Multiple Waveband Temperature Sensor (MWTS)

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Directed Energy Test & Evaluation Conference ,1-3 August 2006

Problem Statement

- **T&E Need**

  Accurate surface temperature measurement of a target in extreme environments in a non-intrusive manner.

- **S&T Challenge**
  - Determine optimum wavebands (suitable for target temperatures, nature of the targets and environments) to measure accurate target surface temperature independent of the emissivity
  - Integrate simultaneously readable multiband QWIPs in a single monolithic focal plane array (FPA) sensor
  - Hardware/software integration and system calibration for remote temperature measurements

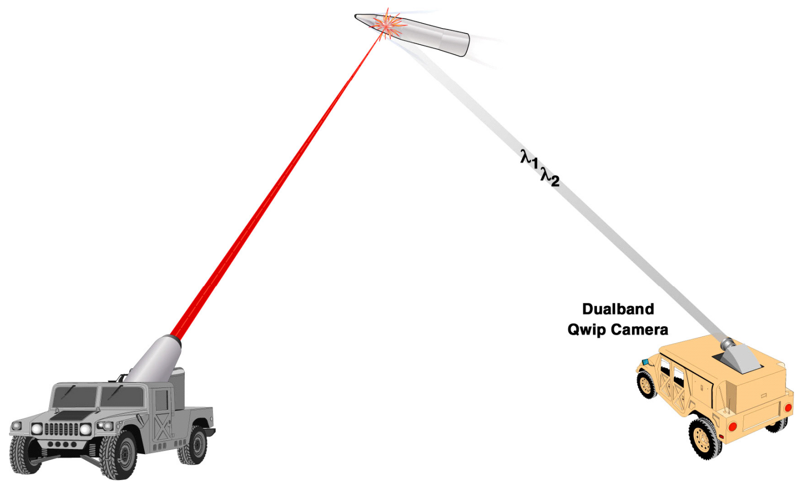
TSTM Objectives – from Dr. McKee's TSTM briefings

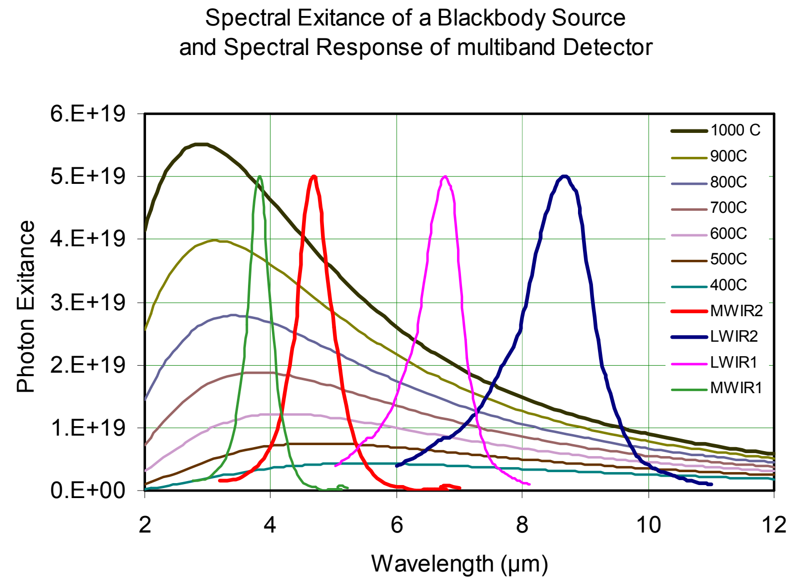
- **Measure temperature of external surfaces of stationary ground targets being heated by laser beams**
- **Requirements from T-SS**
  - Temperature dynamic range: 0° to 3700° C
  - Measurement accuracy: ±1% (of absolute temperature)
  - Sampling rate: 10-100 Hz
  - Spatial resolution: 5 mm
  - Cannot significantly affect laser interaction with target or target's response

Technical Interchange Meeting (4/19/06)
TSTM Alternatives – from Dr. McKee's TSTM briefings

- **Contact Measurements Using Thermocouples**
  - Thermocouples on Front Surface
  - Thermocouples on Back Surface/Embedded Thermocouples
  - Eliminated: outside DETEC purview
- **Non-Contact Measurements Using Radiometery**
  - Single-Color Imaging Radiometer
    - Requires absolute emissivity versus temperature
    - Not robust solution
  - Two-Color Imaging Radiometer
    - Requires relative emissivity versus temperature
  - Hyperspectral Imager
    - Only requires functional dependence of emissivity on wavelength (e.g., linear, quadratic, higher-power)

Project Description





WSMR and JPL will develop and demonstrate a multiband infrared imaging camera with the detectors simultaneously sensitive to multiple distinct color bands for front surface temperature measurements.

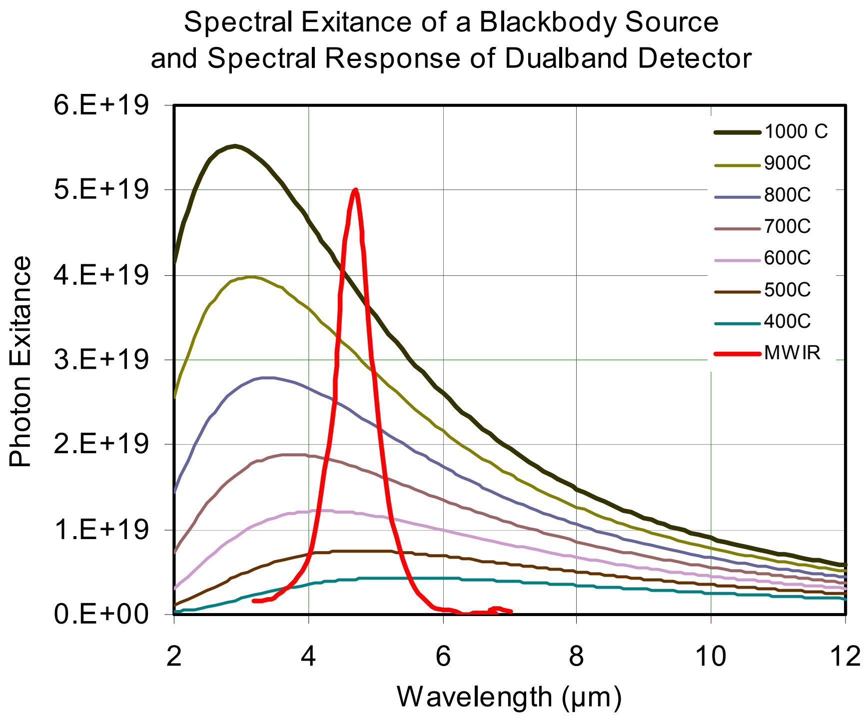
- The measurement system will not affect target dynamics or response to the laser irradiation.
- The simplest criterion for spectral band selection is to choose those practically feasible spectral bands that create the most contrast between the objects or scenes of interest in the expected environmental conditions.

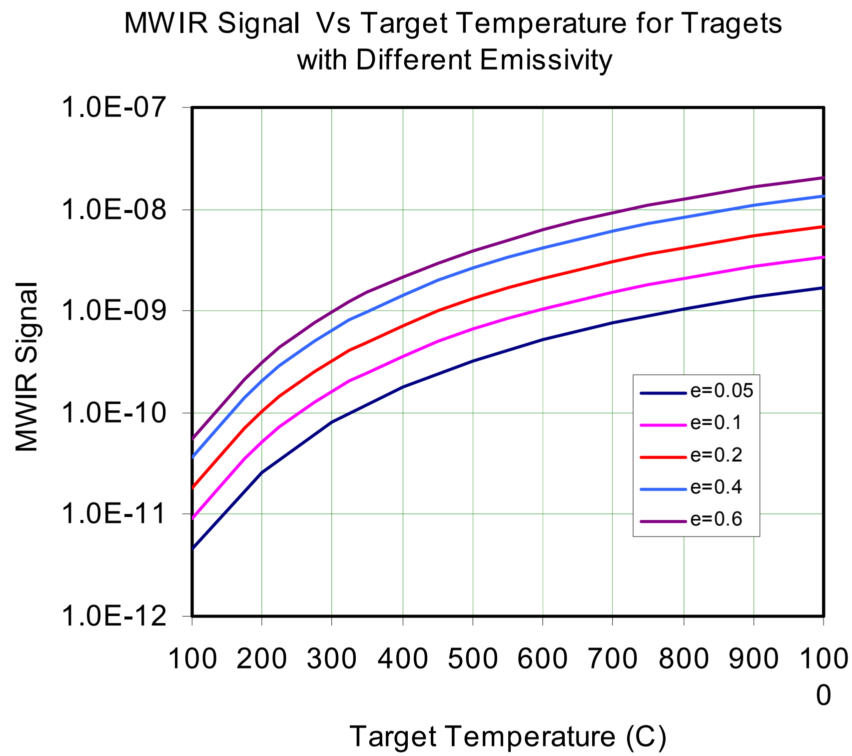
Project Scope

- **Phase 1 : Concept study and optimized sensor design**
  - Model multiband (≥ 2) temperature sensor. Include emissivity, $\varepsilon(\lambda)$ and all detector spectral responses, $R(\lambda)$ and noise.
  - Use existing QWIP IR cameras (dual-band and filtered single-band) to evaluate hot targets, including laser welding setup.
- **Phase 2 : Sensor development and system design**
  - Design and fabrication of 640x512 (or larger) format multiband QWIP focal plane array for TSTM
  - Develop software for remote temperature measurements using DWTS
- **Phase 3 : System Integration and field testing**
  - Integrate multiband QWIP camera system
  - Calibration and characterization of the camera system
  - Field testing at WSMR

