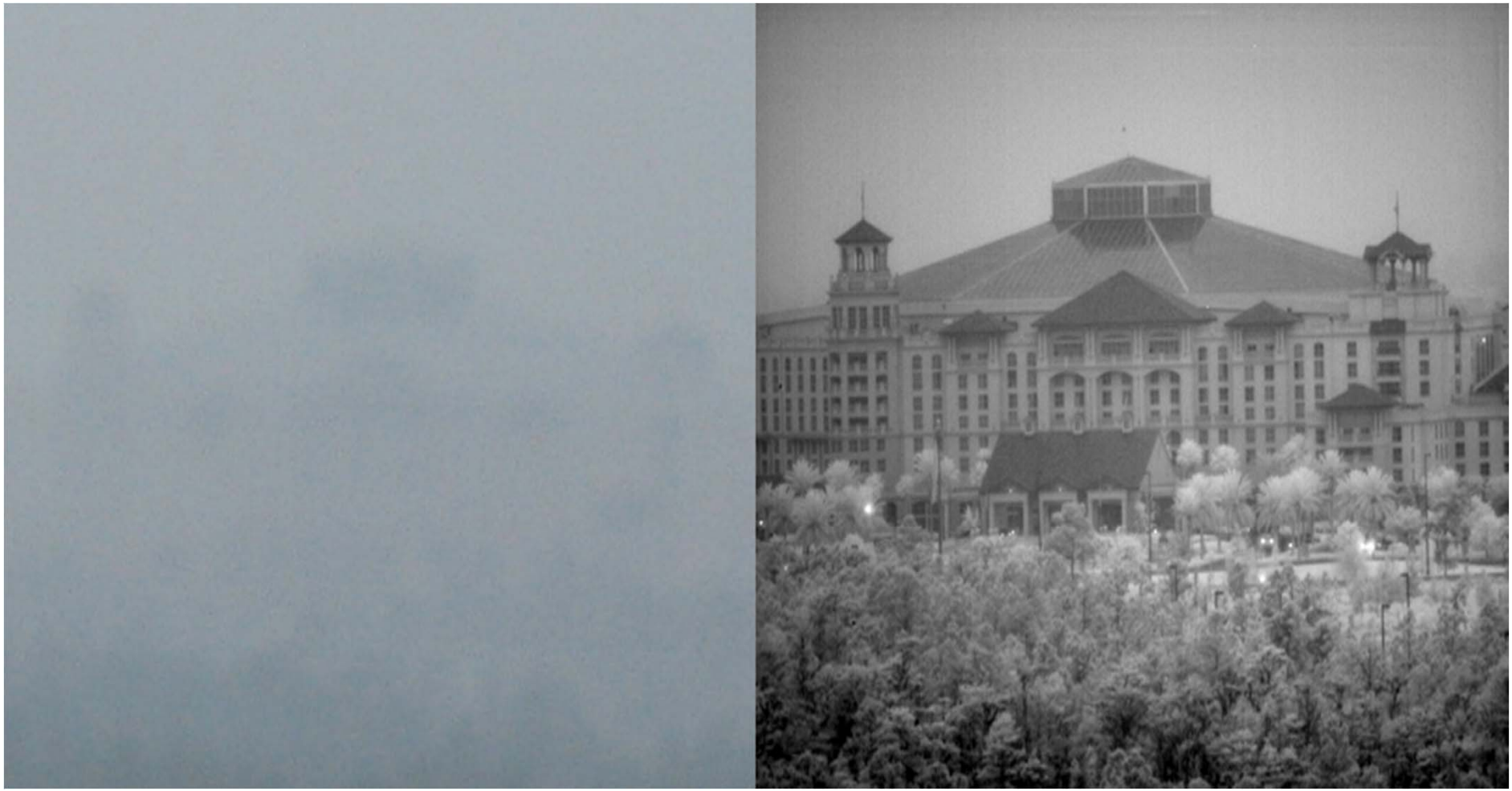
- **Inspection/Sorting**
  - **Agricultural products**
  - **Plastic Sorting**
  - **Pharmaceutical materials, QC**
  - **Semiconductors**
  - **Solar cell inspection**
- **Telecommunications**
- **Thermal Measurements**
  - **above 100ºC**
- **Spectroscopy**
- **Medical Imaging**
  - **Optical Coherence Tomography**
  - **Dental Trans-illumination**
- **Infrared Reflectography**
  - **Artwork**
  - **Ancient texts**

Two Major Industrial Segments

- **Imaging - Observing a scene to make an image**
  - Thermal analysis: metal smelting, furnace monitoring, hot glass processing
  - Machine Vision Inspection: agriculture, pharmaceutical, semiconductors, solar cell electroluminescence
    - Detect or see through coatings
  - Surveillance: Imaging through haze
  - Dentistry: Imaging caries and enamel erosion in teeth

- **Spectral - Looking at multiple wavelengths to conduct an analysis**
  - Biomedical: Optical Coherence Tomography, multi-spectral imaging
  - Telecommunication: Monitor multiple wavelengths simultaneously
  - Sorting: plastic recycling, agriculture product classification
  - General spectroscopy: scientific investigation, chemical ID

Seeing Through Haze – Orlando, Florida



Visible **SWIR**

Imaged in late afternoon in high humidity, 300 mm lens, 1.5 km distant

San Francisco Skyline – 3 km

- Haze penetration capability provides overall sharper image
- Significantly increases “seeing distance”

Seeing Through Dust – Pine Barrens, New Jersey

- Scattering is a strong function of both wavelength and particle size
- Short wavelength scatter to the 4^{th} power
- Long wavelengths attenuated linearly with size

Seeing Through Smoke Forest Fire – Mt. Hood

Cloud Cap Gimbal holds two cameras

Video switches back and forth from Visible to SWIR

This unique ability of SWIR applies to haze and fog, too!

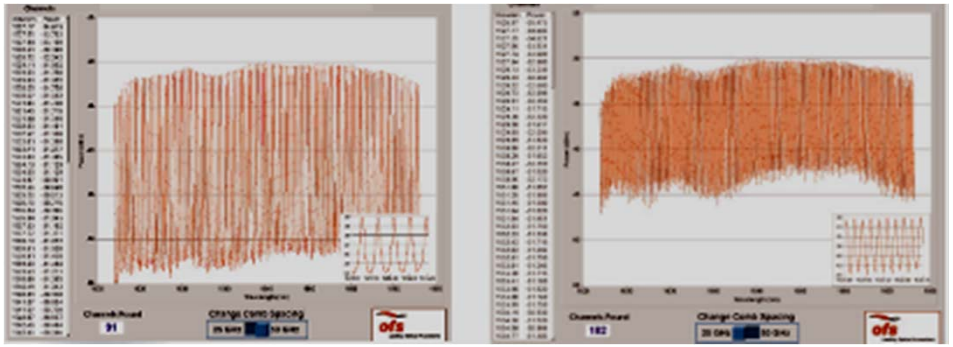
Smoker in SWIR

- Easily detected in cluttered environment
- Washington, DC
- October 2008/9:00 PM
- Range – 1000 ft
- Lens – 200mm SWIR optimized stopped to f8

Walking smoker stands out strongly!!!

