Seeing Beyond the Visible

Doug Malchow
Manager, Industrial Business Development
Goodrich Corporation
ISR Systems - Princeton
• 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

Photoelectric effect

- Infrared: No electrons emitted
- Visible/Ultraviolet: Electrons emitted depending on the surface material
- X-ray: Electrons always emitted
- Gamma-rays: Electrons always emitted

E_{\text{Threshold}} = hf

Where: E = energy of photon
h = Planck's constant
f = frequency
Energy Source Emits

Photoelectric effect

- Infrared: No electrons emitted
- Visible / Ultraviolet: Electrons emitted depending on the surface material
- X-ray: Electrons always emitted
- Gamma-rays: Electrons always emitted

\[ E_{\text{Threshold}} = hf \]

Where:
- \( E \) = energy of photon
- \( h \) = Planck's constant
- \( f \) = frequency

Image courtesy of ESA / AOES Mediala
Microsoft clip art
Energy Source Emits

Photoelectric effect

Infrared
No electrons emitted

Visible / Ultraviolet
Electrons emitted depending on the surface material

X-ray
Electrons always emitted

Gamma-rays
Electrons always emitted

$E_{\text{Threshold}} = hf$
Where: $E =$ energy of photon
$h =$ Planck's constant
$f =$ frequency

Image courtesy of ESA / AOES Mediala
Microsoft clip art
Interacts with Stuff

- The energy is:
  - Reflected
    - Specular
    - Diffuse
  - Diffracted
  - Scattered,
  - Refracted (bent)
  - Absorbed
    - Heat
    - Re-radiated
    - Selective $\lambda$
  - Transmitted

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

- The energy is:
  - Reflected
    - Specular
    - Diffuse
  - Diffracted
  - Scattered,
  - Refracted (bent)
  - Absorbed
    - Heat
    - Re-radiated
    - Selective $\lambda$
  - Transmitted

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

- The energy is:
  - Reflected
    - Specular
    - Diffuse
  - Diffracted
  - Scattered,
  - Refracted (bent)
  - Absorbed
    - Heat
    - Re-radiated
    - Selective $\lambda$
  - Transmitted

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

Scatter

Reflections

Diffuse Reflection
The energy is:

- Reflected
  - Specular
  - Diffuse
- Diffracted
- Scattered,
- Refracted (bent)
- Absorbed
  - Heat
  - Re-radiated
  - Selective $\lambda$
- Transmitted
Is Displayed

Gamma and X-ray

Deep UV

UV - Visible - NIR

SWIR

MWIR

LWIR

TeraHertz

Car paint
Bruises
Fingerprints
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
• 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

Tooth X-ray: http://doctorspiller.com/copyright_info.htm
Tooth: http://upload.wikimedia.org/wikipedia/commons/thumb/b/b8/Lower_wisdom_tooth.jpg/220px-Lower_wisdom_tooth.jpg
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
UV Imaging

- Shorter wavelength than violet light but longer than X-ray
- Therefore higher energy than violet, but less than X-rays
- Very energetic, UV rays can break chemical bonds, making molecules unusually reactive
  - capable even of ionizing atoms
- Images bacteria, melanin, fingerprints, UV coatings
- Induces fluorescence at longer (visible) wavelengths

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
UV Imaging

- Shorter wavelength than violet light but longer than X-ray.
- Therefore, higher energy than violet but less than X-rays.
- Very energetic, UV rays can break chemical bonds, making molecules unusually reactive—capable even of ionizing atoms.
- Images bacteria, melanin, fingerprints, UV coatings.
- Induces fluorescence at longer (visible) wavelengths.