Modeling

SINGLE BAND IR SENSOR OUTPUT





- **Absolute value of the emissivity is required to measure the target temperature using a Single band sensor**

Modeling

Dualband Sensor Output

$$I_1(T) = \varepsilon_1 A_{pix} \Omega_{lens} \int_{\lambda_{1,\min}}^{\lambda_{1,\max}} R_1(\lambda) L_{e,\lambda}(\lambda, T) d\lambda$$

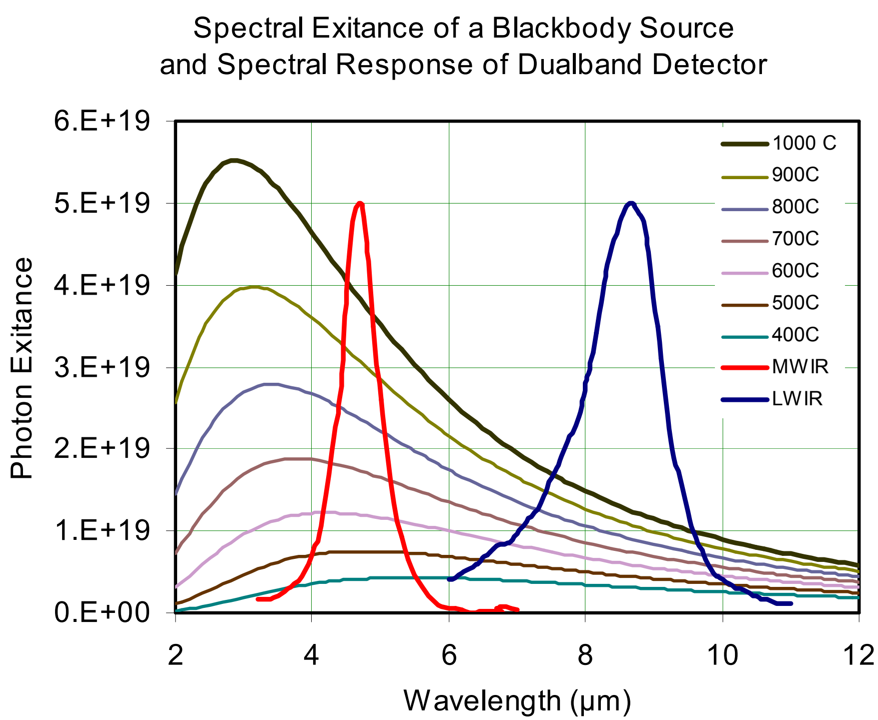
$$I_2(T) = \varepsilon_2 A_{pix} \Omega_{lens} \int_{\lambda_{2,\min}}^{\lambda_{2,\max}} R_1(\lambda) L_{e,\lambda}(\lambda, T) d\lambda$$

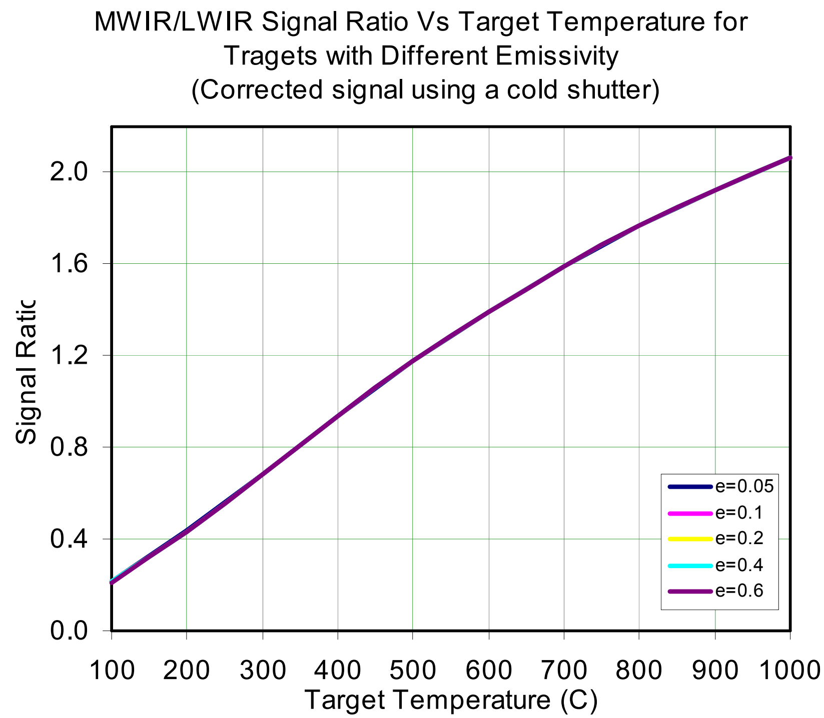
I

$$\frac{I_1}{I_2} = \frac{\varepsilon_1}{\varepsilon_2} \int_{\lambda_{1,\min}}^{\lambda_{1,\max}} \frac{R_1(\lambda)}{\lambda^5 \left(e^{hc/\lambda kT} - 1\right)} d\lambda \Bigg/ \int_{\lambda_{2,\min}}^{\lambda_{2,\max}} \frac{R_2(\lambda)}{\lambda^5 \left(e^{hc/\lambda kT} - 1\right)} d\lambda$$

- **Emissivity ratio is required to determine the target temperature using dual band signal ratio**

Dualband Sensor Output





- **If the emissivity is same in both spectral bands, signal ratio eliminates the emissivity dependence**

Modeling

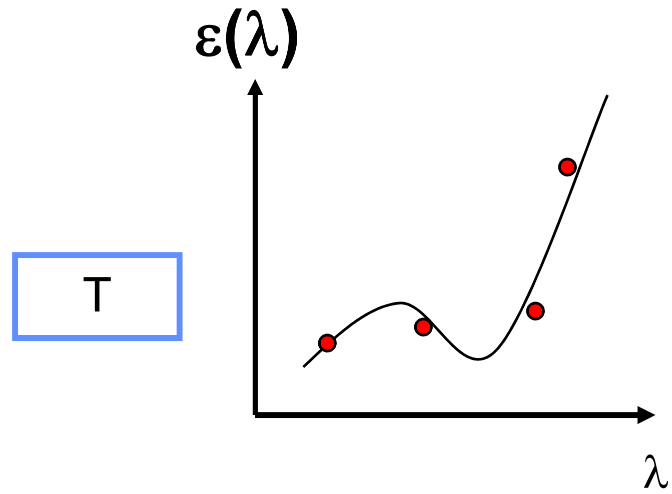
Multiband Sensor Output

$$I_1(T) = \varepsilon_1 A_{pix} \Omega_{lens} \int_{\lambda_{1,\min}}^{\lambda_{1,\max}} R_1(\lambda) L_{e,\lambda}(\lambda, T) d\lambda$$

$$I_2(T) = \varepsilon_2 A_{pix} \Omega_{lens} \int_{\lambda_{2,\min}}^{\lambda_{2,\max}} R_2(\lambda) L_{e,\lambda}(\lambda, T) d\lambda$$

$$I_3(T) = \varepsilon_3 A_{pix} \Omega_{lens} \int_{\lambda_{3,\min}}^{\lambda_{3,\max}} R_3(\lambda) L_{e,\lambda}(\lambda, T) d\lambda$$

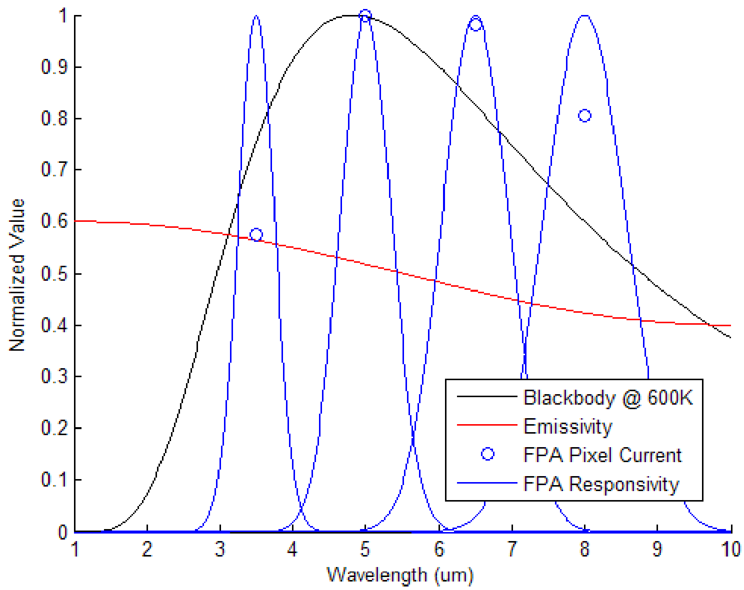
$$I_4(T) = \varepsilon_4 A_{pix} \Omega_{lens} \int_{\lambda_{4,\min}}^{\lambda_{4,\max}} R_4(\lambda) L_{e,\lambda}(\lambda, T) d\lambda$$



