In-situ Measurements using a Configurable Architecture Additive Testbed System

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Outline

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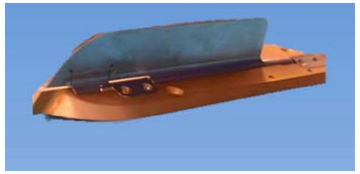
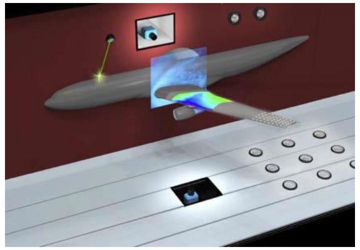
- Configurable Architecture Additive Testbed (CAAT)
  - Overall Description for Selective Laser Melting
  - Calibration of Near Infrared (NIR) Camera
- Measurement Results
  - Melt Pool Imaging on Ti-6Al-4V Plate
  - Comparison to Optical Microscopy
- Recent Efforts
  - Part Builds with In-situ Measurements using Upgraded Cameras
  - Registration and Comparison to Ex-situ X-ray CT
- Summary

NASA Transformational Tools and Technologies (TTT) Project Introduction





Resource & Project Support:
Business Lead: Laura Farrell (GRC)
Center Analysts: Cecelia Town (ARC), Glenda Almeida (AFRC), Laura Farrell (GRC), Tracey Frisby (LaRC)
NRA Manager: Tracey Frisby (LaRC)
Scheduler: Joyce Moran (GRC)
Project Support Analyst: Jeanie Feagan (GRC)

Executive Team:
Project Manager – Michael Rogers (ARC)
Deputy Project Manager – Dale Hopkins (GRC)
Associate Project Manager – Joe Morrison (LaRC)

Project Center Liaisons:
ARC Andrew Meade
AFRC Steve Cumming
GRC Azlin Biaggi-Labiosa
LaRC Melissa Rivers

Enduring Discipline Research Areas
(with Technical Leads)

Dale Hopkins
Discipline Strategy Management

- **Materials and Structures (M&S)** Steve Arnold (GRC)
- **Combustion** Jeff Moder (GRC), Kathy Tacina (GRC)
- **Controls** Dennis Culley (GRC), Steve Riddick (LaRC)
- **Communications/Cybersecurity** Casey Bakula (GRC)

Joe Morrison
Discipline Strategy Management

- **Revolutionary Computational Aerosciences (RCA)** Mujeeb Malik (LaRC)
- **Innovative Measurements (IM)** Tom Jones (LaRC)
- **Multidisciplinary Design, Analysis, and Optimization (MDAO)** Erik Olson (LaRC), (Acting)
- **Autonomous Systems (AS)**
  - Human Machine Teaming
  - Other enabling disciplines

  Chris Teubert (ARC)

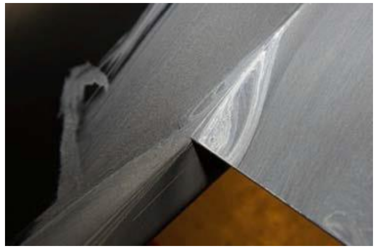
Sub-projects
(Aligned with ARMD Priorities)

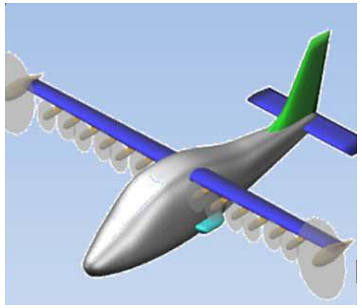
Foundational Electrified Aircraft Propulsion
Azlin Biaggi-Labiosa
Sub-project Manager
M&S
MDAO
Controls

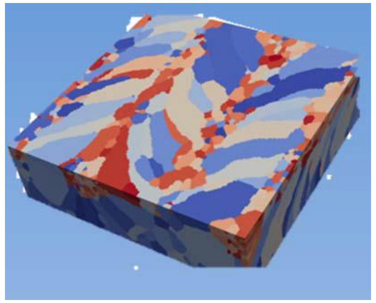
Revolutionary Aviation Mobility
Vanessa Aubuchon
Sub-project Manager
AS
MDAO
Controls
Comm/Cybersecurity

Reduced Life Cycle Cost
Melissa Rivers
Sub-project Manager
RCA
IM
M&S

Enabling Supersonic Transport
Azlin Biaggi-Labiosa
Sub-project Manager
Combustion
M&S







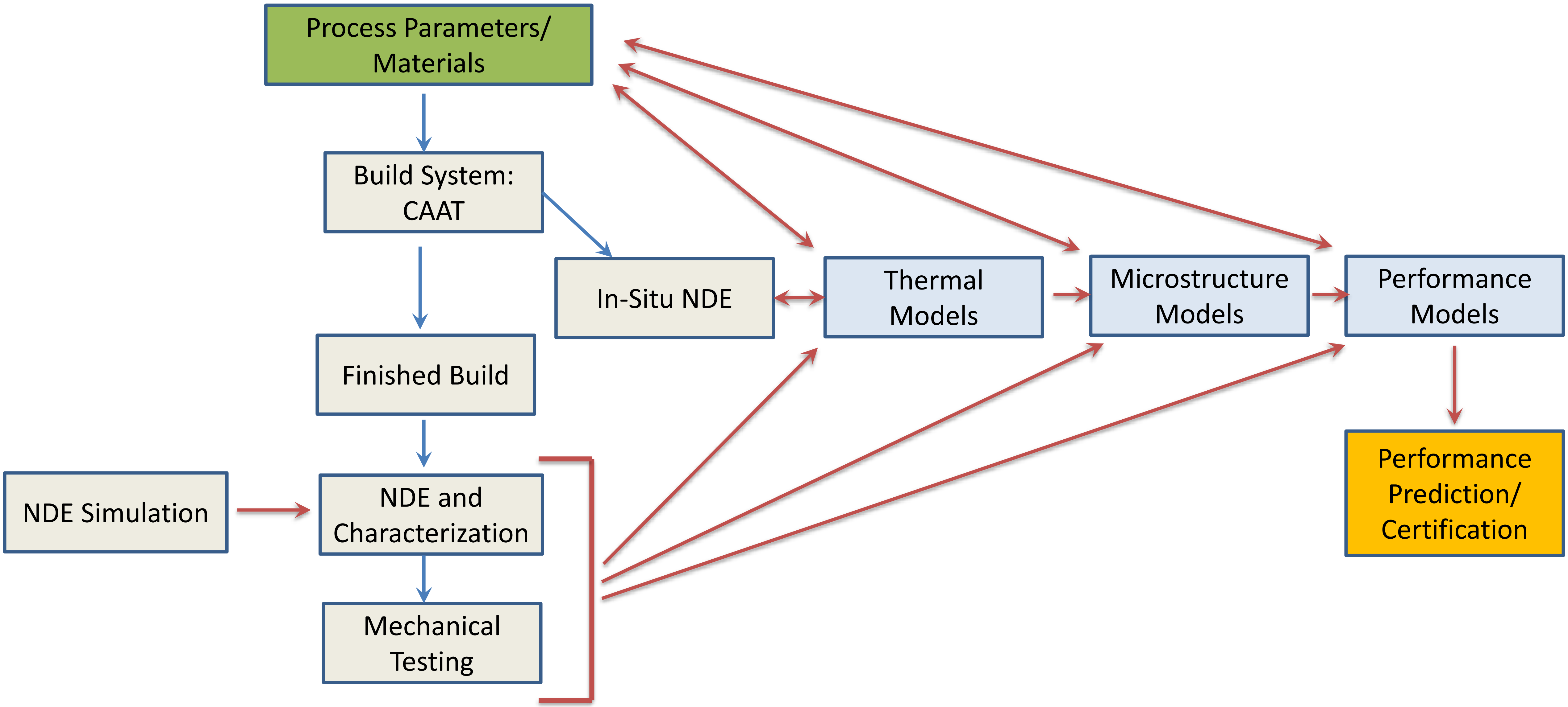
Subproject: Materials and Structures

Objectives:

Reduce the total Life Cycle Costs by:

1. **Enabling Certification by Analysis to reduce surprises during flight tests**
   - Develop and validate eddy resolving methods for airframe and propulsion system applications
   - Design and execute CFD validation experiments
   - Develop pressure & temperature sensitive paints to support dynamic measurements
   - Develop applicable velocimetry techniques for time-resolved unsteady flow
2. **Increase manufacturing rate and reduce weight of materials during production**
   - Develop computational validation of additive and other advanced manufacturing processes
   - Advance rapid manufacturing of composite unitized structures
   - Develop advanced materials and structural concepts
3. **Decreasing the amount of required maintenance during Operations and Maintenance Phase**
   - Enable predictive maintenance methods through advances in data fusion methods and techniques

NASA Transformational Tools and Technologies Project
Additive Manufacturing (Metals)



In-situ Measurements using Configurable Architecture Additive Testbed (CAAT)

Objectives

• Investigate the use of a low cost in-situ near infrared (NIR) sensor for real time measurement of the thermal history for improved additive manufactured builds.