Compact Spectral Engine

- Monitor and control WDM lasers
- Alignment of components
  - Arrayed Waveguide Gratings
  - Diode Lasers
- General Inspection
  - Light loss from waveguides
- High-speed data reception
- Stress monitoring via fiber

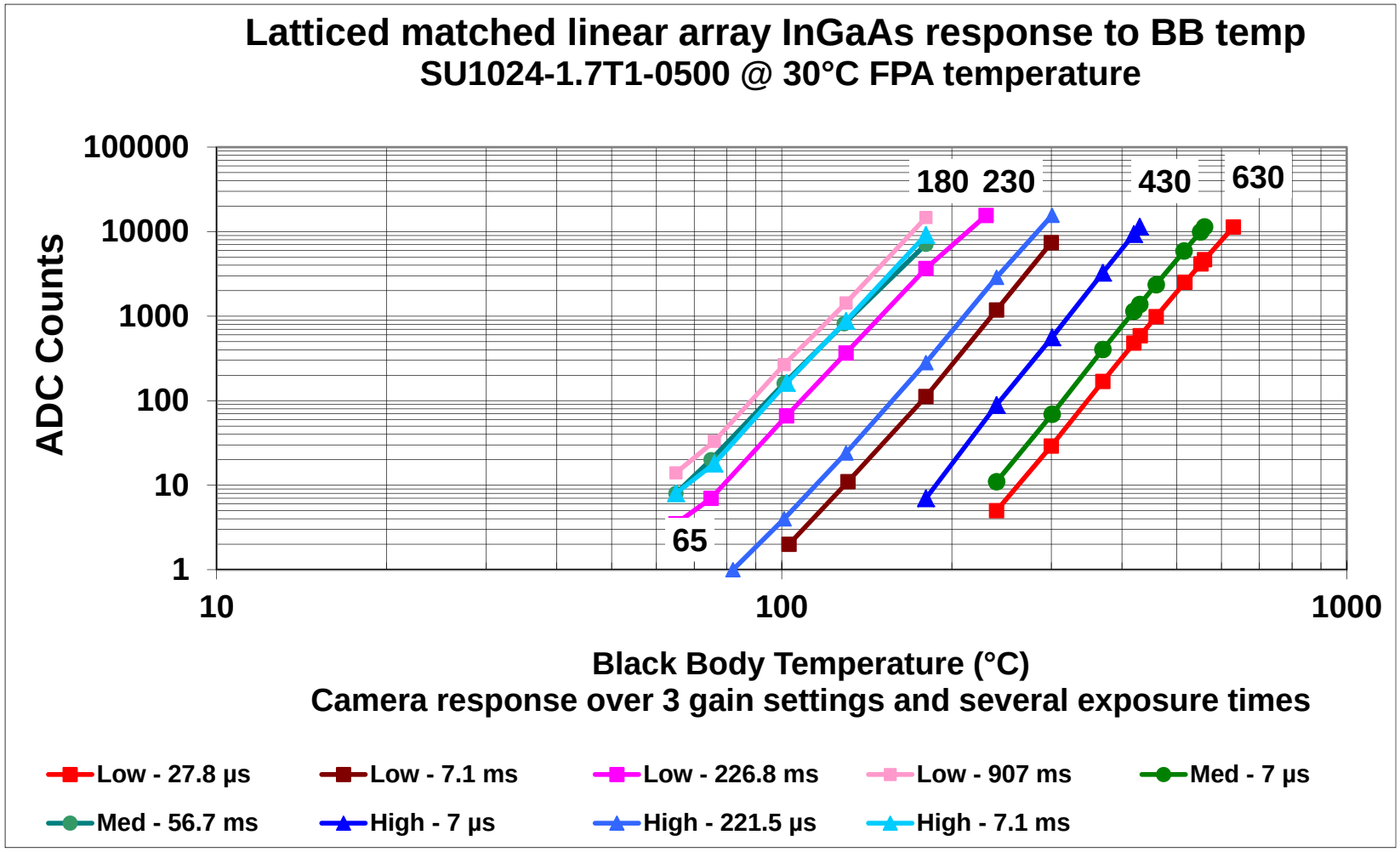


Industrial Process Monitoring

- Plastic Sorting
- Agricultural Sorting
- Fruit and Vegetable Inspection
- Seed Sorting