- **Target temperature can be determined by fitting a smooth function for ε(λ)**
- **Technique provides a built-in confidence measure of the T and ε(λ) solutions – the rms error in the nonlinear solution of the equations**

Simulation of Multi-Wave Infrared Temperature Measurement

- Matlab model that can simulate infrared imaging by an arbitrary number of bands
- Includes spectral variation of detector responsivity, target emissivity, and optics



First, the infrared imaging is simulated with all quantities known to obtain the 'measured' detector currents

$$\text{current}_{\text{band n}}(T) \sim \int_{\text{band n}} \text{emissivity}(\lambda,T) \cdot \text{blackbody}(\lambda,T) \cdot \text{responsivity}(\lambda)\, d\lambda$$

Next, the temperature is the found by solving a non-linear system of equations

- Temperature and emissivity are unknown, emissivity represented by polynomial

$$\text{emissivity}(\lambda) = a_0 + a_1\lambda + a_2\lambda^2 + \ldots$$

- Detector responsivity is known
- System of equations

$$\text{current}_1 \sim \int_{\text{band 1}} \text{emissivity}(\lambda) \cdot \text{blackbody}(\lambda,T) \cdot \text{responsivity}(\lambda)\, d\lambda$$

$$\text{current}_2 \sim \int_{\text{band 2}} \text{emissivity}(\lambda) \cdot \text{blackbody}(\lambda,T) \cdot \text{responsivity}(\lambda)\, d\lambda$$

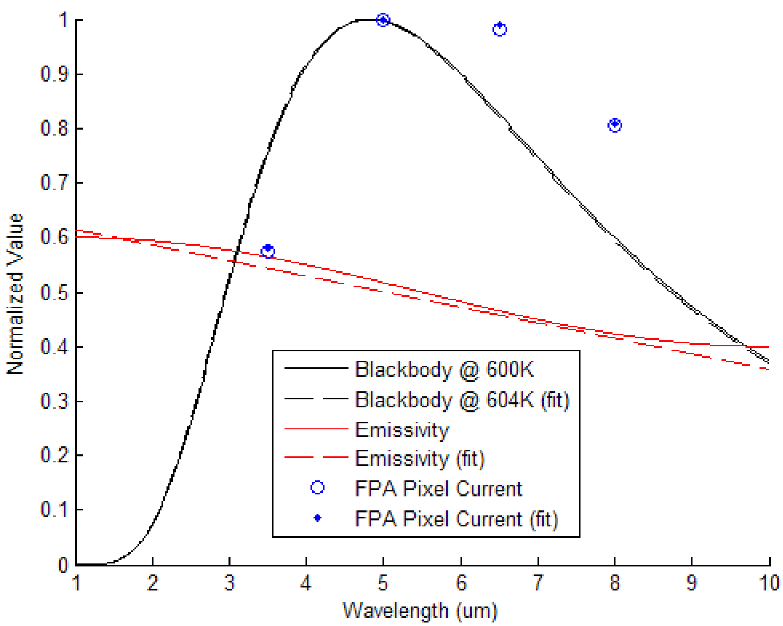
$$\ldots$$

$$\text{current}_N \sim \int_{\text{band N}} \text{emissivity}(\lambda) \cdot \text{blackbody}(\lambda,T) \cdot \text{responsivity}(\lambda)\, d\lambda$$

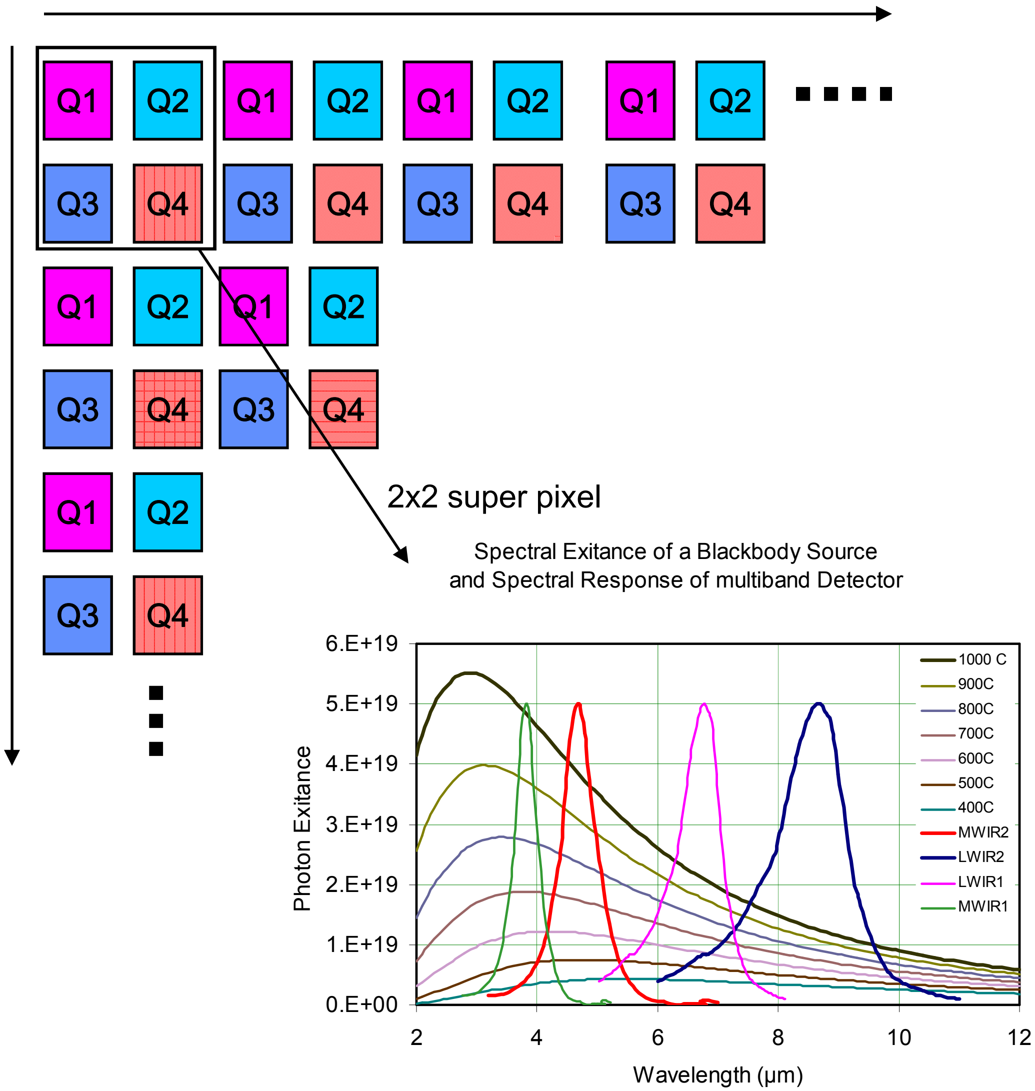
→ Non-linear solver determines best fit for temperature (T) and emissivity (a_0, a_1, a_2 …)

Simulation of Multi-Wave Infrared Temperature Measurement

Result of non-linear fit comparing 'actual' and fit values blackbody temperature, emissivity, and detector band currents



Multiband QWIP Array

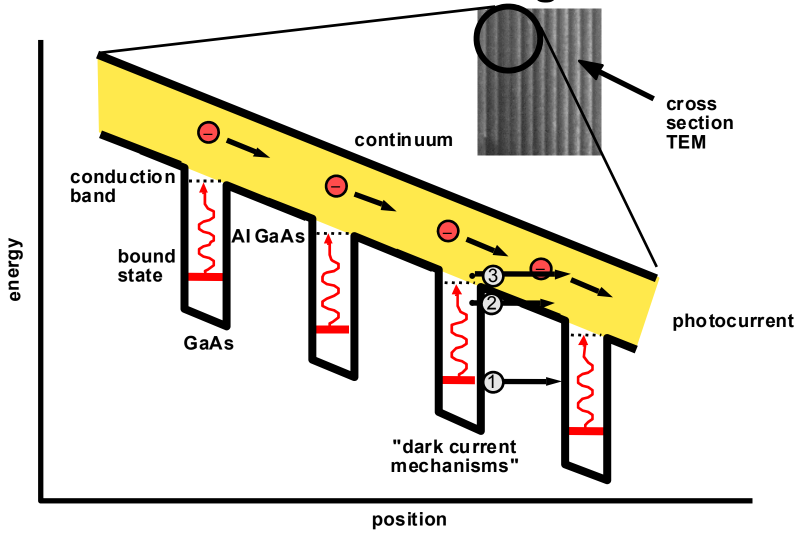


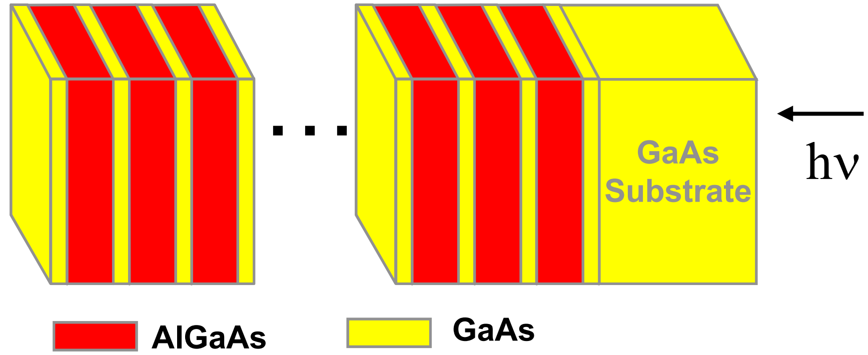
- The FPA area array is divided into 2x2 sub-pixel areas that function as superpixels for temperature measurement
- Each QWIP sub-pixel is sensitive to one specific wavelength band (four)
- Temperature and emissivity are assumed constant over each superpixel area