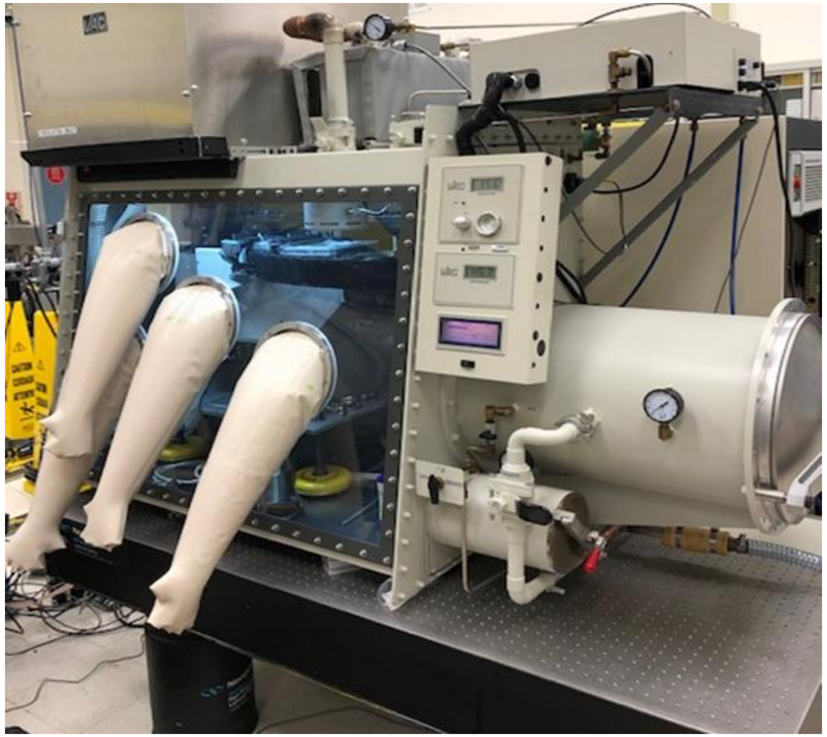
• Calibrate the NIR sensor and investigate the measured melt pool size based on varying process parameters.

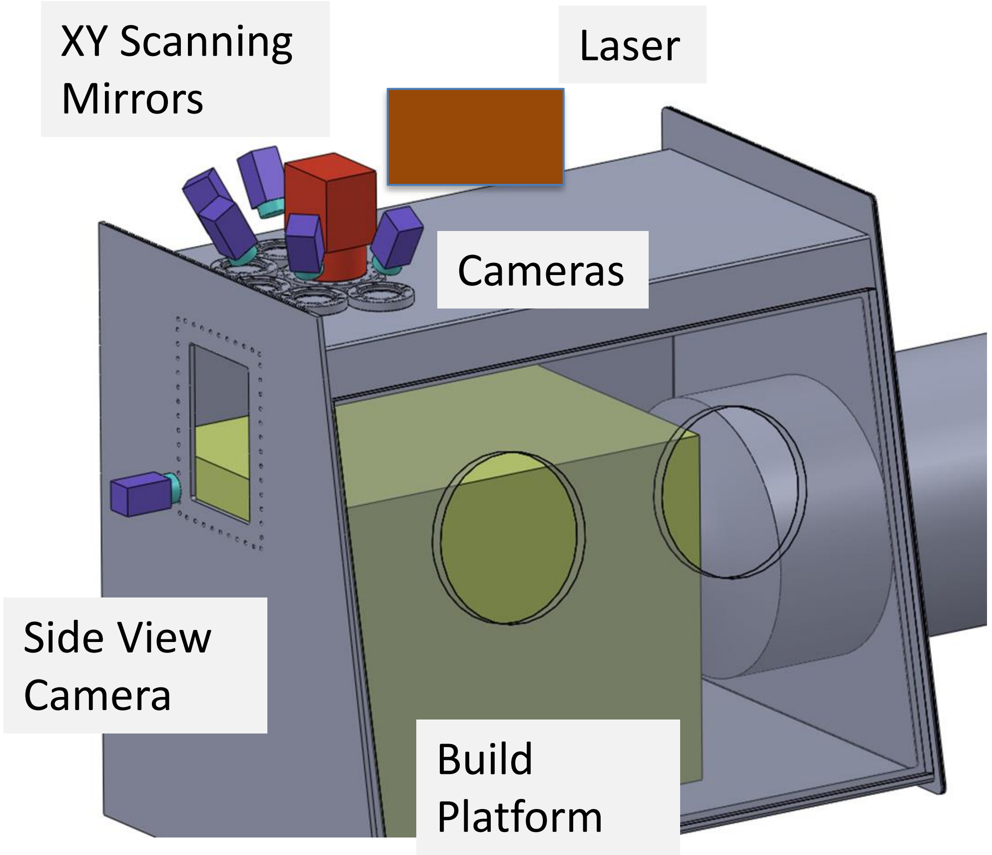
• Compare the melt pool width with microscopy measurements.

Payoffs

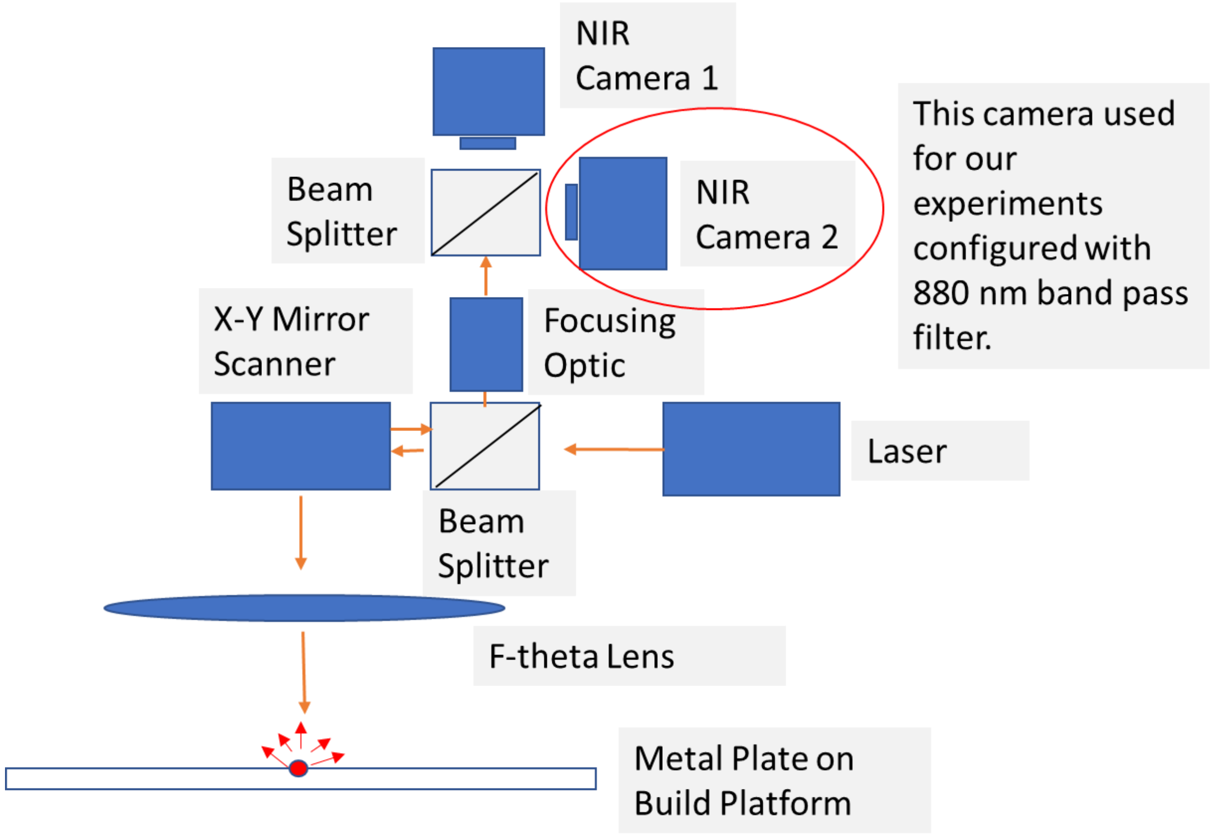
• Additively manufactured parts must be certified for broad application onto aircraft structures. By documenting the thermal history, process parameters for microstructure can be evaluated and real time inspections can be performed during the AM build. These results can be used to validate thermal models and build process parameters.