SUI line scan cameras

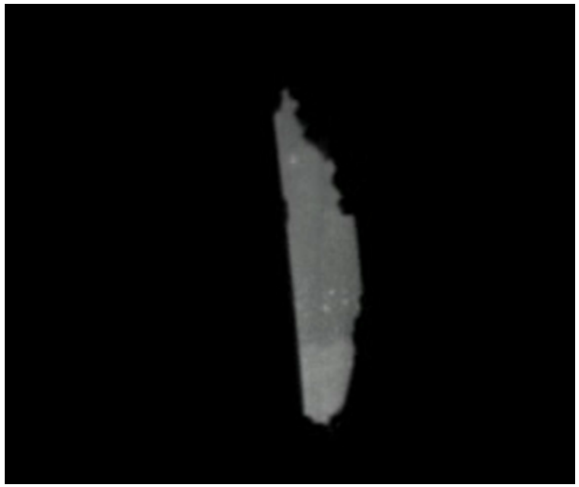
Temperature Sensitivity

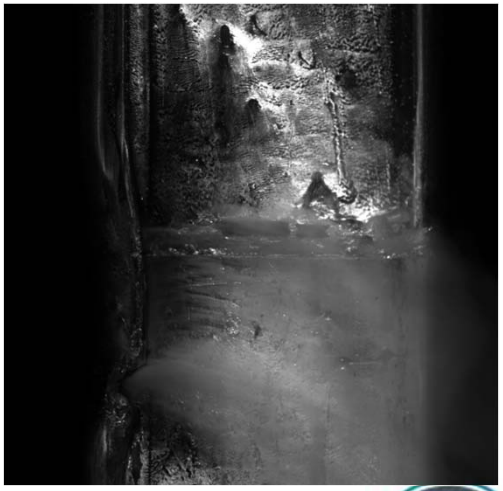


Lens at fixed f/1.4 aperture

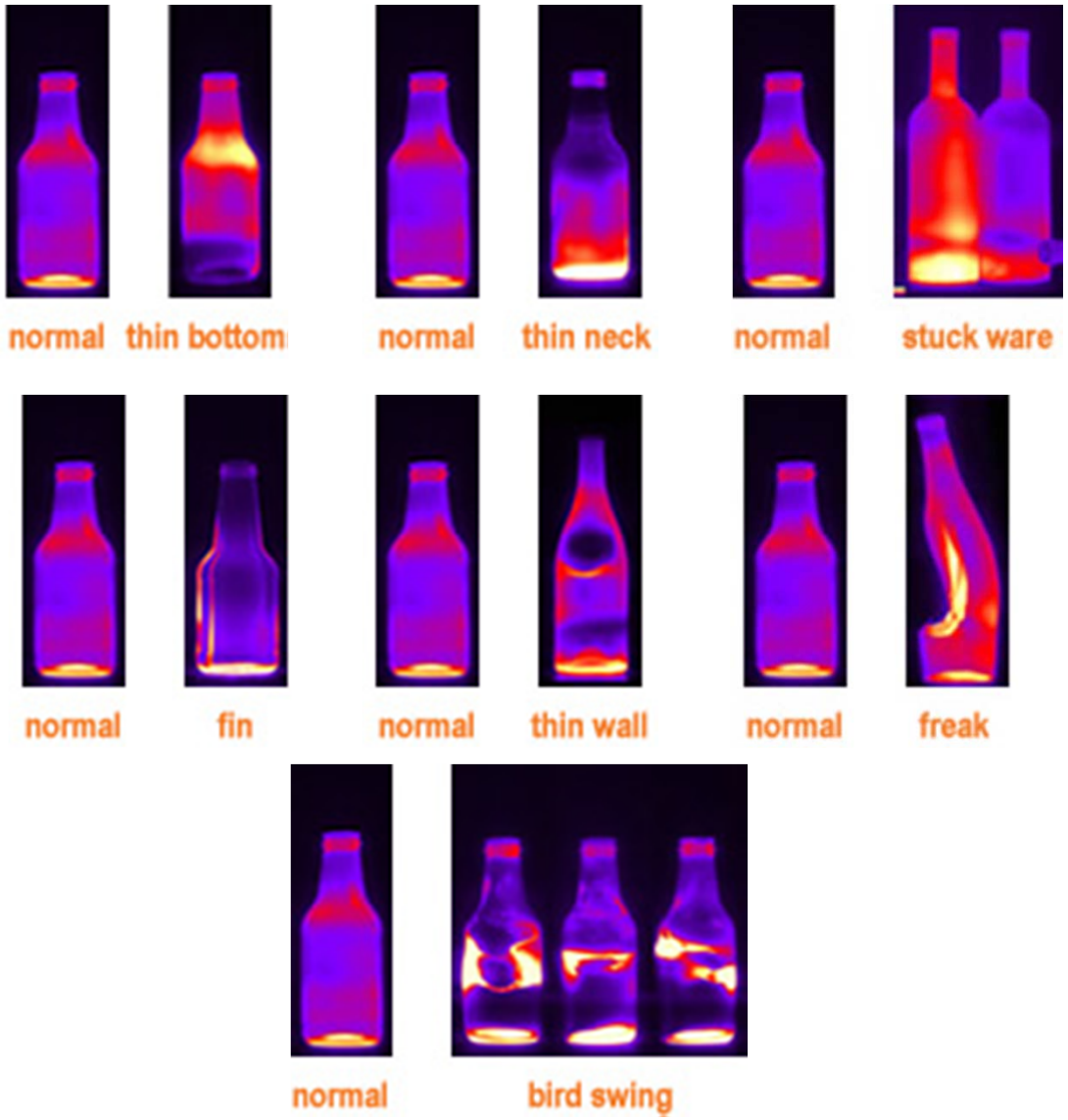
Industrial Thermal Imaging

- Lattice matched InGaAs is useful for imaging thermal processes above 100ºC
  - Too cold for silicon cameras
  - Glass is opaque at longer wavelengths
- Glass manufacturing
- Smelting of metals
- Furnace monitoring



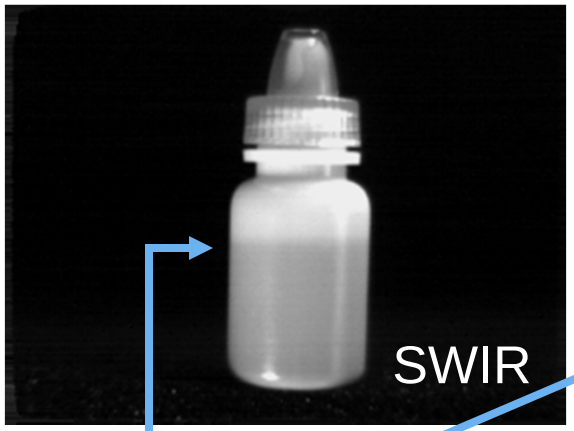


Hot Hollow Glass Mfg

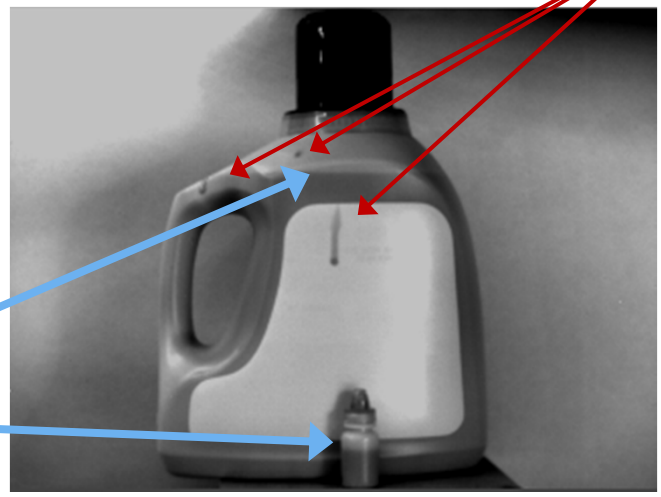


- Bottles placed on conveyor after molding
- SWIR images inside and outside
- Glass stringers difficult to image after cooled
  ←