Detector Development

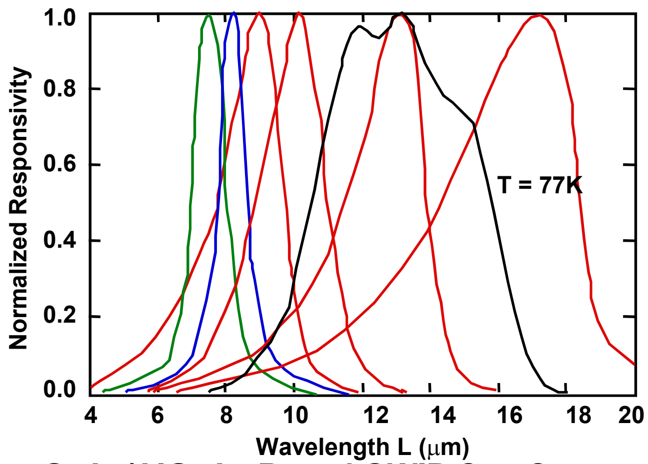
QUANTUM WELL INFRARED PHOTODETECTOR (QWIP) TECHNOLOGY

Conduction Band Diagram

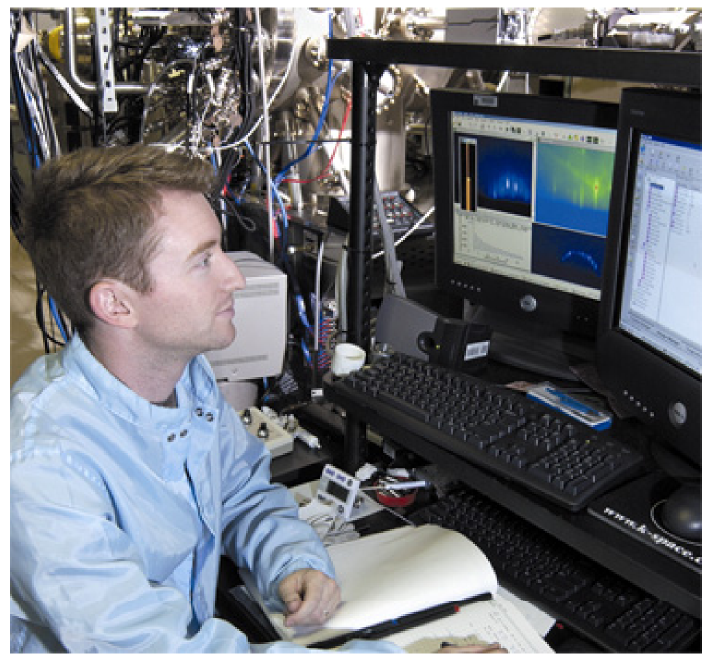




GaAs/AlGaAs Based QWIP Spectrums



GaAs/AlGaAs Based QWIP Can Cover a Very Broad Infrared (3-25 μm) Region



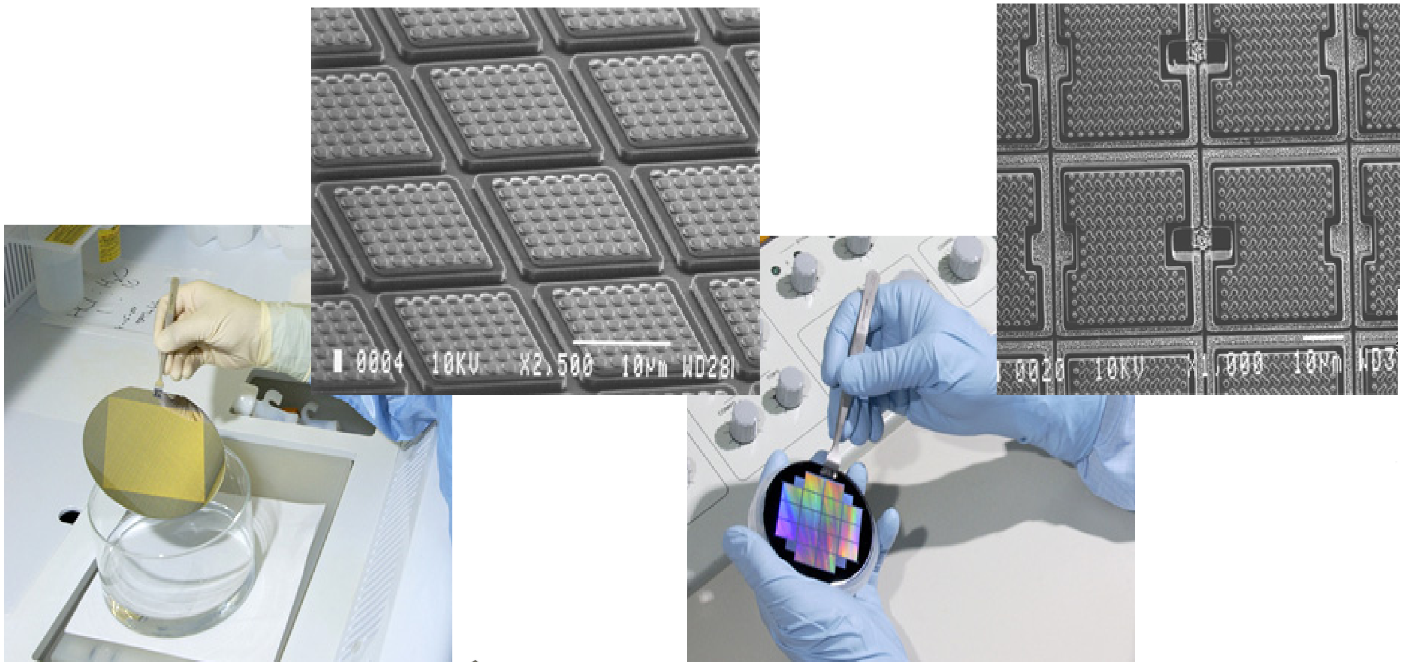
Veeco 4-inch capable GEN-III Molecular Beam Epitaxy Growth Machine

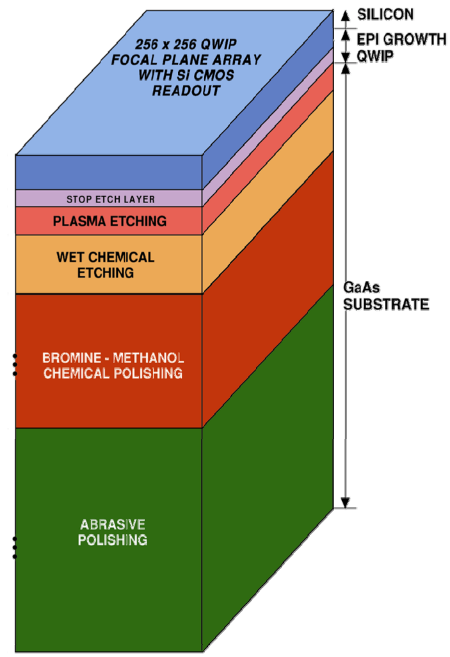
Detector Development

QWIP Capabilities

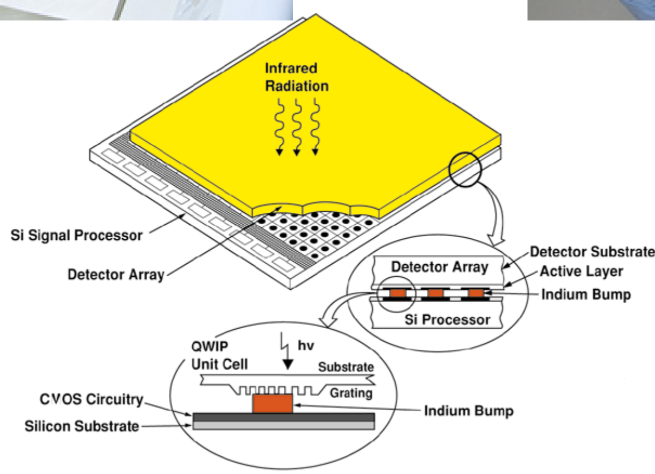
- Mid, Long wavelength IR detectors using wide band gap materials (e.g. GaAs/AlGaAs)
- Based on artificially created quantum structures
- Tailorable wavelength and bandwidth
  - GaAs substrate based QWIPs : > 4 μm wavelength range
  - InP substrate based QWIPs : 3 – 8 μm wavelength range
  - Typical spectral bandwidth ~ 10%
  - Stackable to form a multi-color QWIP
- High yield mature fabrication process