CAAT System Layout

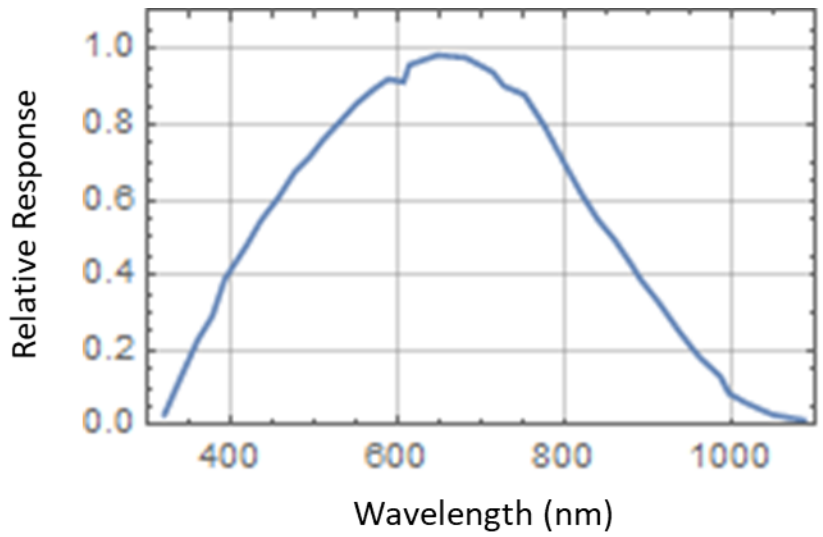




Co-axial NIR Optical Path



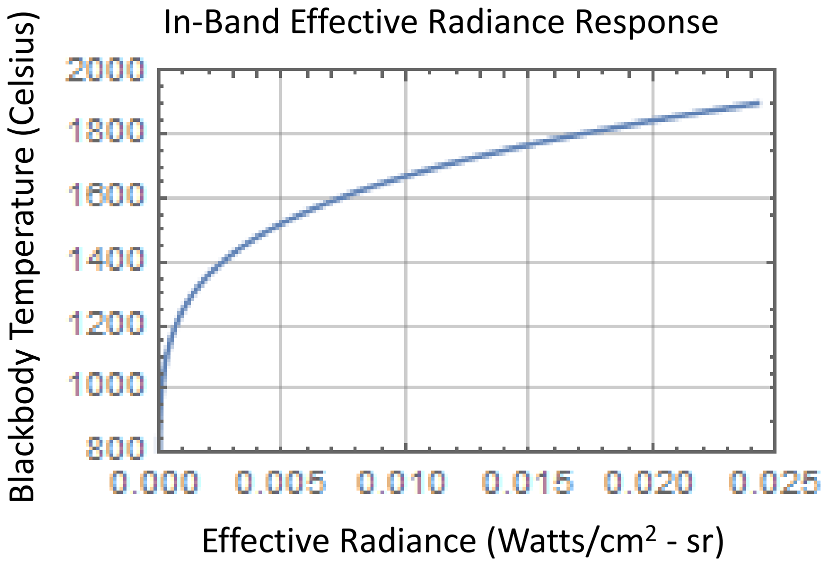
Basler acA640-750um

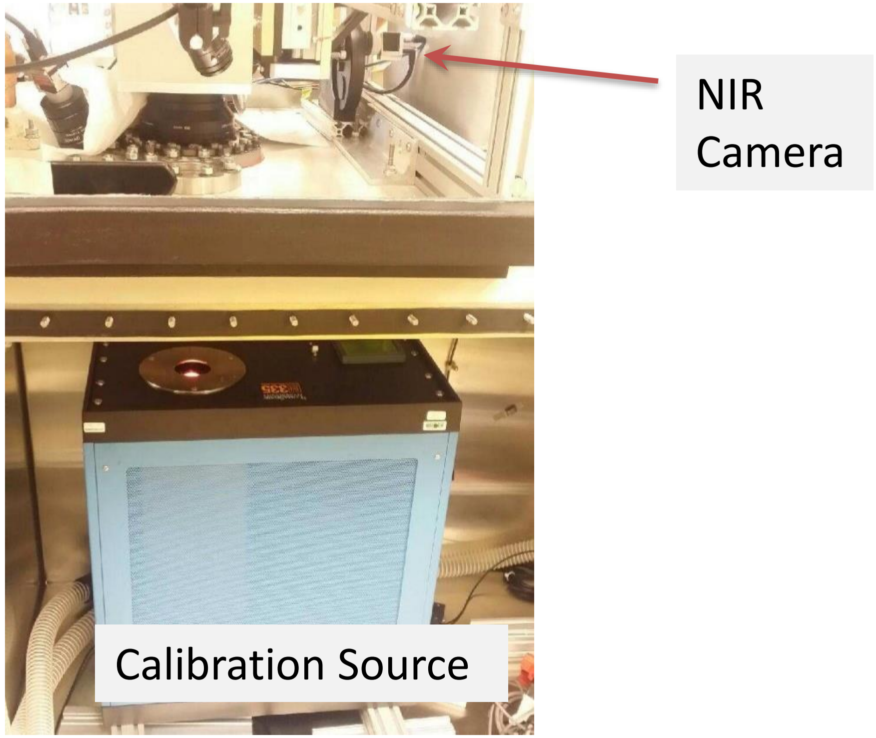


- NIR camera has 640 x 480 FPA, maximum frame rate = 751 Hz, pixel pitch is 4.8 x 4.8 um, configured with focusing optics and 880 nm narrow bandpass filter (875-884nm), resolution approximately 8.55 microns, ROI for images 144 x144, and provides frame rate of approximately 2,000 Hz.

Effective Radiance and Calibration

$$Radiance = \frac{1}{2}\int_{\lambda_1}^{\lambda_2} \frac{c_1}{\lambda^5\left(e^{\frac{c_2}{(\lambda\,(T+273.15))}}-1\right)} * \ sensor(\lambda) * filter(\lambda) * d\lambda \quad \text{where } c_1 = 2 * h * \ c^2 \quad \text{and} \quad c_2 = \frac{h * c}{k}$$





- Spectral band 875 to 884 nm defined by the 880 nm narrow bandpass filter.
- Camera frame rate approximately 2,000. Hertz with ROI pixel array size of 144x144.
- Temperatures used were 900, 1000, 1100, 1200, 1300, 1400, and 1500 degrees C for integration times were varied 59, 75, 100, 150, 300, 500, 700, 900, 1200, and 1500 micro-seconds.

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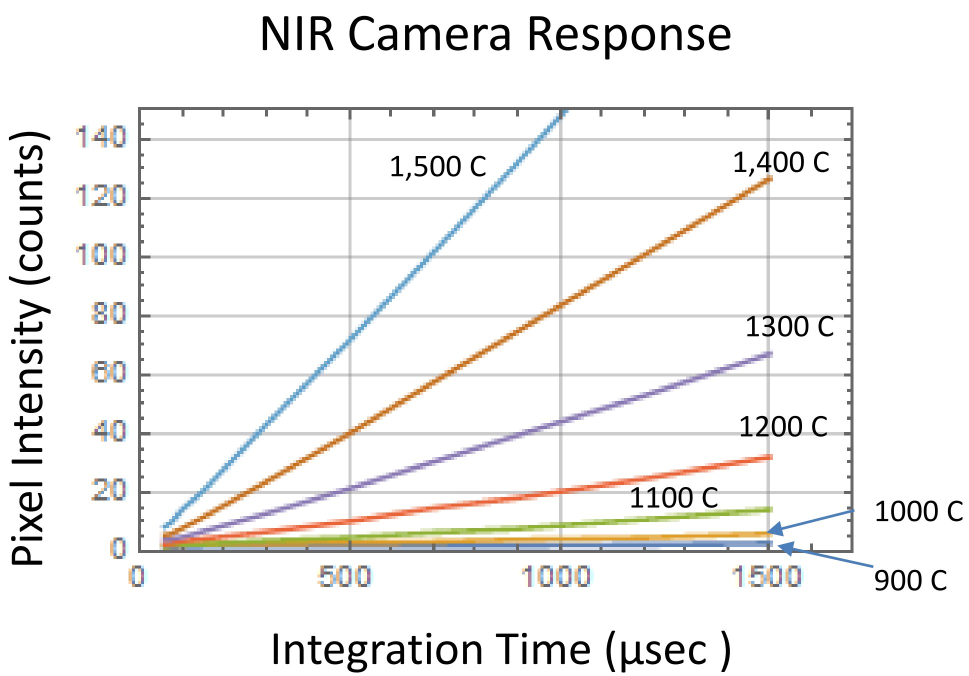
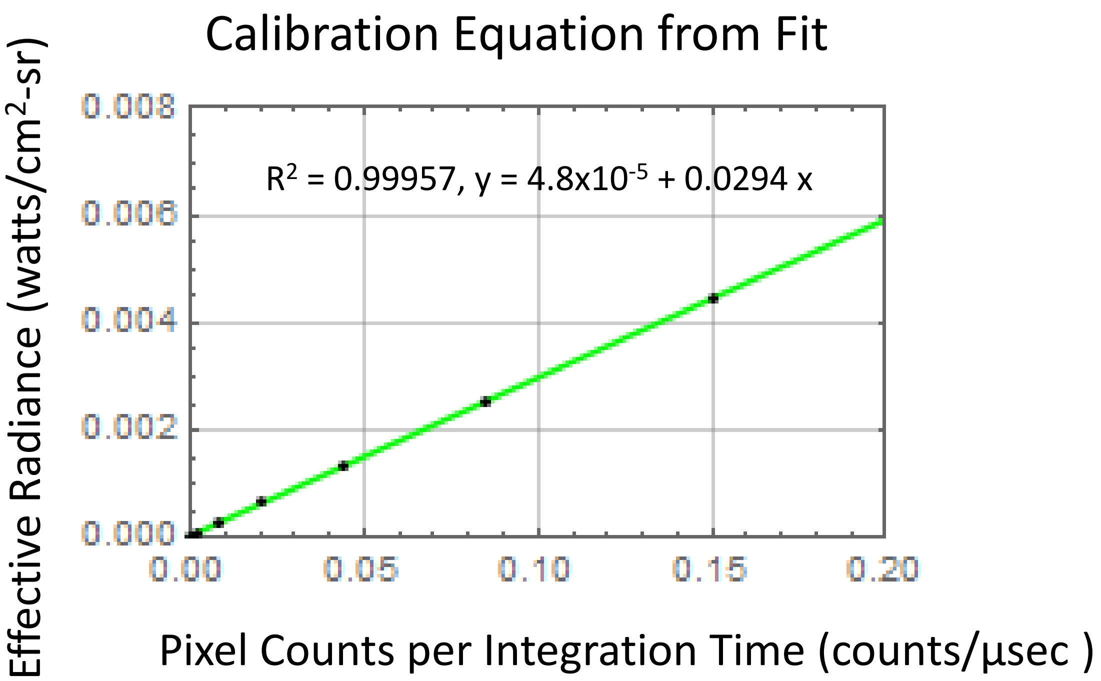
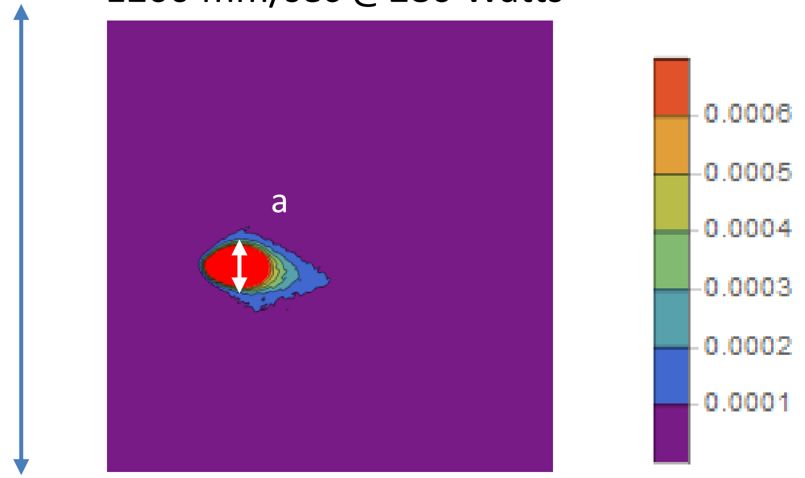
NIR Camera Calibration from Blackbody Radiation Source