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 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

Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.
Infrared

- Covers 750 nm to 1 mm (400 THz to 300 GHz)
  Subdivided into three sub-bands:

  - **Near-infrared or Short-Wave Infrared**, 750 to 2,500 nm (400 to 120 THz)
    - Photon interactions similar to visible light
    - Thermal emissions over 100 °C
    - Overtones (harmonics) of molecular vibrations absorb for remote chemical ID

  - **Mid-infrared**, 2.5 to 10 μm from 120 to 30 THz.
    - Hot objects (black-body radiators) radiate strongly.
    - Chemical ID via absorbed due to fundamental frequency of molecule vibrations

  - **Far-infrared**, 10 μm to 1 mm (30 THz to 300 GHz). The lower part of this range may also be labeled Terahertz or microwaves.
    - absorbed by so-called rotational modes in gas-phase molecules, by molecular motions in liquids, and by phonons in solids.
    - The water in Earth's atmosphere absorbs so strongly in this range that it renders the atmosphere in effect opaque but with "windows")
    - in astronomy 200 μm up to a few mm aka "sub-millimetre",
    - 3 THz to 0.3 THz aka Terahertz band
Infrared

IR Detectors

Thermal Micro-bolometers below dashed black curve ↓↓
Infrared - Thermal

- Visible
- Sun
- SW
- LW

Spectral Radiant Emittance

Wavelength (micrometers)

6000K
4000K
3000K
2000K
1000K
500K
300K
200K

Images © FLIR
Infrared - Thermal

Images © FLIR
Thermal MV

- FLIR Application Stories – Automation
  - raw steel quality
Thermal MV

- FLIR Application Stories – Automation
  - raw steel quality
FLIR Application Stories – Automation
  - raw steel quality
Terahertz

- 0.1 mm (or 100 \(\mu m\)) infrared to 1.0 mm microwave aka the long-wavelength edge of far-infrared light.
- From 3000 GHz (\(3 \times 10^{12}\) Hz or 3 THz) to 300 gigahertz (\(3 \times 10^{11}\) 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).
Terahertz

- 0.1 mm (or 100 μm) infrared to 1.0 mm microwave aka the long-wavelength edge of far-infrared light.
- From $3 \times 10^{12}$ Hz or 3 THz to $3 \times 10^{11}$ 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).
• 0.1 mm (or 100 \(\mu m\)) infrared to 1.0 mm microwave aka the long-wavelength edge of far-infrared light.

• From 3000 GHz (\(3 \times 10^{12}\) Hz or 3 THz) to 300 gigahertz (\(3 \times 10^{11}\) 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

The diagram illustrates the quantum efficiency of different materials across various wavelength bands. The bands are categorized into Visible (0.5 - 0.7 μm), Near-Infrared (NIR) (0.75 - 1.0 μm), Short-Wave Infrared (SWIR) (1.0 - 2.0 μm), Medium-Wave Infrared (MWIR) (2.0 - 5.0 μm), and Long-Wave Infrared (LWIR) (5.0 - 12 μm). Each band corresponds to different applications and technologies, such as Si I²CCD, Standard InGaAs (1.7 μm), NIR/SWIR InGaAs, InGaAs (2.6 μm), and NVG (Gen III) materials, which are indicated by specific curves and markers on the graph.

Glass lenses transmit in the SWIR range, which is crucial for applications requiring high transmission and low absorption.
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

![Graph showing quantum efficiency vs. wavelength with specific bands highlighted: visible, NIR, SWIR, and the range where glass lenses transmit.](image-url)
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
Imaged in late afternoon in high humidity, 300 mm lens, 1.5 km distant

SWIR
San Francisco Skyline – 3 km

- Haze penetration capability provides overall sharper image
- Significantly increases “seeing distance”
Scattering is a strong function of both wavelength and particle size.

- Short wavelength scatter to the 4\textsuperscript{th} power.
- Long wavelengths attenuated linearly with size.
This unique ability of SWIR applies to haze and fog, too!
• 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!!!

Smoker in SWIR
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

Latticed matched linear array InGaAs response to BB temp
SU1024-1.7T1-0500 @ 30°C FPA temperature

Lens at fixed f/1.4 aperture
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
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
• 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
• 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)

Capillary network in ON Head (en-face)

Optical Nerve Head showing arteries & veins (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
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 monocrystalline
Photoluminescence Inspection Finished Cell

- 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
Three layers, each with own luminescence:
- GaInP @ 700 nm
- InGaAs @ 940 nm
- Ge @ 1550-1800 nm
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
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

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

Rotated polished side to camera: sharper image

6”x6”x10” Brick
Imaging through Silicon Bricks, Ingots

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

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

Rotated polished side to camera: sharper image

6”x6”x10” Brick
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

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