Detector and FPA Fabrication Process





FPA Thinning Process

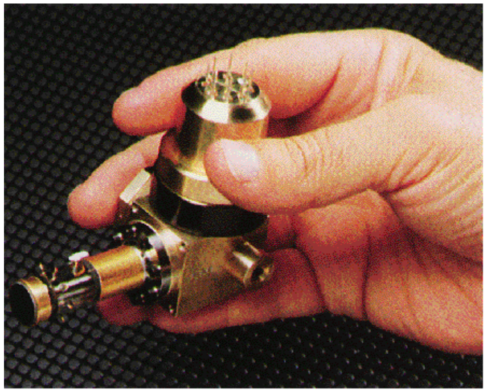


Advantages of Thinning

- ➢ No FPA delamination
- ➢ No optical cross-talk
- ➢ Increased optical coupling

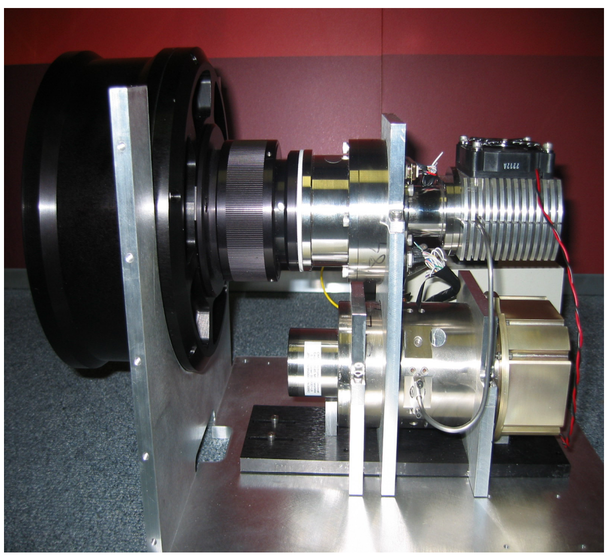
Hybridization Process

Camera Integration



Integrated with coolers

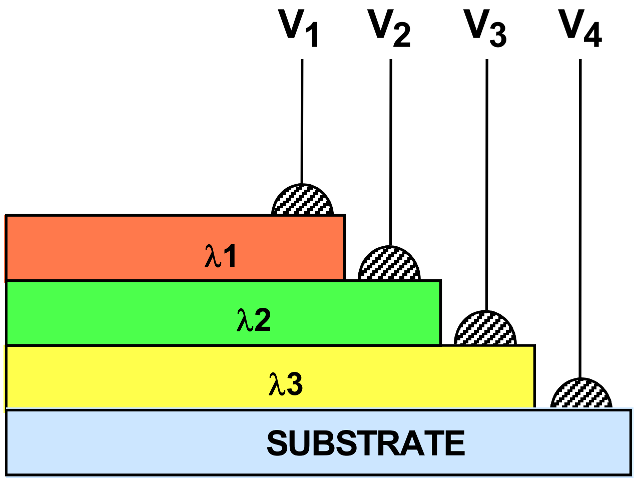
640x512 QWIP Camera

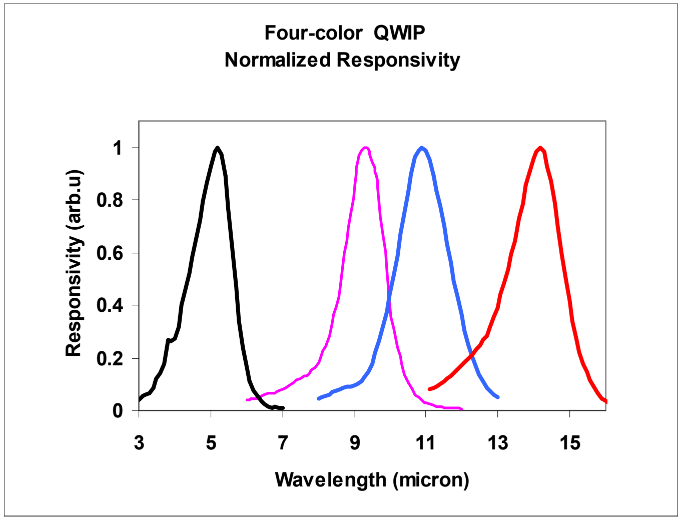


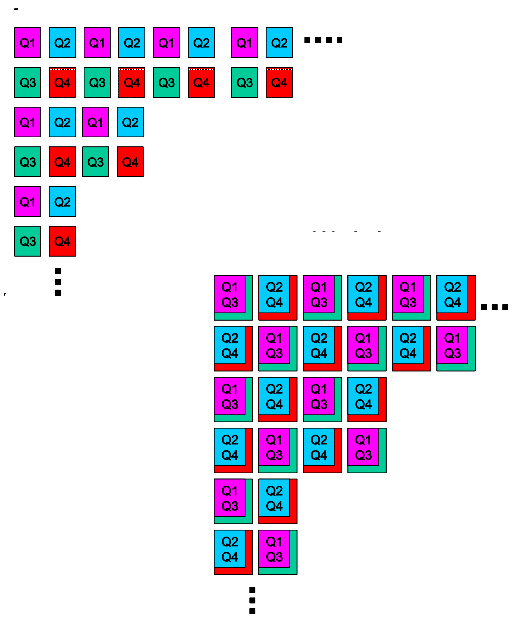
1024x1024 QWIP Camera

256x256 QWIP Camera

Multiband QWIPs

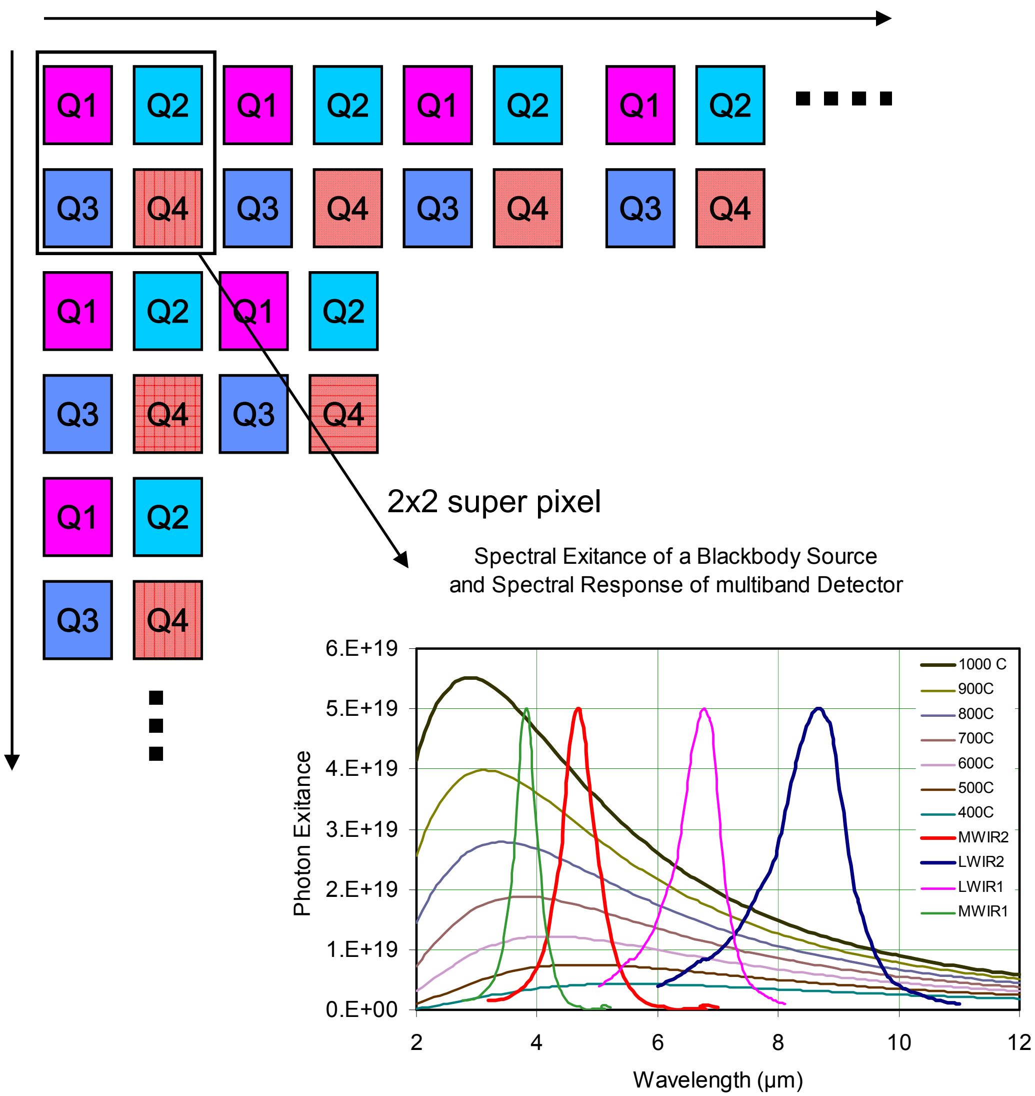






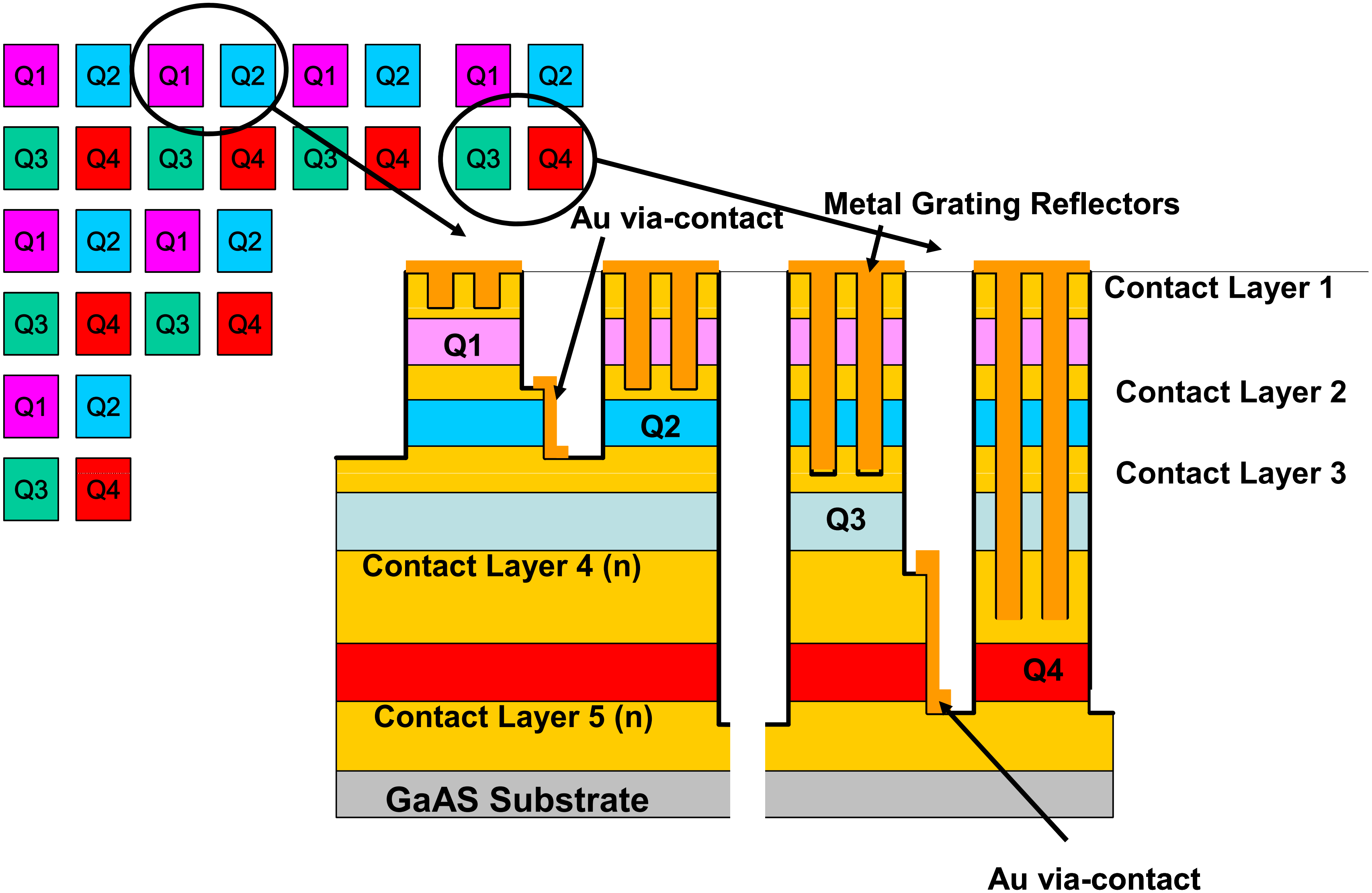
- **Monolithically grown stack of detectors**
- **Each stack absorbs photons within a specific wavelength band defined by the detector (both long & short cut-off)**
- **Rest of the photons transmit to the next stack**
- **Spatially separated colors**
  - One pixel reads one color
- **Pixel co-located design**
  - One pixel reads several colors
  - Multi-cell ROIC