In-situ NIR Melt Pool Imaging Results

1200 mm/sec @280 Watts

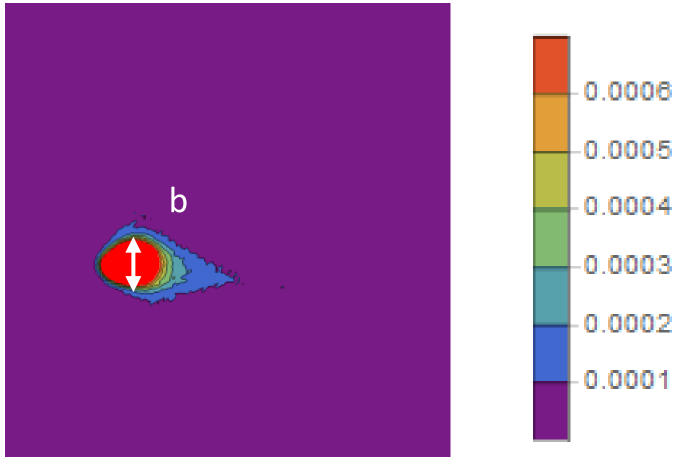


Effective Radiance (watts/cm^2-sr)

1.2 mm

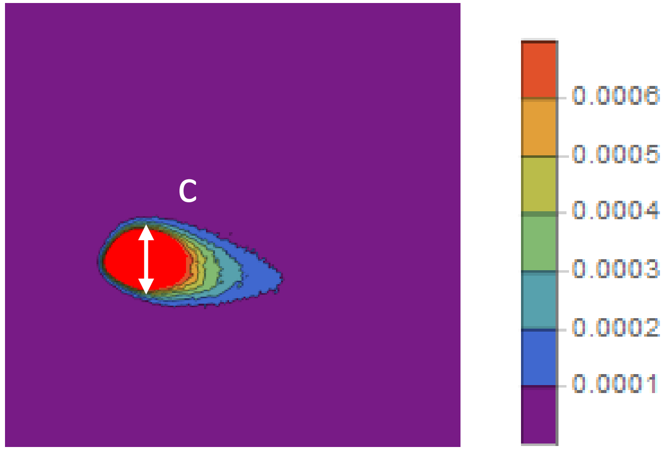
Direction of Travel

750 mm/sec @280 Watts

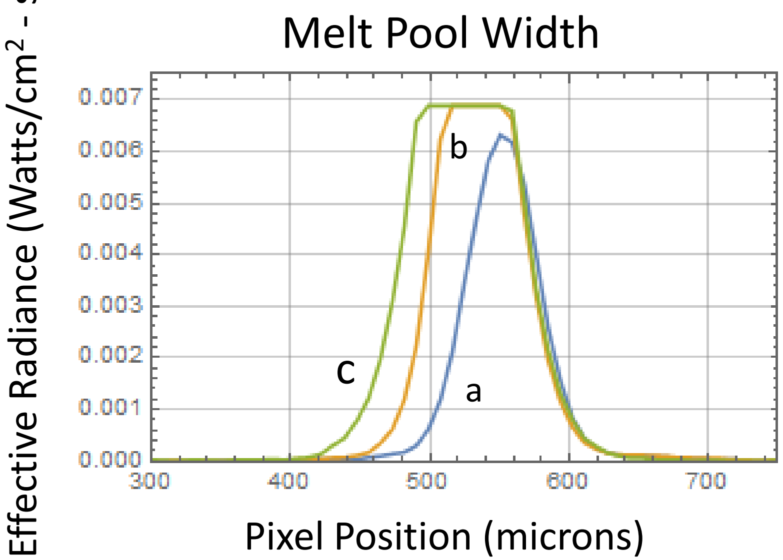


Effective Radiance (watts/cm^2-sr)

500 mm/sec @280 Watts



Effective Radiance (watts/cm^2-sr)

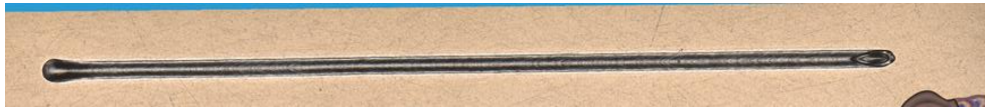


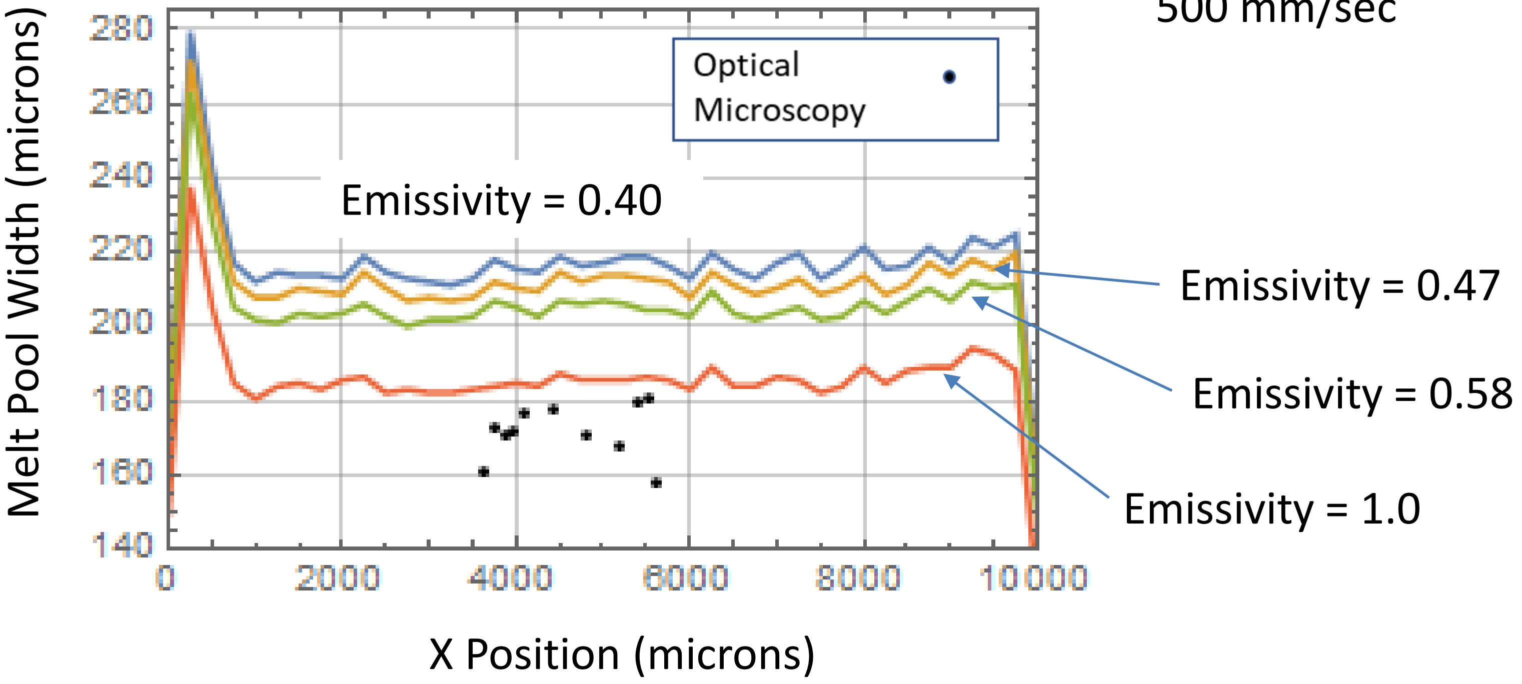
Requirements for Measurement of Melt Pool Width

- Radiometric calibration for interpretation of camera imagery.
- Thermal camera pixel resolution – Measured Pixel Resolution Approximately 8.55 microns.
- Solidus temperature value – 1605 Degrees C (Ti-6Al-4V).
- Blurring due to movement of laser beam vs. camera integration time.
- Surface emissivity value (vary with material, surface geometry and temperature).
- Accurate destructive measurements using microscopy.

Melt Pool Imagery (Laser Scanning 500 mm/sec) for Various Emissivity Values Compared to Optical Microscopy – Blurring Uncorrected

Top Down Image



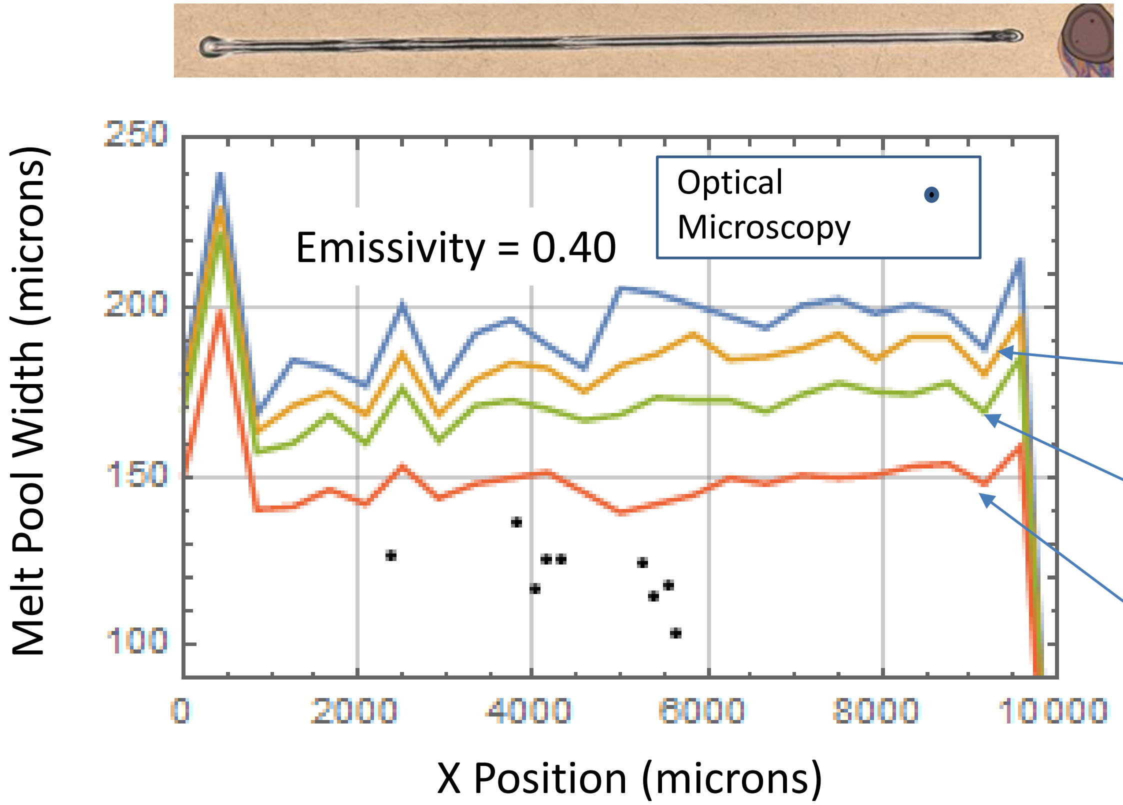


Laser Scanning Direction →

Laser Velocity = 500 mm/sec

Melt Pool Imagery (Laser Scanning 750 mm/sec) for Various Emissivity Values Compared to Optical Microscopy – Blurring Uncorrected