Inspection Applications

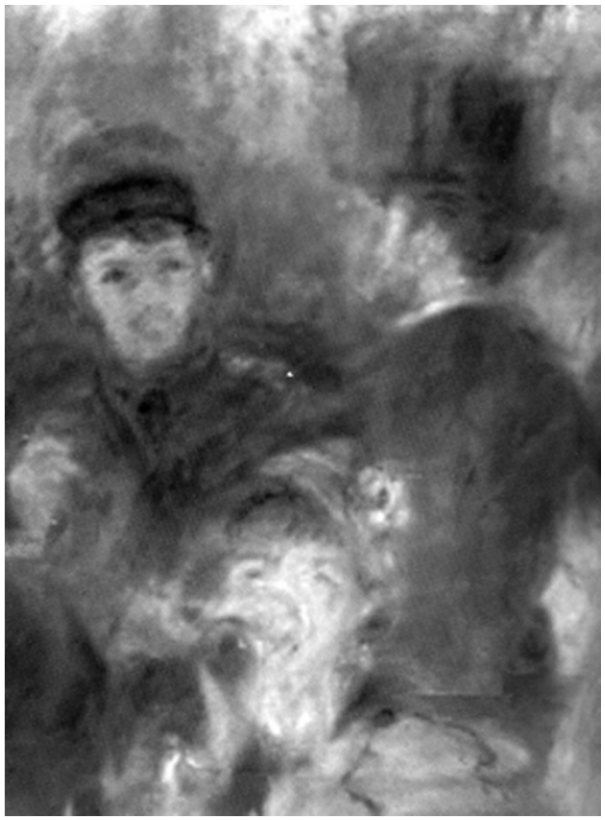


- Some plastics transmit SWIR light but are opaque to visible light
- Water based contents absorb in SWIR
- Product in bottle
- Product on bottle



Imaging through Paint

Art Research and Restoration



Renoir's Luncheon of the Boating Party

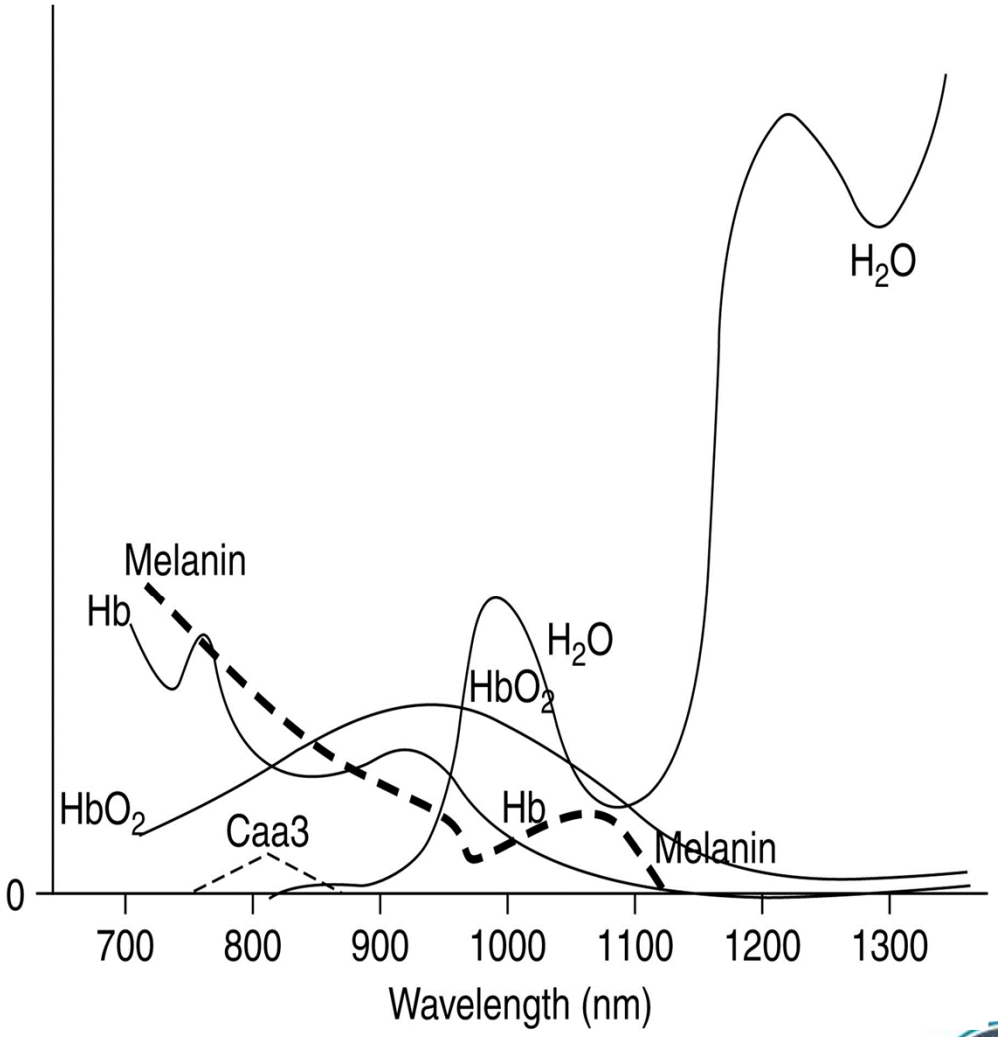
Courtesy of the Phillips Collection, Washington, DC

SWIR Penetrates Disguises and Makeup

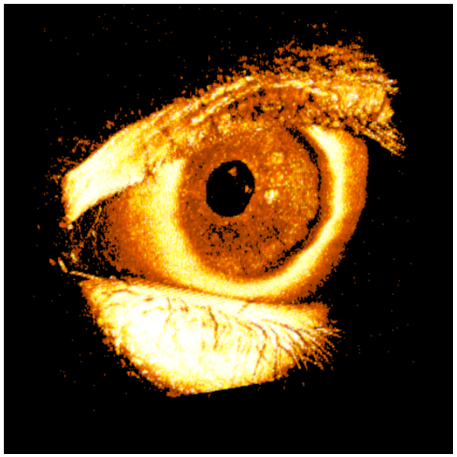
- The high reflectivity of natural hair makes it appear white
- Note the different materials in costume

