Thermographic and FE Simulation of the DMLS Process at NIST

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Outline

- Background
- Our Objectives
- FE Simulation of DMLS
- Thermography Experimental Setup
  - Results: Initial ‘Radiant Intensity’ Videos
  - Camera Calibration
  - Results: Conversion to ‘Temperature’
- Discussion
- Future endeavors
- Conclusions

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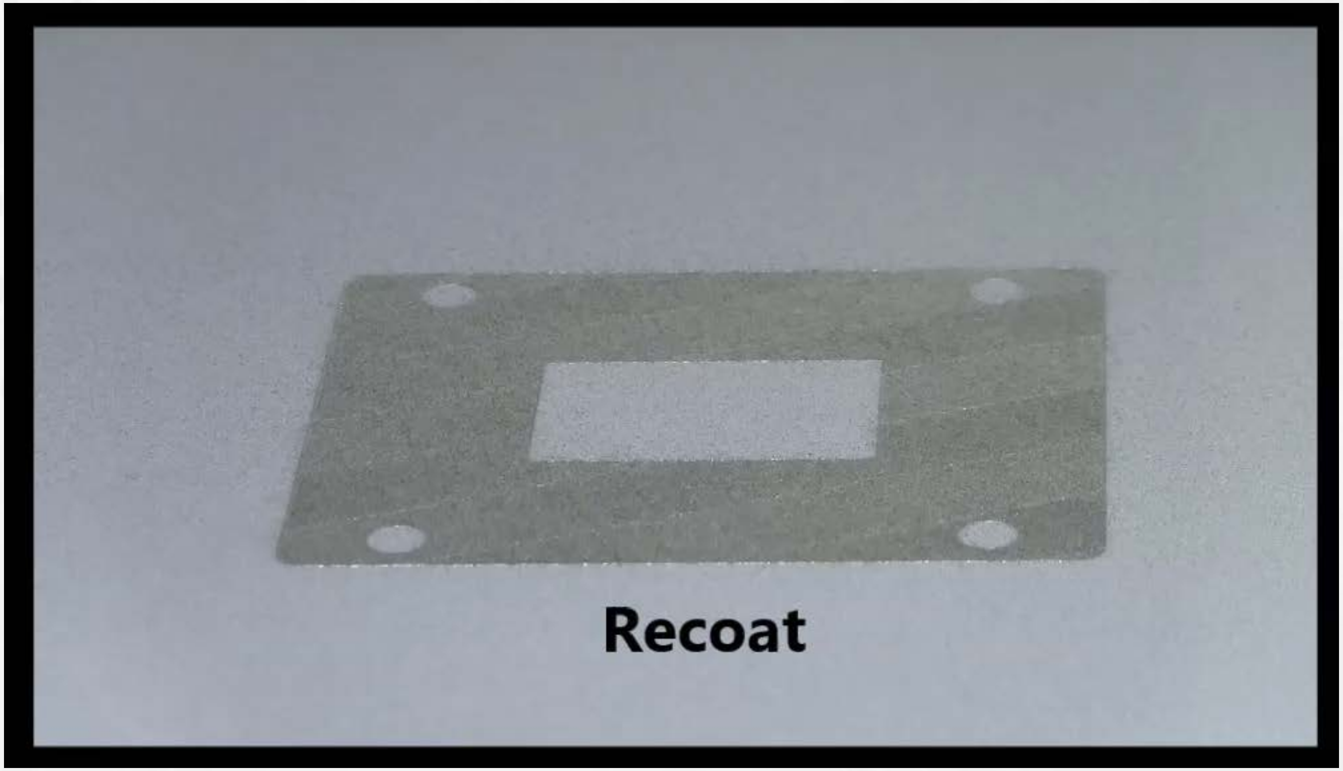
Background

- Example of DMLS process on EOS M270 machine
  - 200 W laser, 100 μm spot diameter
  - ≈ 0.8 m/s scan speed
  - ≈ 30 μm metal powder particles, ≈ 20 μm layer thickness



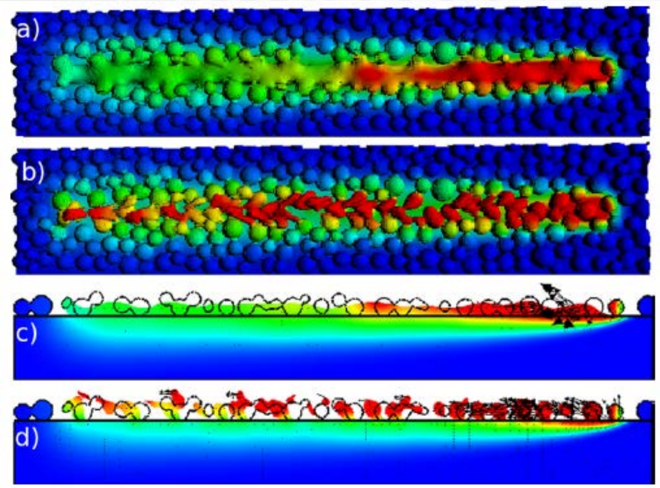
Background

- What are the challenges?*
  - Residual stress, distortion, surface finish, defects…
  - Lack of sensors for monitoring and control
  - Fundamental understanding of DMLS physics
- Temperature is **a key signature** of the physical processes
- Simulations will be key to understanding process and predicting
- How can we compare thermal measurements with simulations in an *accurate*, *scientifically sound* way?