Top Down Image



Laser Scanning Direction →

Laser Velocity = 750 mm/sec

Emissivity = 0.47

Emissivity = 0.58

Emissivity = 1.0

Removal of Blurring using Inverse Filtering

- Laser velocity of 500 and 750 mm/sec combined with camera integration time (200 microseconds) results in ~ 12 pixel and ~ 18 pixel blur respectively.
- Use Weiner inverse filtering technique to remove camera blur.

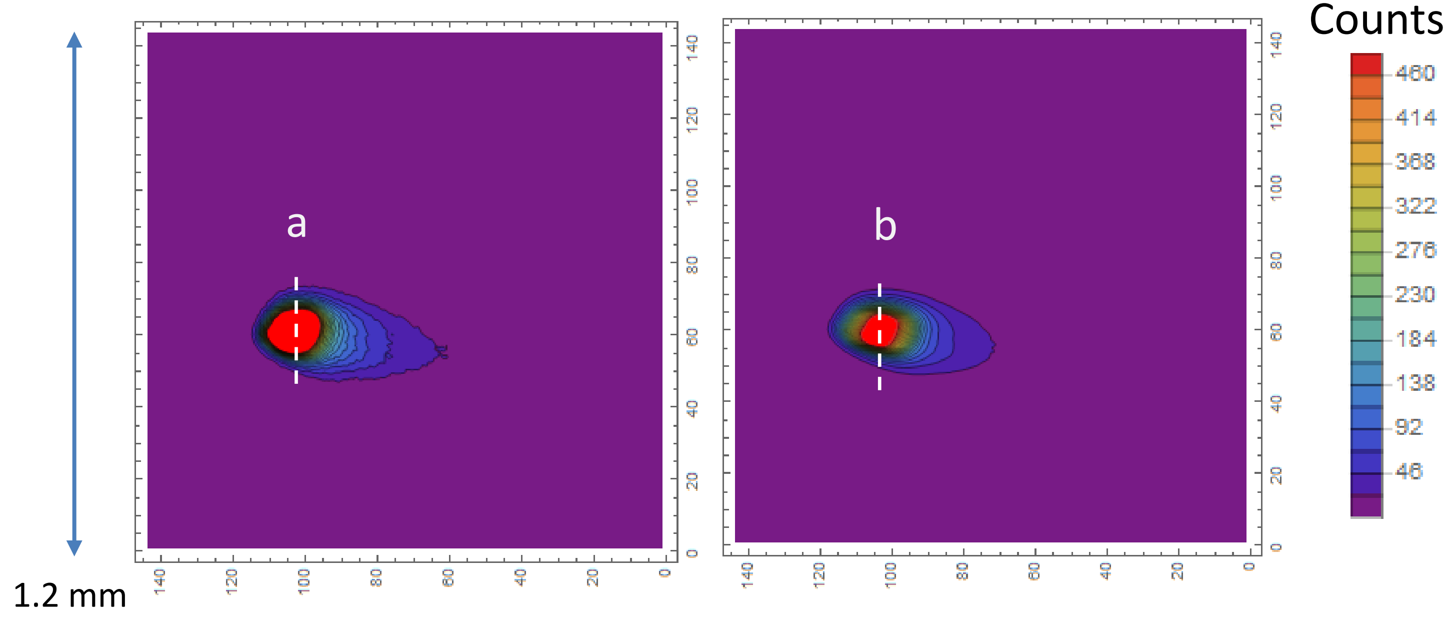
$$W(u,v) = \frac{H^*(u,v)}{|H(u,v)|^2 + K(u,v)}$$

$$Deblurred\ Image\ (u,v) = W(u,v) BlurredImage\ (u,v)$$

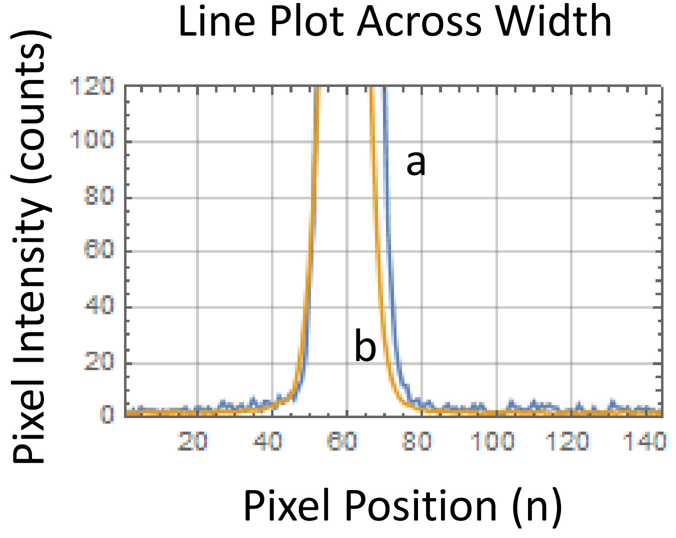
Blurred

Deblurred

Intensity Counts



Line Plot Across Width

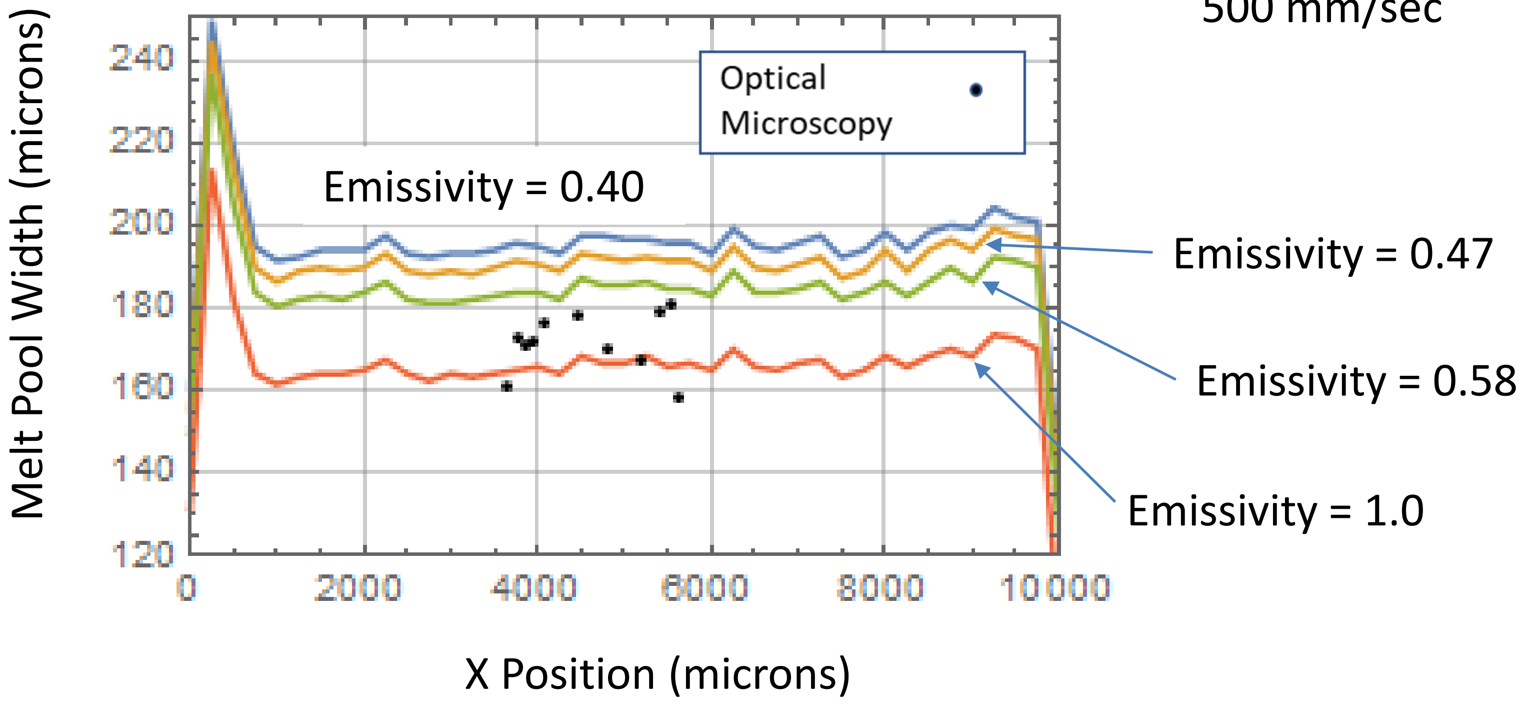


Melt Pool Imagery (Laser Scanning 500 mm/sec) for Various Emissivity Values Compared to Optical Microscopy – Blurring Corrected