Multiband QWIP Array



- The FPA area array is divided into 2x2 sub-pixel areas that function as superpixels for temperature measurement
- Each QWIP sub-pixel is sensitive to one specific wavelength band (four)
- Temperature and emissivity are assumed constant over each superpixel area

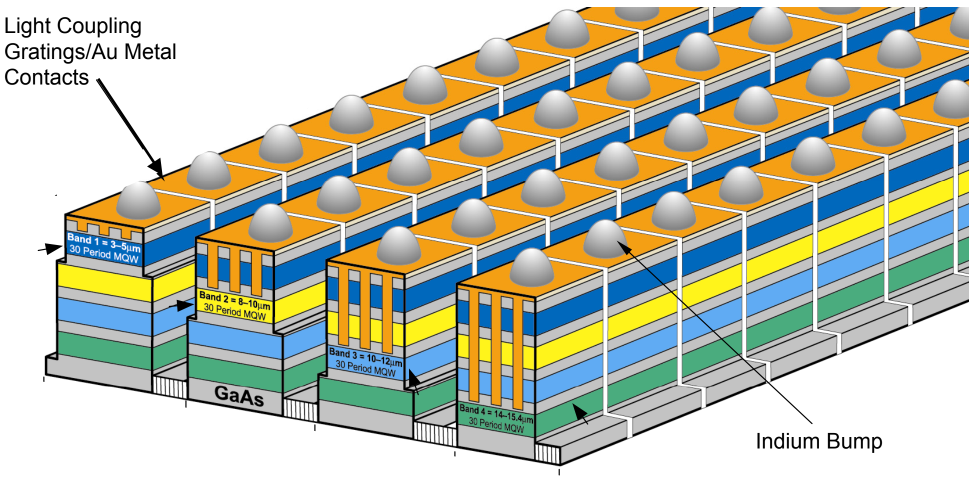
Proposed multiband QWIP Array

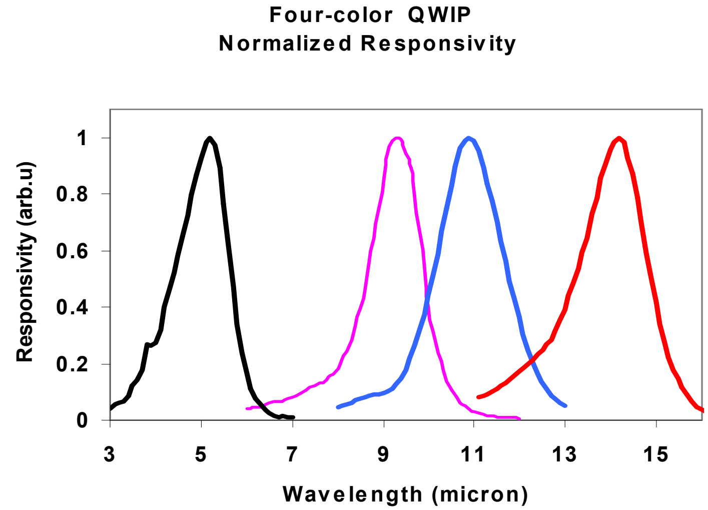


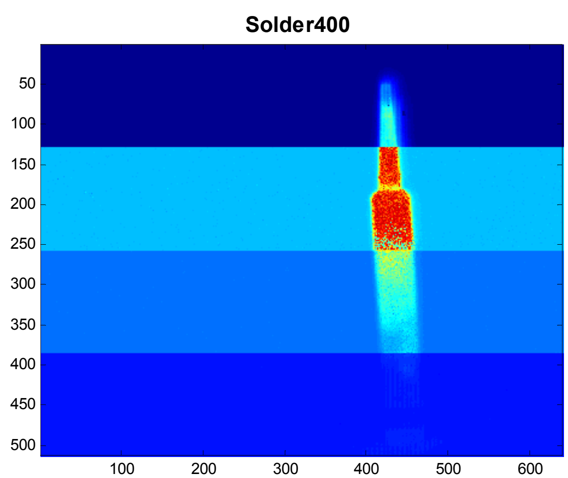
JPL multiband QWIPs

- **JPL has already developed and demonstrated several multiband QWIP cameras**
  - 640x512-format dualband interlaced QWIP camera
  - 640x512-format Dual broadband QWIP camera
  - 640x512-format spatially separated four-band QWIP camera
  - 320x256-format pixel co-located dualband QWIP camera
- **Proposed multiband camera is unique**
  - Previously demonstrated four-band FPA has four subsections (640x128) and each subsection is sensitive to different spectral bands
  - 2x2 super cell sensitive to four different spectral bands