NIR Therapeutic Windows

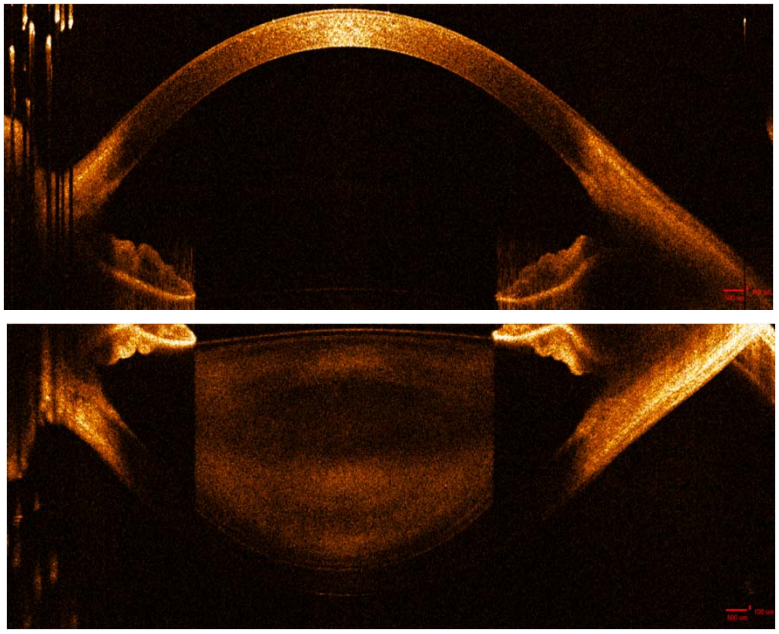
- Melanin in skin becomes transparent at 800 nm
- Water absorption has peaks at 980 and 1210, continues to rise logarithmically (shown x20 scale)
- Main windows:
  - 650 to 950 nm
  - 1000 to 1150 nm
  - 1250 to 1400 nm



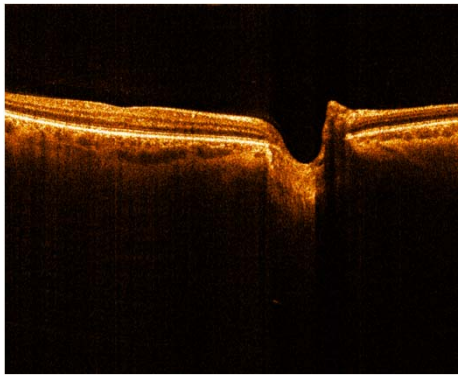
Optical Coherence Tomography



Above and center
8 mm image depth
13 µm axial resolution
1310 µm center wavelength



Top: from cornea to iris;
Below: lens and folded over cornea image

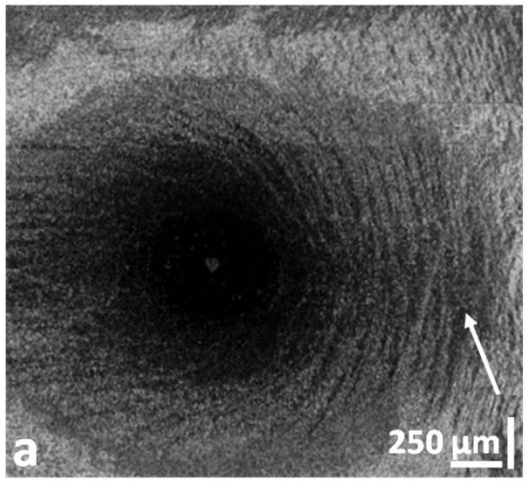


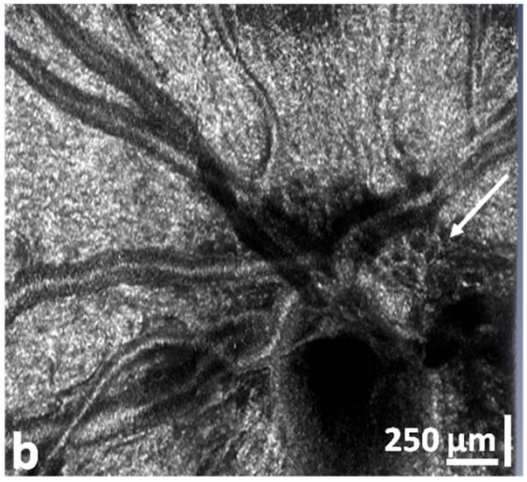
Above: retinal
6.3 mm image depth
11 µm axial resolution
1070 µm center wavelength

- Uses backscattered photons to capture structure versus depth
- Applications in the eye, blood vessels, throat, teeth, integrated circuits, composites
- High speed line scan cameras enable 3-D imaging in a blink

1060nm UHROCT of the Human Retina

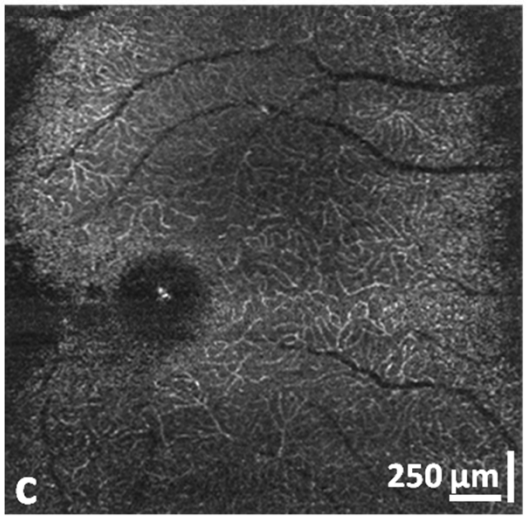
Healthy retina showing nerve fiber bundles (en-face)

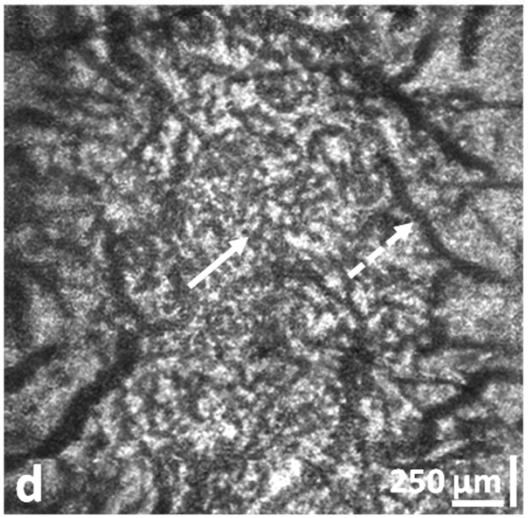




Optical Nerve Head showing arteries & veins (en-face)

Capillary network in ON Head (en-face)