Top Down Image

Laser Scanning Direction →

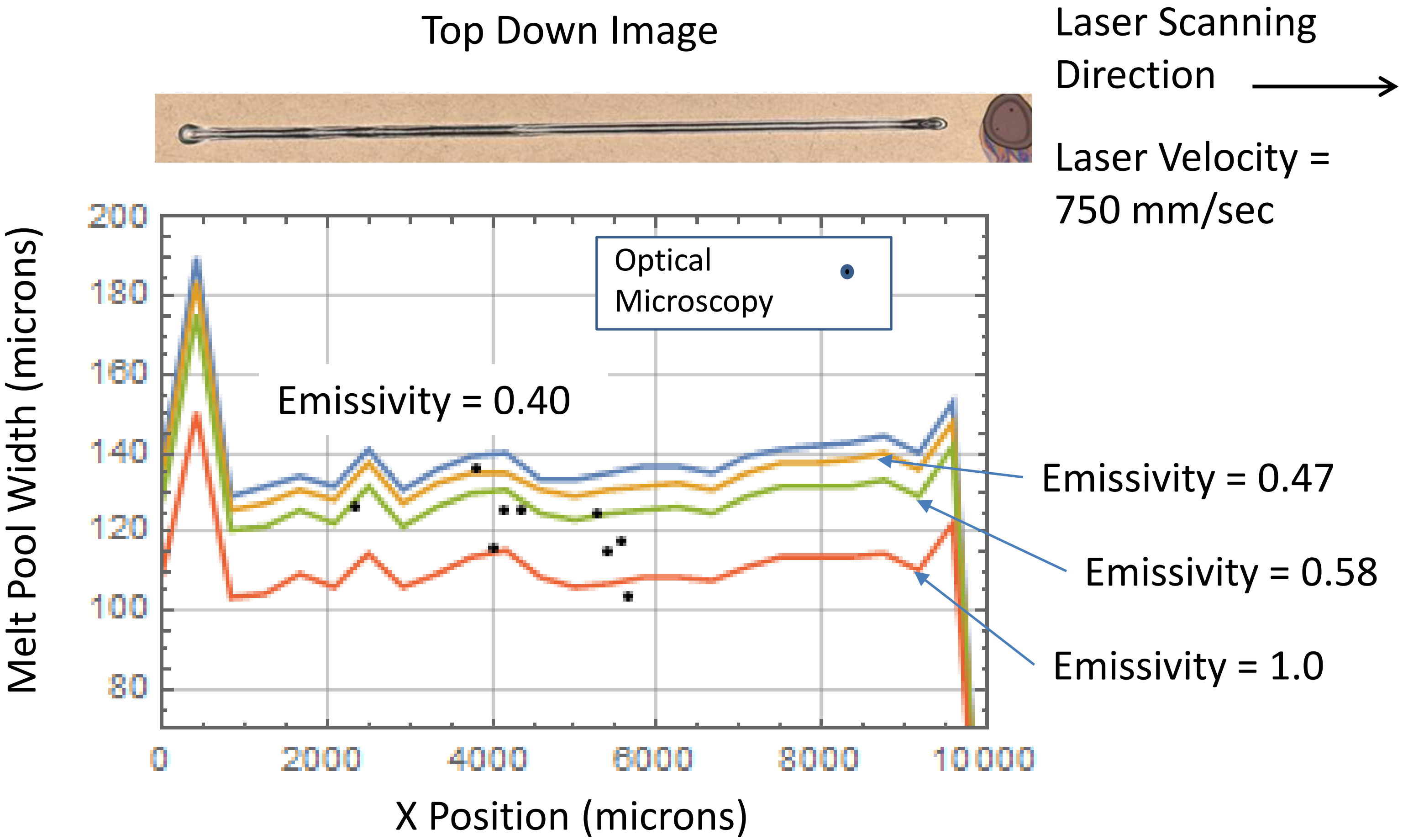
Laser Velocity = 500 mm/sec



Melt Pool Imagery (Laser Scanning 750 mm/sec) for Various Emissivity Values Compared to Optical Microscopy – Blurring Corrected

Laser Scanning Direction →

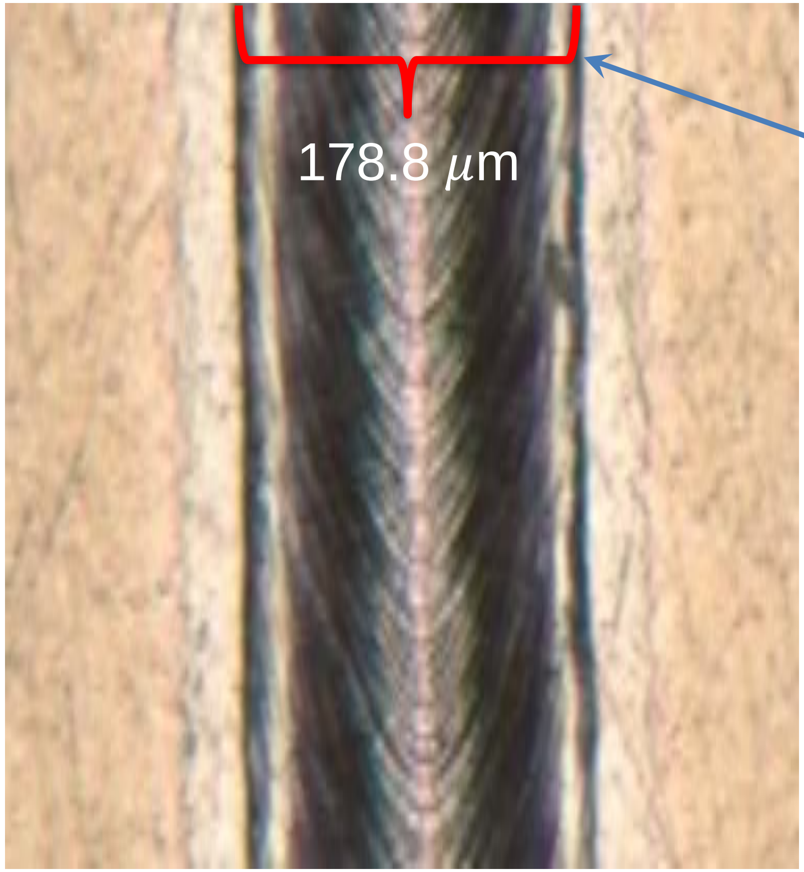
Laser Velocity = 750 mm/sec



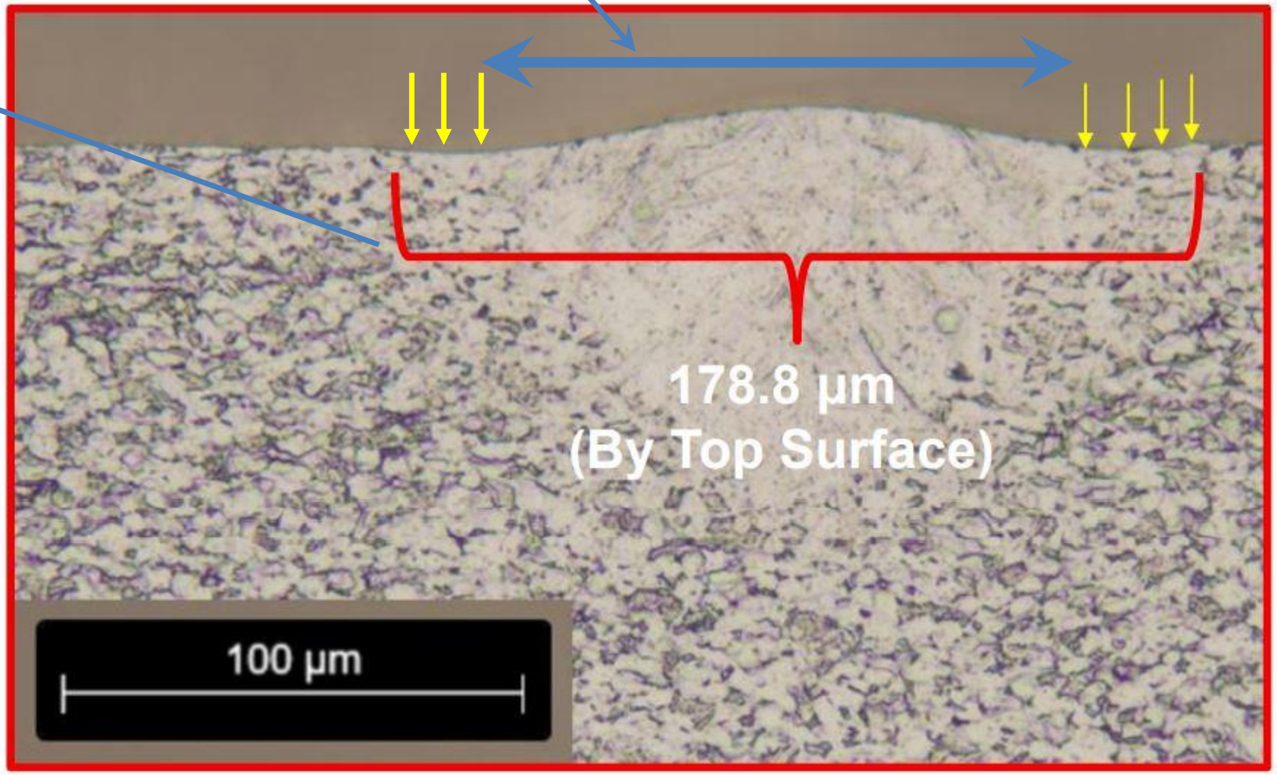
- Inverse deblurring filter helps with agreement, however other factors might be contributing to these errors such as plume effects, calibration errors, sensor blooming, etc.