Four Band QWIP FPA



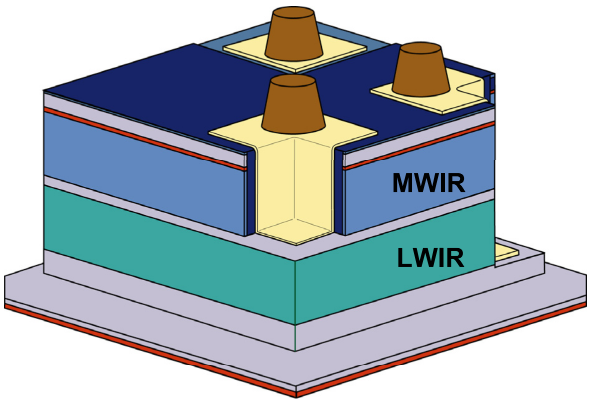




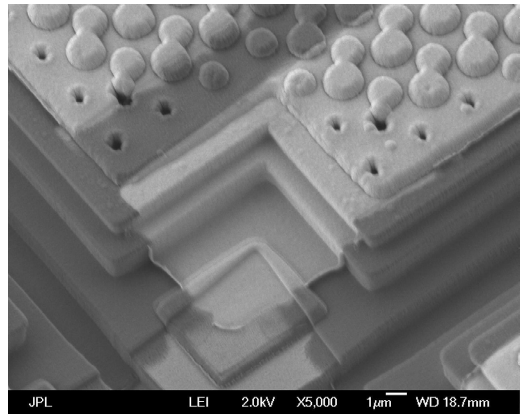
4-COLOR IMAGE

TWO 4-COLOR FOCAL PLANE ARRAYS DELIVERED TO NASA GSFC's HYPER-SPECTRAL IMAGING SPECTROMETER PROJECT

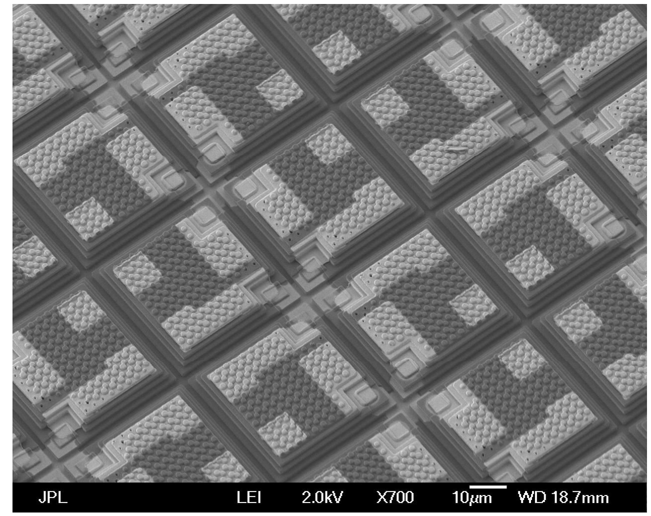
Pixel Co-located Simultaneously Readable Dualband QWIP FPA