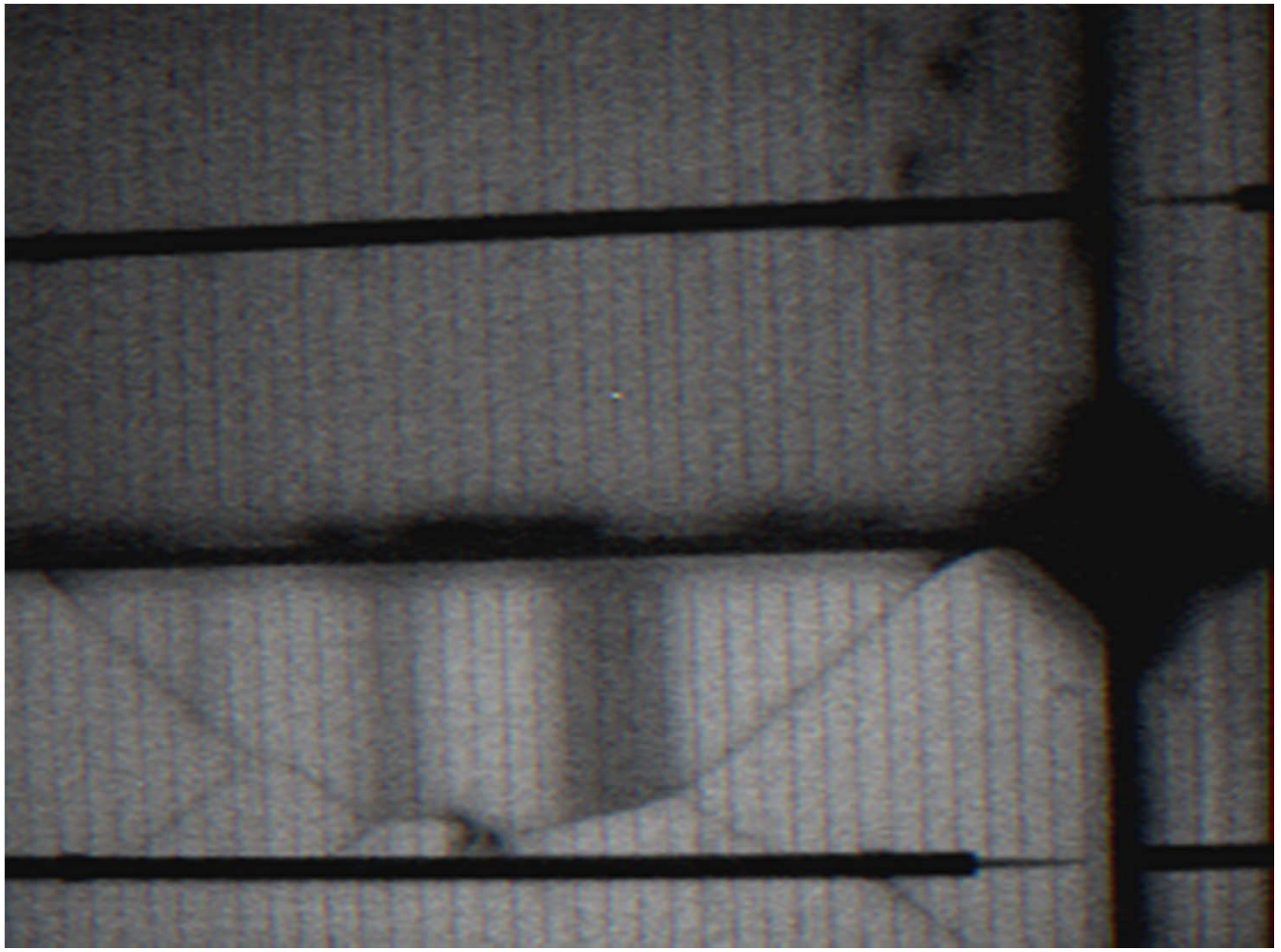




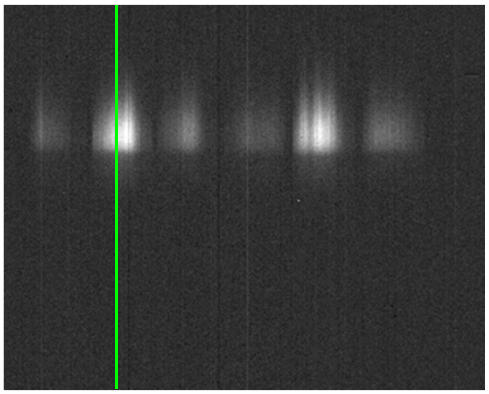
Chorio-capillaries network (deeper image at edges shows larger vessels)

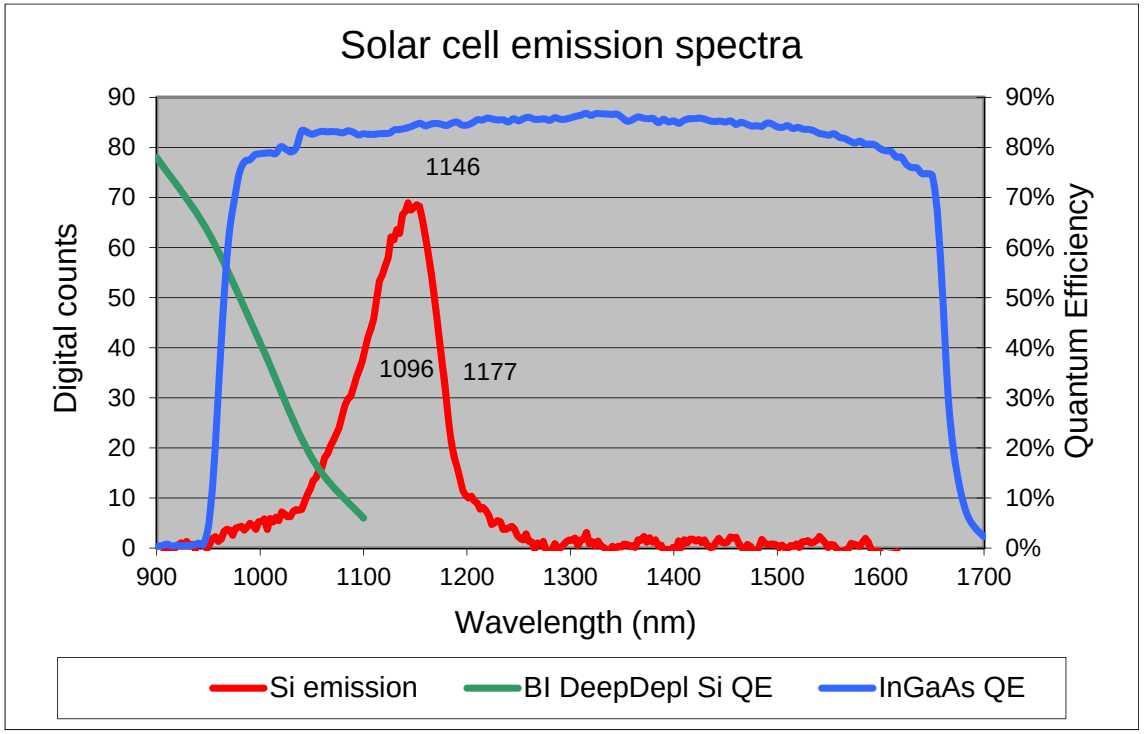
Electroluminescence: Panels

- Commercial panel
- Cracks and non-uniformities revealed
- Bias of 18.3 V at 2.8 A
- Close up of cracked cell shows cracks, dead regions, and defects on the upper cell