Optical Microscopy Measurement Challenges for Melt Pool Width

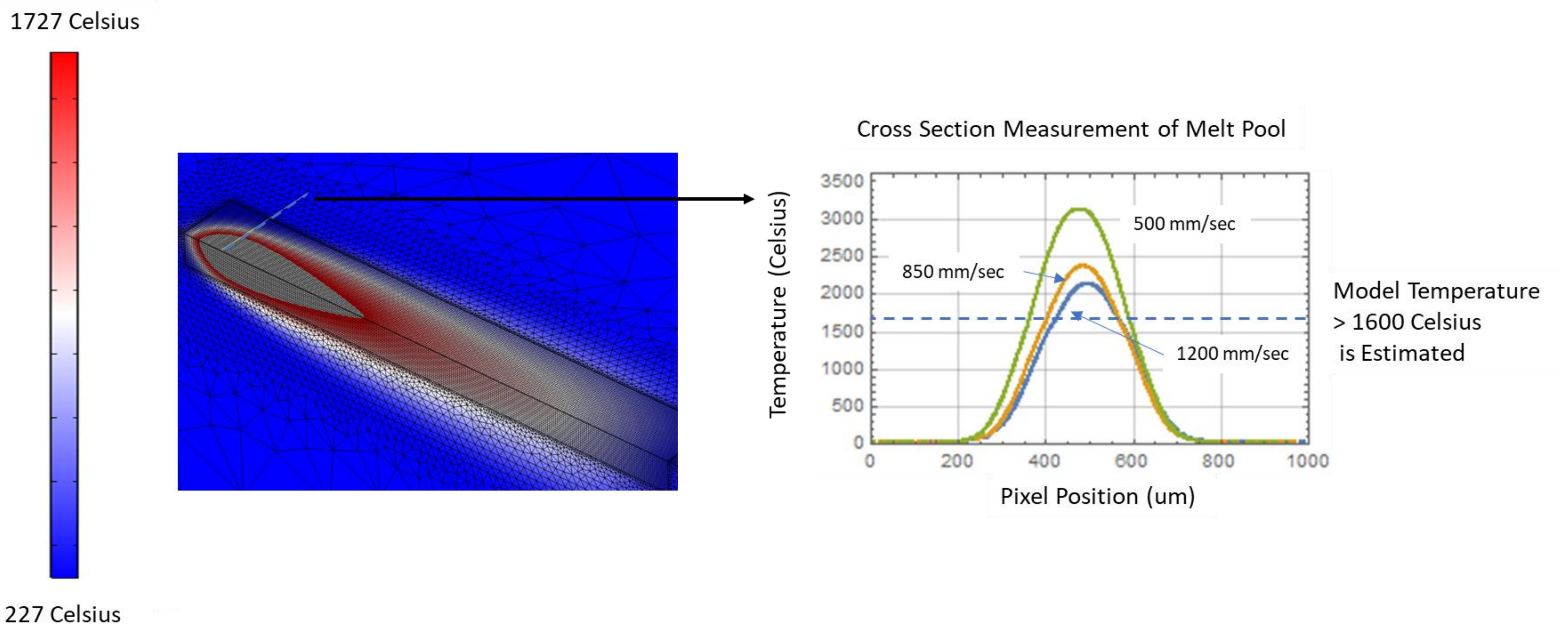
Top Down Image



Melt Pool Width
by Cross Section
133.4 μm

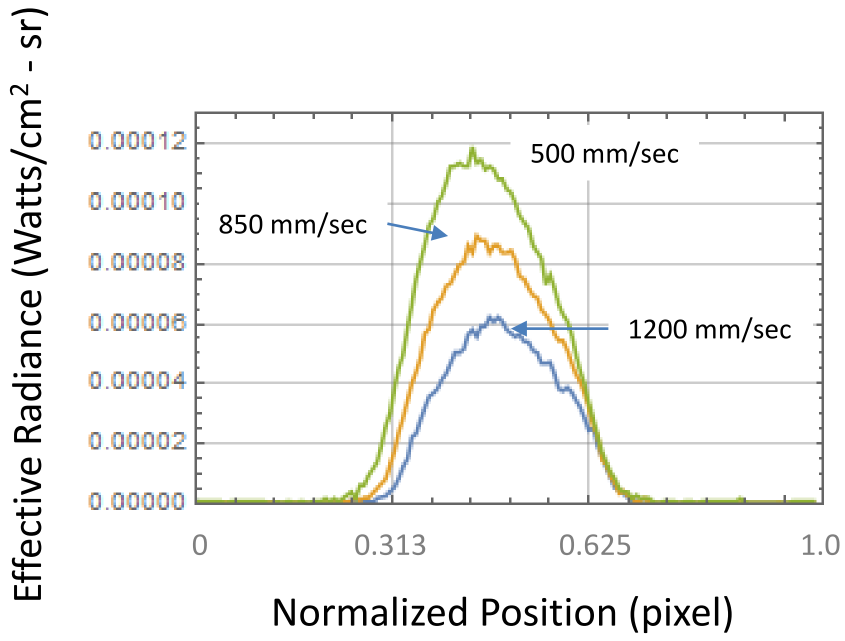


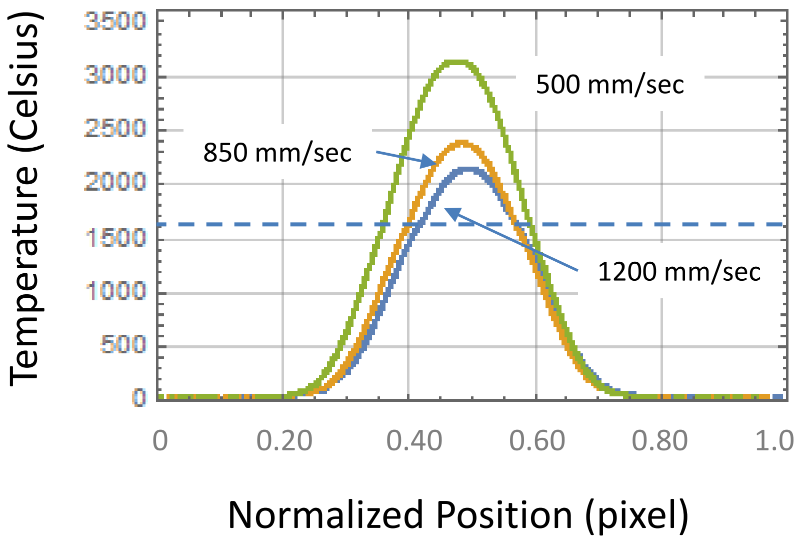
Finite Element Modeling of Surface Temperature



- The COMSOL model uses a volumetric heat source and was calibrated to the optical microscopy measurements. The gray center in the middle shows the melt pool and semi-solid regions.

Preliminary Comparison of Measured Radiance to Model for Melt Pool Width



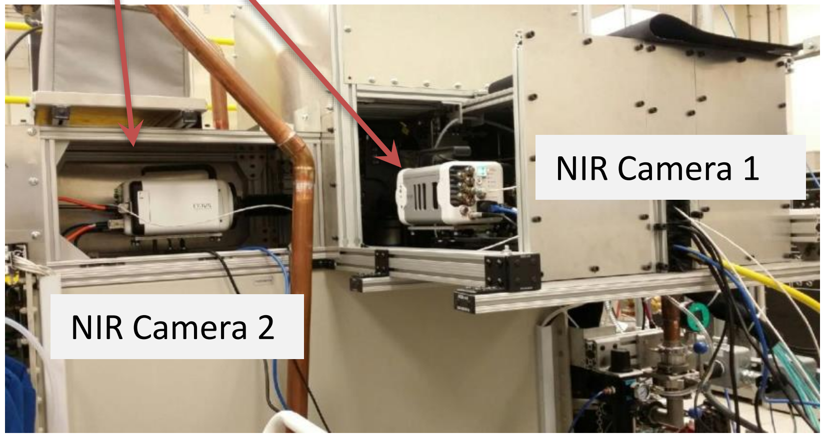


Model Temperature > 1605 Celsius is Estimated

- Comparison of in-situ measured melt pool width to model predictions is progressing.
- Radiometric calibration allows for initial comparisons to models however, emissivity, plume effects, powder splatter, varying melt properties, etc. can make things challenging.

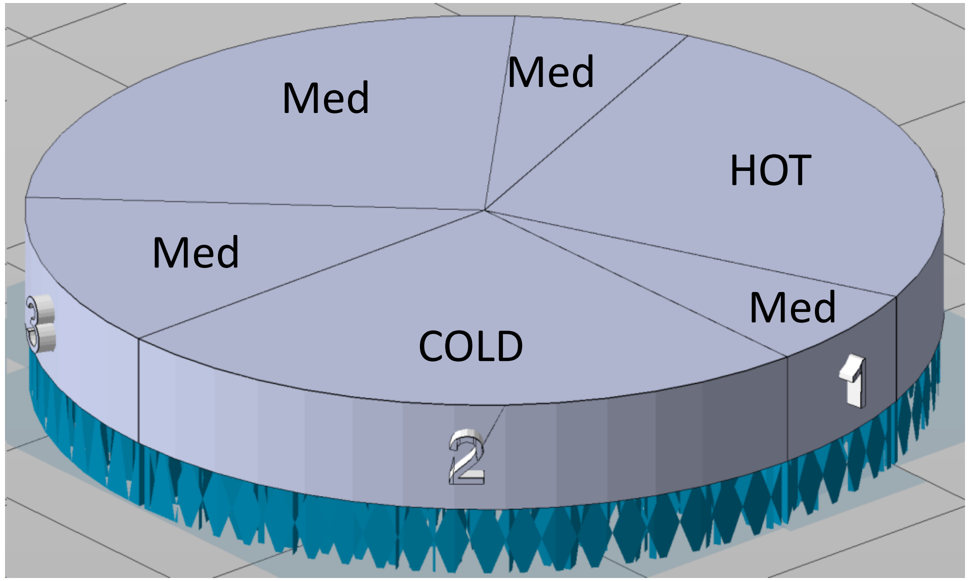
Most Recent Results

- Higher speed cameras installed for improved temporal and spatial imaging.
- Registration of in-situ measurements to X-ray CT.
- Future work: continue/refine comparison of melt pool width measurements to FEM models for given process parameters.