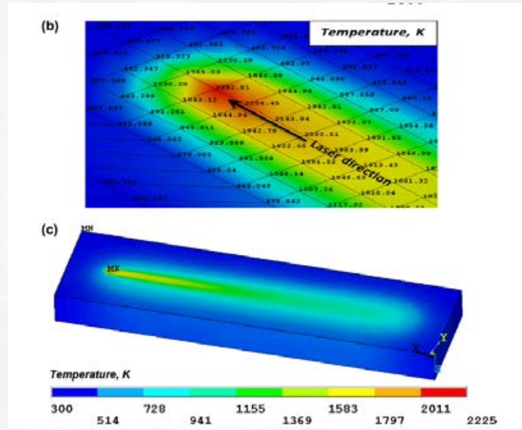
*-Energetics Inc. for National Institute of Standards and Technology (2013). *Measurement science roadmap for metal-based additive manufacturing*.

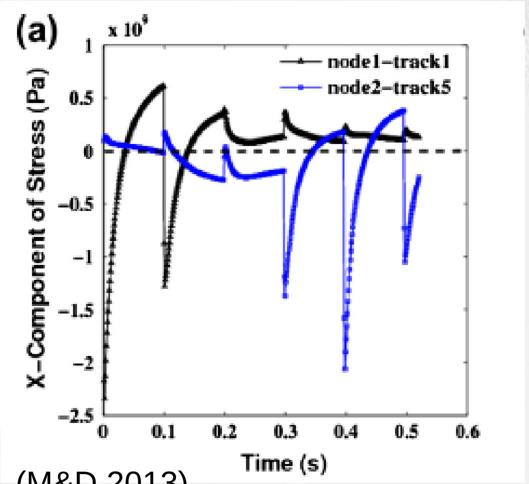
Background

- Process modeling and simulation



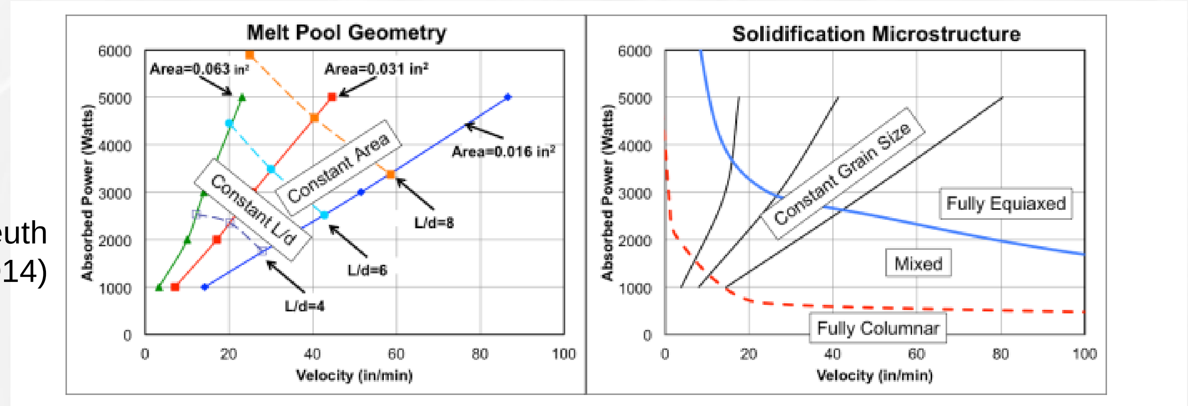
Khairallah et al. (JMPT 2014)





Hussein et al. (M&D 2013)

Gockel and Beuth (SFF 2014)