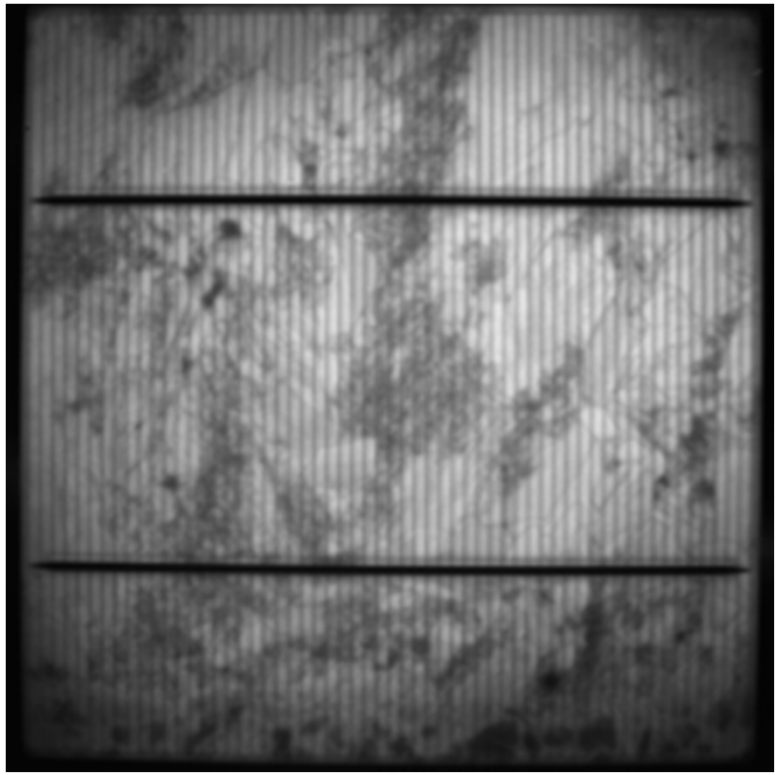
Si Electroluminescence



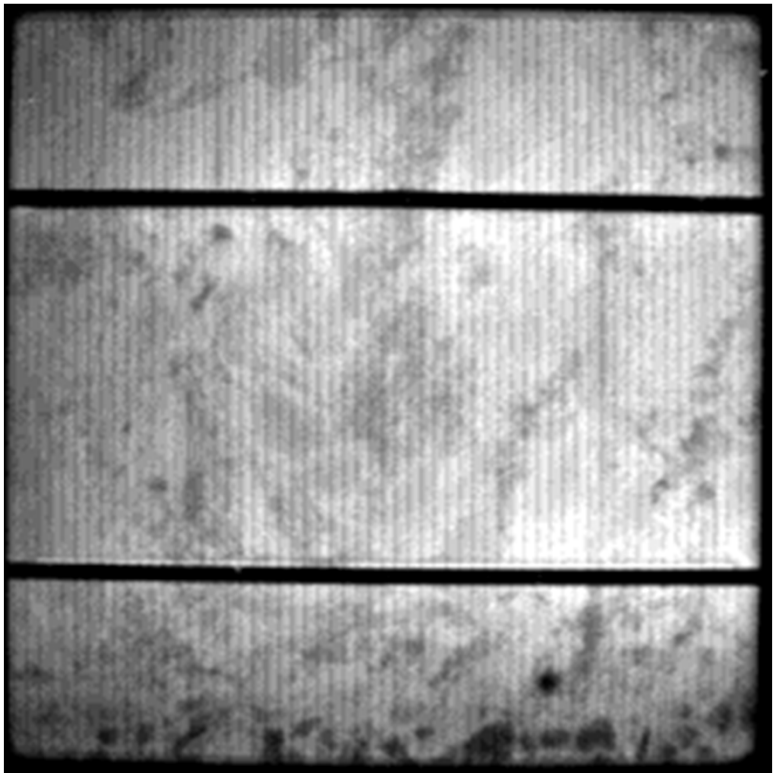


- Imaging spectrograph of 2nd cell on lower row of cells
- Emission at bandgap of silicon
- Spread (width) indicates structure is not pure mono-crystalline