Recent Fabrication using CAAT System

Designed Part



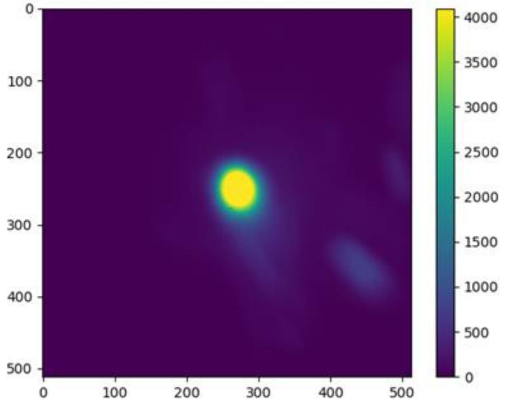
Built Example

- Disk slices represent different build parameters denoted by circumferential numbering scheme.

In-situ Monitoring Mapping of Built Part

As built example part

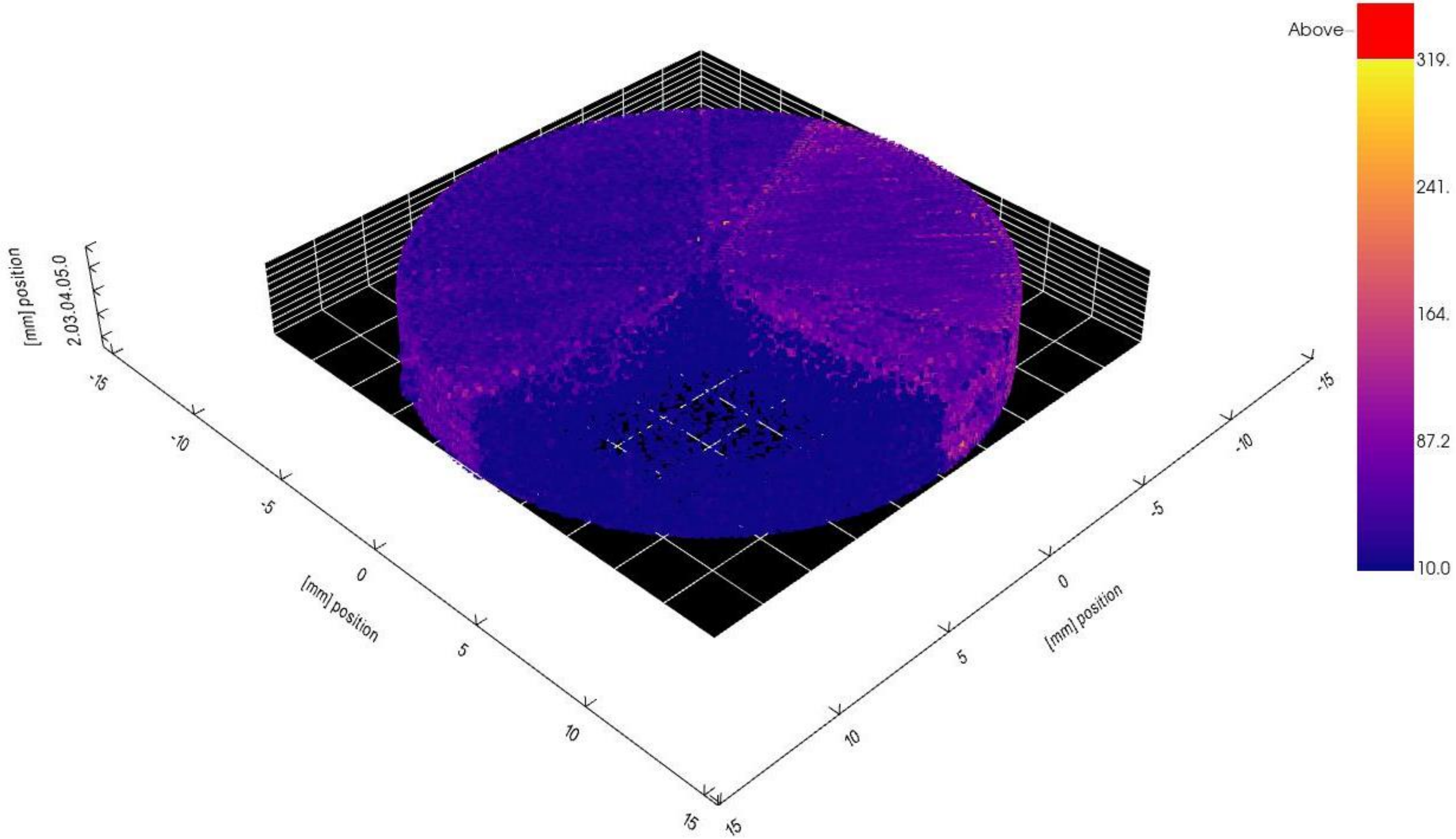
Melt pool image,
3kHz sampling rate @ 12bit



Mean = 112.4 counts

Build mapped with in-situ monitoring measurements

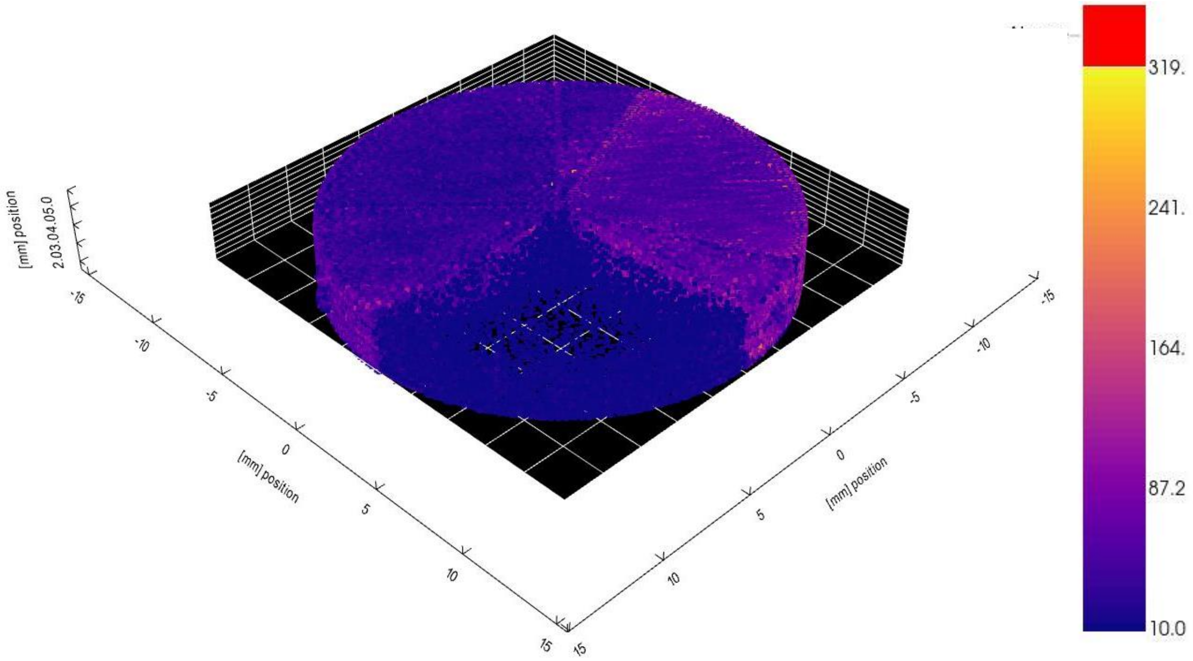
Melt-pool image mean [counts]



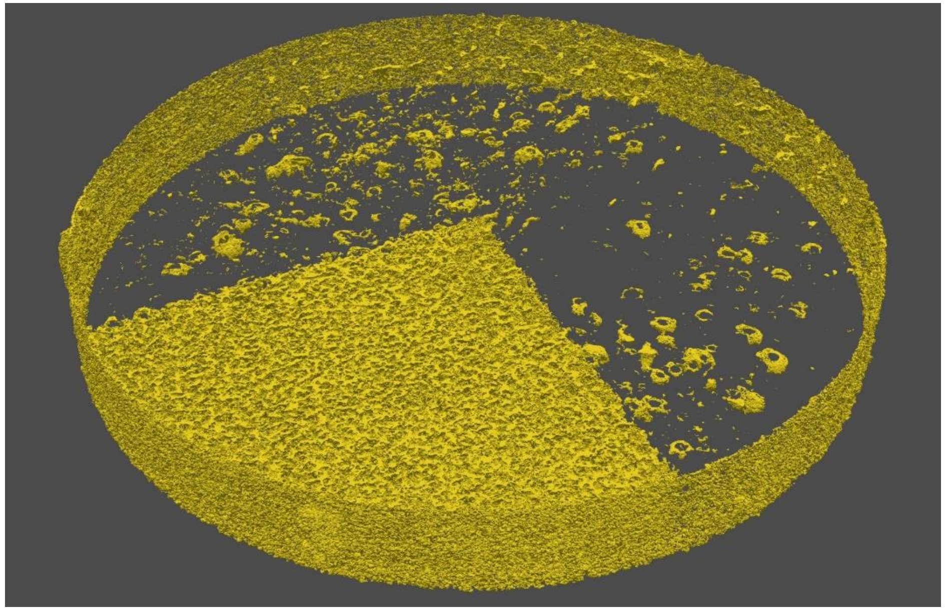
Registered X-ray CT to In-situ Measurements

Build mapped with in-situ monitoring measurements

Melt-pool image mean [counts]



Porosity segmented X-Ray computed tomography



Summary

- A low cost NIR camera was calibrated and used to measure the width of the melt pool on a Ti-6Al-4V plate.

- Blurring effects, due to relatively long integration time, was reduced by inverse filtering.

- Optical microscopy measurements were used to compare the NIR melt pool width with marginal agreement. Need to investigate error in optical microscopy measurements to validate NIR melt pool width measurements.

- CAAT system operational for building AM parts with high-speed cameras used for in-situ measurements.

- Registered in-situ infrared measurements with X-ray CT for volume comparisons.