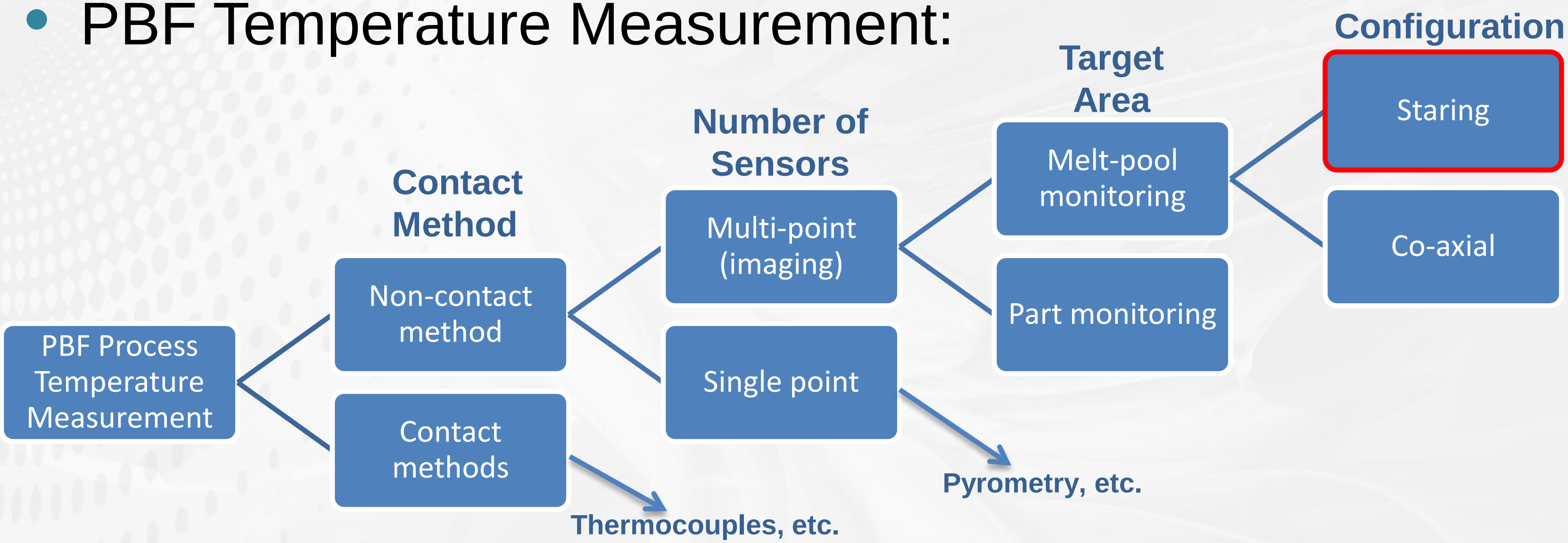


a) Melt pool geometry process map

b) Solidification microstructure process map

Background

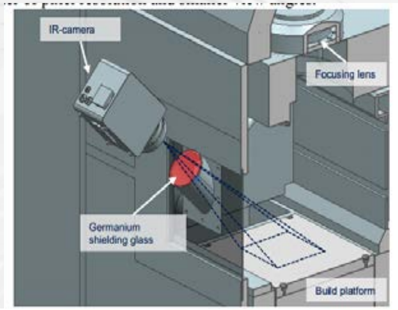
- PBF Temperature Measurement:

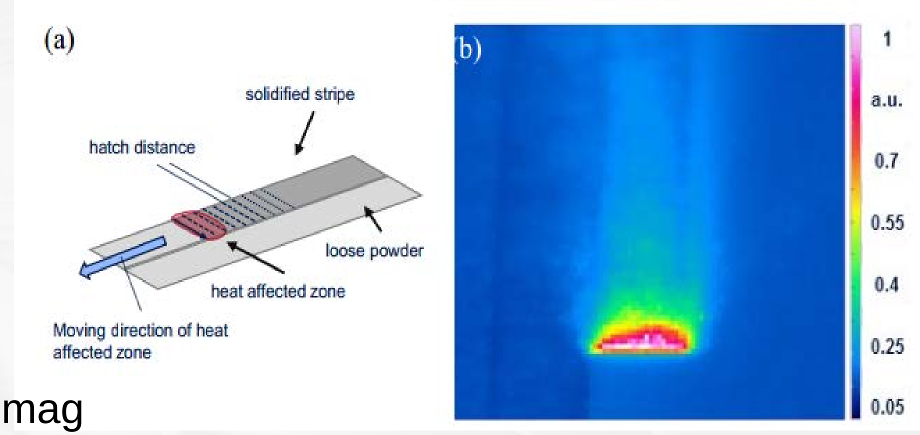


- Why thermography?
  - Non-contact, multi-point…
  - Spatial and temporal variation in temperature
- Why not? Data intensive, speed limited, inaccurate…but still useful.