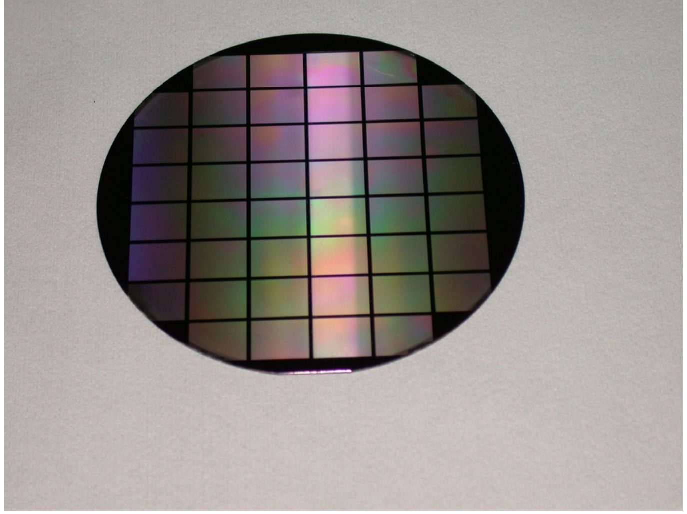
Dualband QWIP device structure



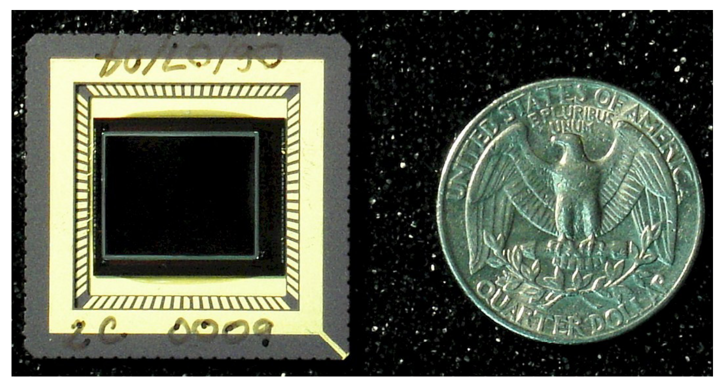
SEM of metal via connects



SEM of dualband QWIP array

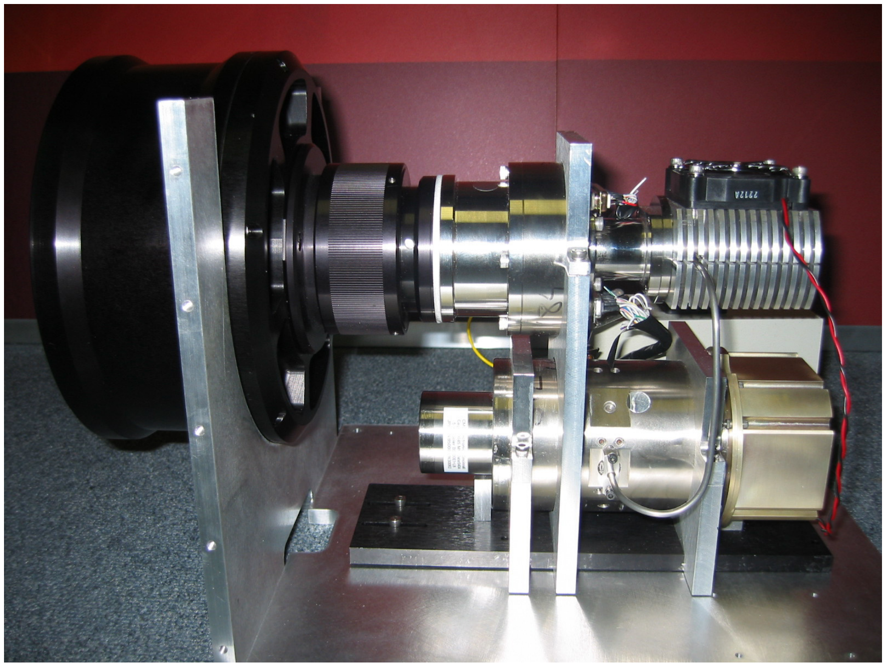


4-inch wafer with 48 detector dies

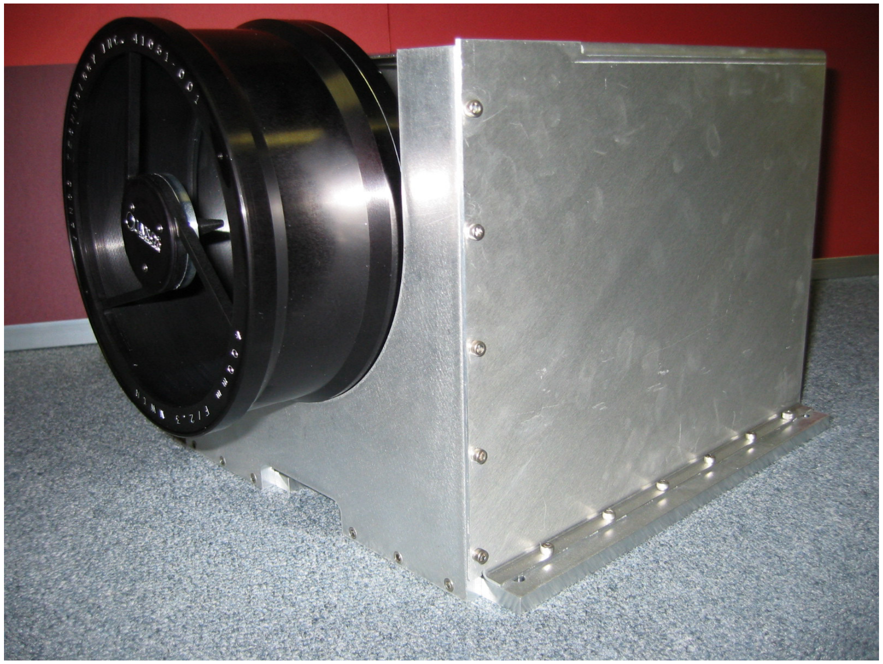


Dualband QWIP FPA HYBRID

320x256 Pixel Dualband QWIP FPA and Camera Delivered to ABL



Dualband sensor engine



320x256 pixel dualband QWIP camera

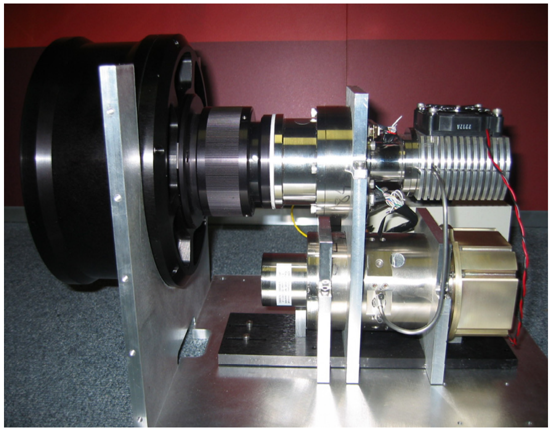
Dualband QWIP Movie

LWIR **MWIR**

Features to look for,
The cigarette lighter produce lots of hot CO_2 gas. So, flare is broader MWIR due to CO_2 emission, where as LWIR (8-9 microns) doesn't have any emission (just the heat).
The hot cigarette lighter flame produce so much MWIR signal, it reflects off from the lens and Jason's face.
The plastic piece Jason is holding is opaque in LWIR, but transparent in MWIR.

Format	- 320x256 pixels, dualband & pixel co-registered
Wavebands	- 4.4-5.1 & 8-9 μm
NEDT	- 22 & 24 mK for 300K background with f/2 optics
QE	- 19% & 15%
Photoconductive gain	- 0.5 & 0.3
Detectivity	- > 2×10^{11} & 1×10^{11} Jones
Operating temp.	- 65 K
Fill factor	- > 85%

Lab/Field Demonstration

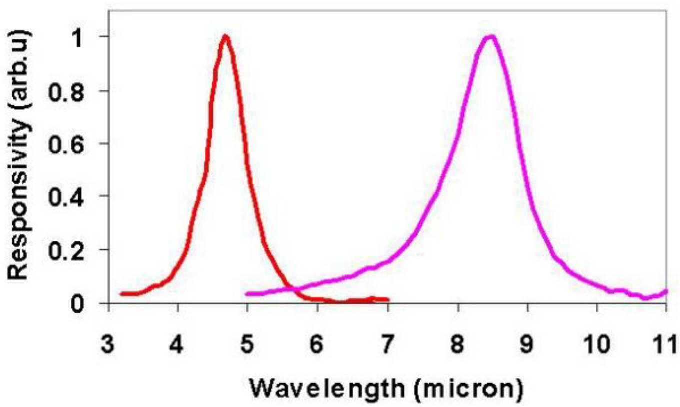


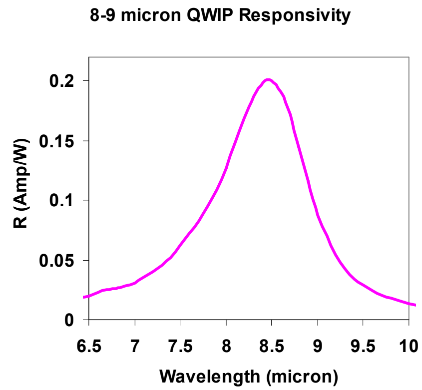
320x256 format Dualband QWIP camera

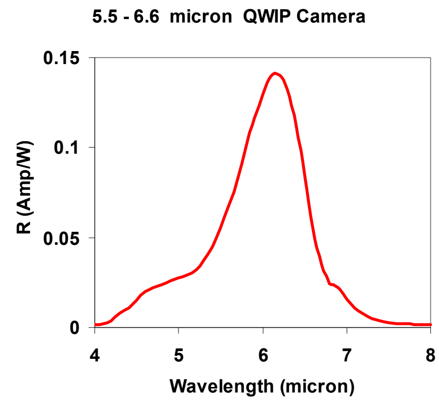
640x512-format Single band QWIP Camera

- **JPL uses existing QWIP cameras for lab/field demonstration during Phase I**
  - 4.3 – 5.2 µm and 8-9 µm pixel co-located 320x256 format dualband camera
  - 8-9 µm single band 640x512 QWIP camera
  - 5.5-6.6 µm single band 640x512 QWIP camera

Lab/Field Demonstration

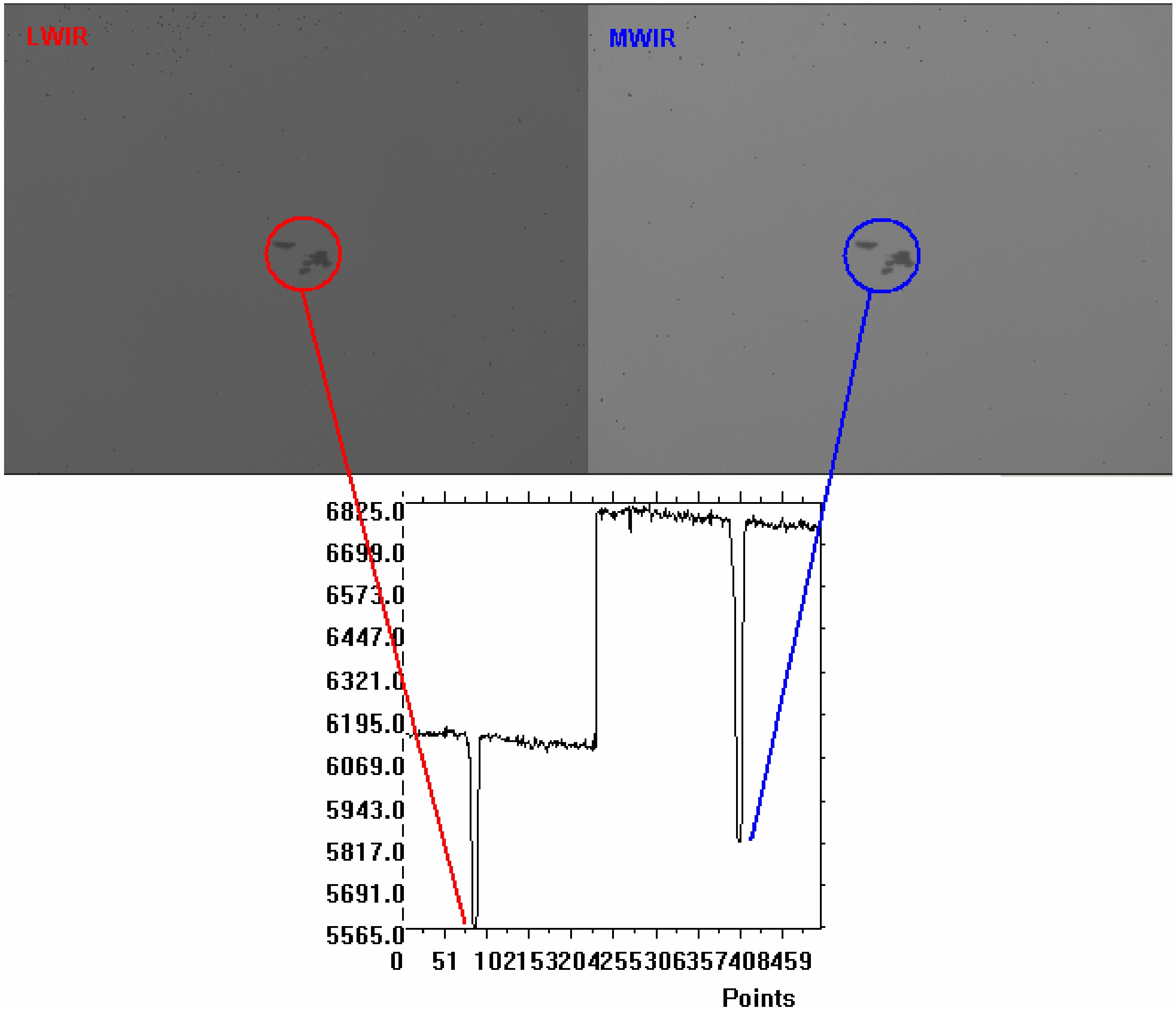






- **Utilize narrowband filters to split the spectral bands**
- **Use static targets (externally heated plates, hot plates, black-body)**
- **Cameras are pre-calibrated using a calibrated blackbody**
- **30Hz frame rate with variable integration times**
- **Post-process data to retrieve target temperature with possible error margins**
- **Image melting heated metals at a laser welding & cutting setup (Advance Technology Company – Pasadena)**

MWIR/LWIR PIXEL COLOCATED SIMULTANEOUS DUALBAND IMAGERY



Wrap Up

- **The multiband temperature measurement technique overcomes the major limitation (unknown emissivity) of the dual-waveband temperature sensor**
- **Study of two innovative approaches during Phase I**
  - The 2x2 pixel, 4-band temperature measurement technique utilize only a minor modification of demonstrated 4-band QWIP technology
  - A broad single-band QWIP camera combined with a computed tomography imaging spectrometer to disperse light from a pinhole array at the input field stop