Photoluminescence Inspection Finished Cell



PL - SWIR 16 ms exposure time

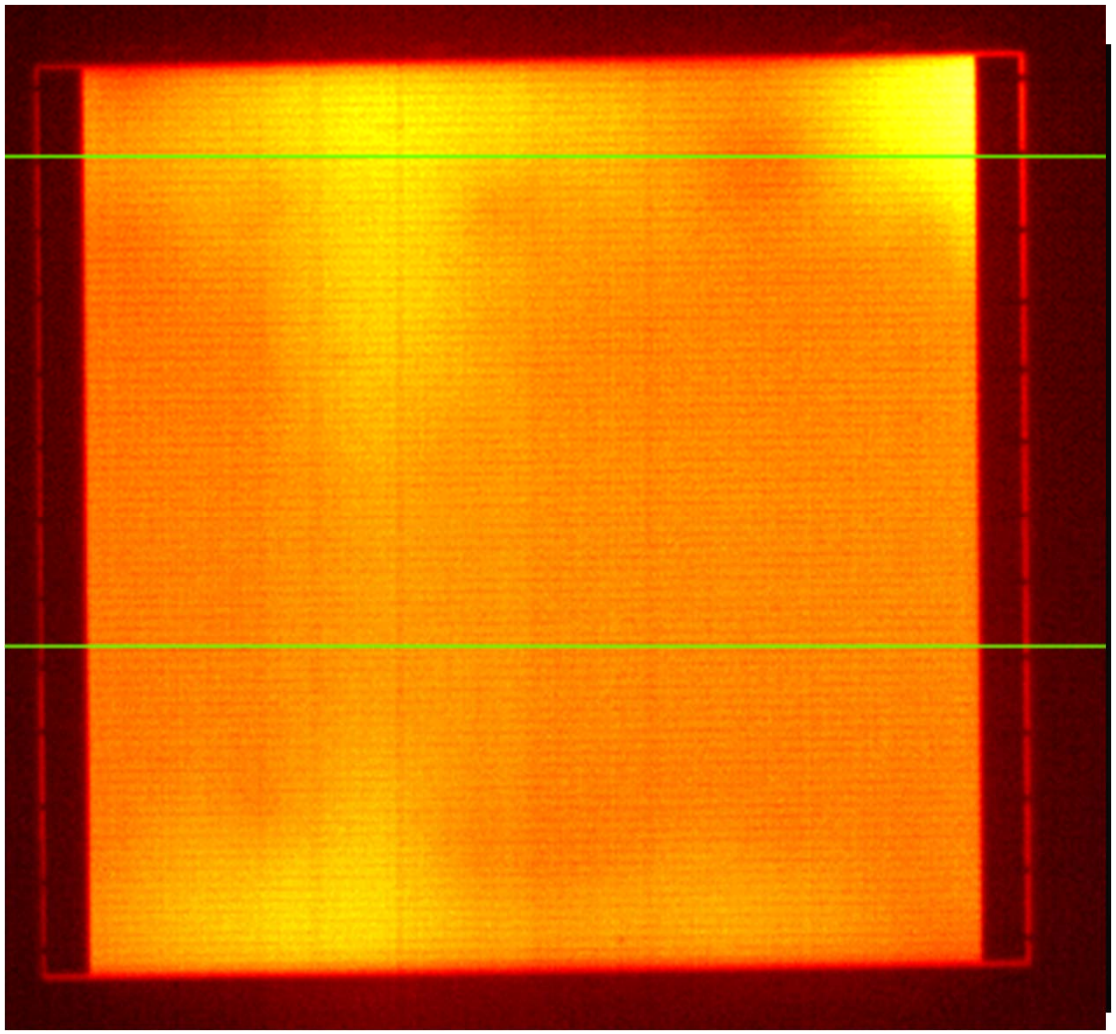


PL - Silicon BI CCD – 1 second ET
EL w/1.5 V bias – SWIR 16 ms

- Flood illuminated with ~30 W of diffuse laser light at 810 nm
- Filtered with 1000 nm long pass filter – 1 for SWIR, 3 for CCD
- PL is non-contact; EL requires electrical connections

Multi-spectral Triple Junction EL Inspection

- Three layers, each with own luminescence:
  - GaInP @ 700 nm
  - **InGaAs @ 940 nm**
  - Ge @ 1550-1800 nm
  - Top layer shows more point defects than other layers
  - Some appear in all three
    - likely surface dig or dust
  - Uniformity similar but different for each layer
  - Line scan camera

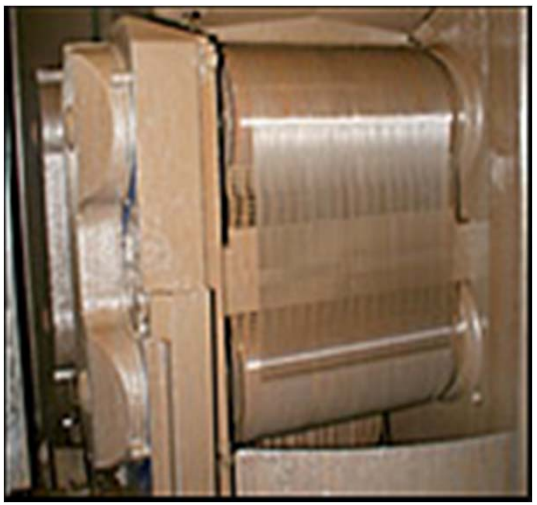


Imaging through Silicon Bricks, Ingots

How pure is your material?

Who will do the inspection?

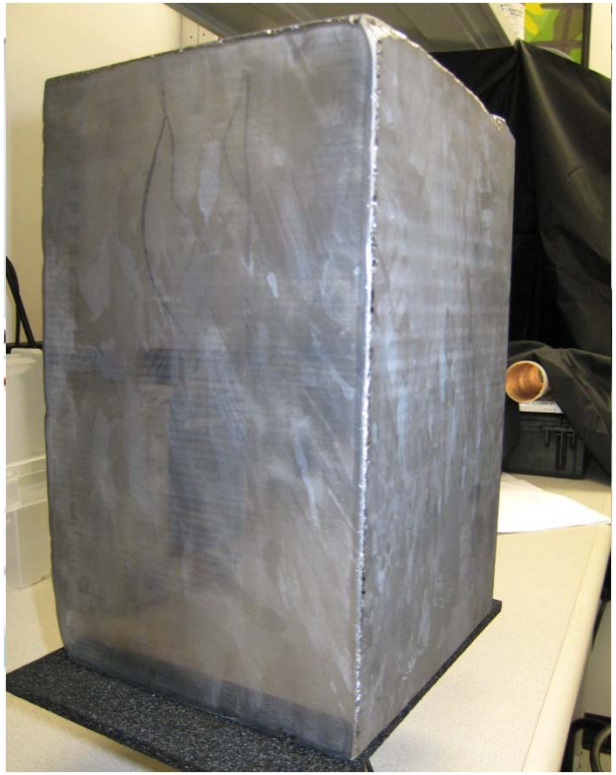
Raw material producer or cell manufacturer?



Eliminate the waste prior to the slicing and dicing process!

Imaging through Silicon Bricks, Ingots

High Quality Silicon Brick cut from larger ingot and polished on one face



Rotated polished side to camera: sharper image

Maglite flashlight 36” from backside of the block. AF Chart against backside of block.

6”x6”x10” Brick

SWIR Summary

- The short wave infrared covers the wavelength range from 0.7 to 2.5 microns
- InGaAs detectors cover much of this range, enabling small cameras with low power and weight because of high sensitivity at room temperature for SUI process
- Imaging in the SWIR is different from visible imaging due to differences in optical scattering, and spectral absorbance
- Imaging in the MWIR and LWIR is different from SWIR in that the thermal emission of objects dominate the scene, rather than reflection of ambient light
- SWIR machine vision inspection applications help to:
  - see ‘invisible’ transparent coatings,
  - see through opaque coatings,
  - see through silicon,
  - sort materials, agricultural products, and pharmaceutical chemicals
  - Align and monitor the telecommunications network

Contact Information

UTC Aerospace Systems

Douglas Malchow
Manager, Industrial Business Development

Sensors Unlimited, Inc.
3490 US Route 1, Building 12
Princeton, New Jersey
USA

Phone: (609) 524-0249
Email: doug.malchow@utas.utc.com

www.sensorsinc.com