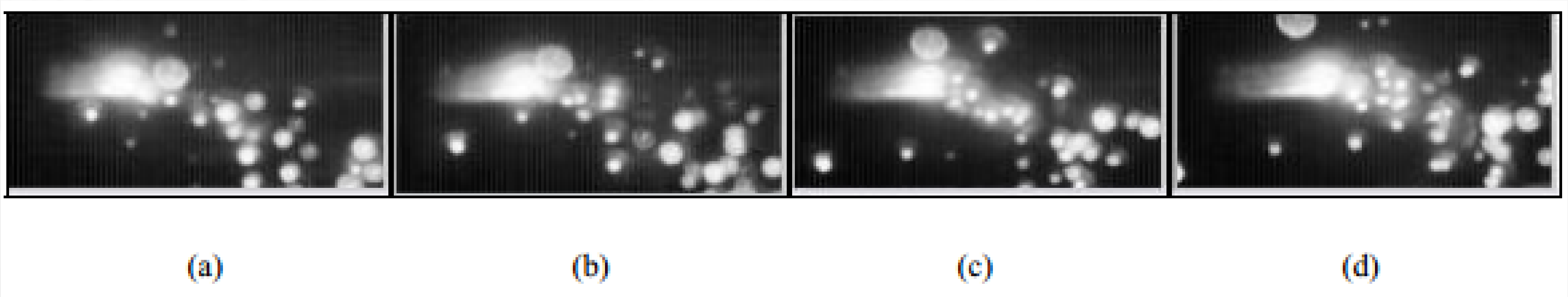
Background

- State of art: Melt pool monitoring of DMLS or SLM
- Krauss et al. (SFF 2012)
  - EOS M270, 50 fps, 5-15 ms int. time
- Bayle et al. (SPIE 2008)
  - Phenix PM100
  - MIR camera, 136x64 pixels, 2031 fps, 0.05 ms int.time
  - Only paper found with high speed, high mag thermal imaging of commercial SLM process





(Krauss et al., SFF 2012)



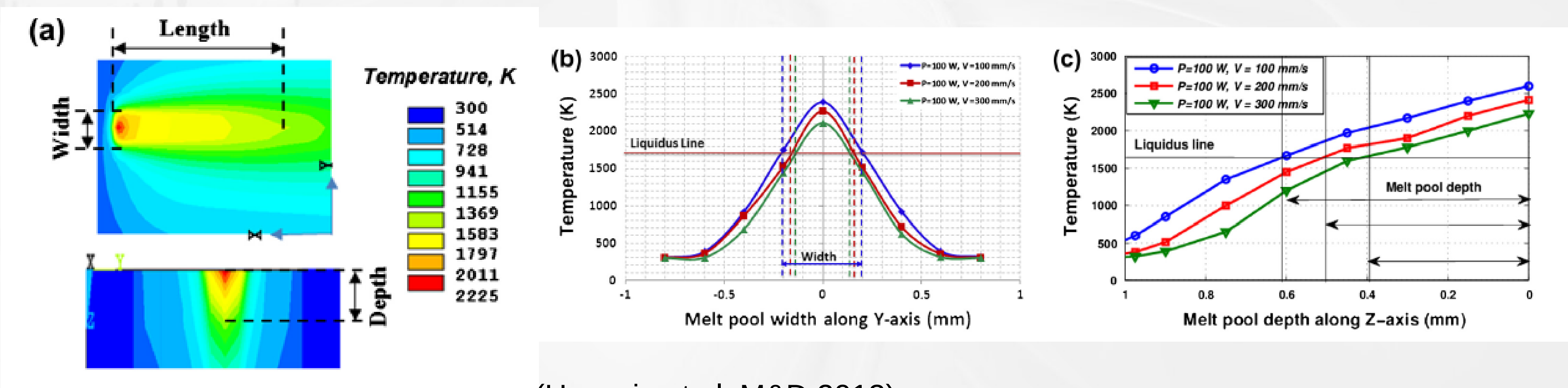
(Bayle and Doubenskaia SPIE 2008)

Objectives

- Our objectives for thermography of DMLS:
  - Provide data to <u>improve and verify process simulations</u>
  - Investigate relationship between input parameters – process signatures to <u>guide future development of sensing methods for feedback control</u>
- Objectives for simulation:
  - Achieve results comparable to experiment measurements (temperature, structure, metallurgy, …)
  - Sensitivity analysis of process parameters and /or simulation parameters
  - Incorporate metallurgical phase and residual stress predictive modeling based on temperature history of part
- Provide well characterized, quantitative measurements and results
- "…*when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind*…" - William Thompson – First Baron Kelvin

Objectives

- Note on our objectives:
  - Thermal video is not a measurand: one is defined and extracted from the thermal video (see Annex D of GUM guide)
    - Temperature value of a pixel? Real surface temperature? Rate of change of temperature?
  - Must weigh <u>accuracy</u>, <u>feasibility</u>, and <u>utility</u> of results in designing experiment (and selecting/defining a measurand)
  - 'Holy Grail' measurand commonly cited is the 'melt pool size' and 'melt pool temperature'



(Hussein et al. M&D 2013)

FE Simulation

ABAQUS

One layer multiple hatch scanning simulation

Two cases

- Scan on solid specimen
- Scan on one layer of powder on the solid substrate

Material: EOS PH1 (Stainless Steel 15-5)

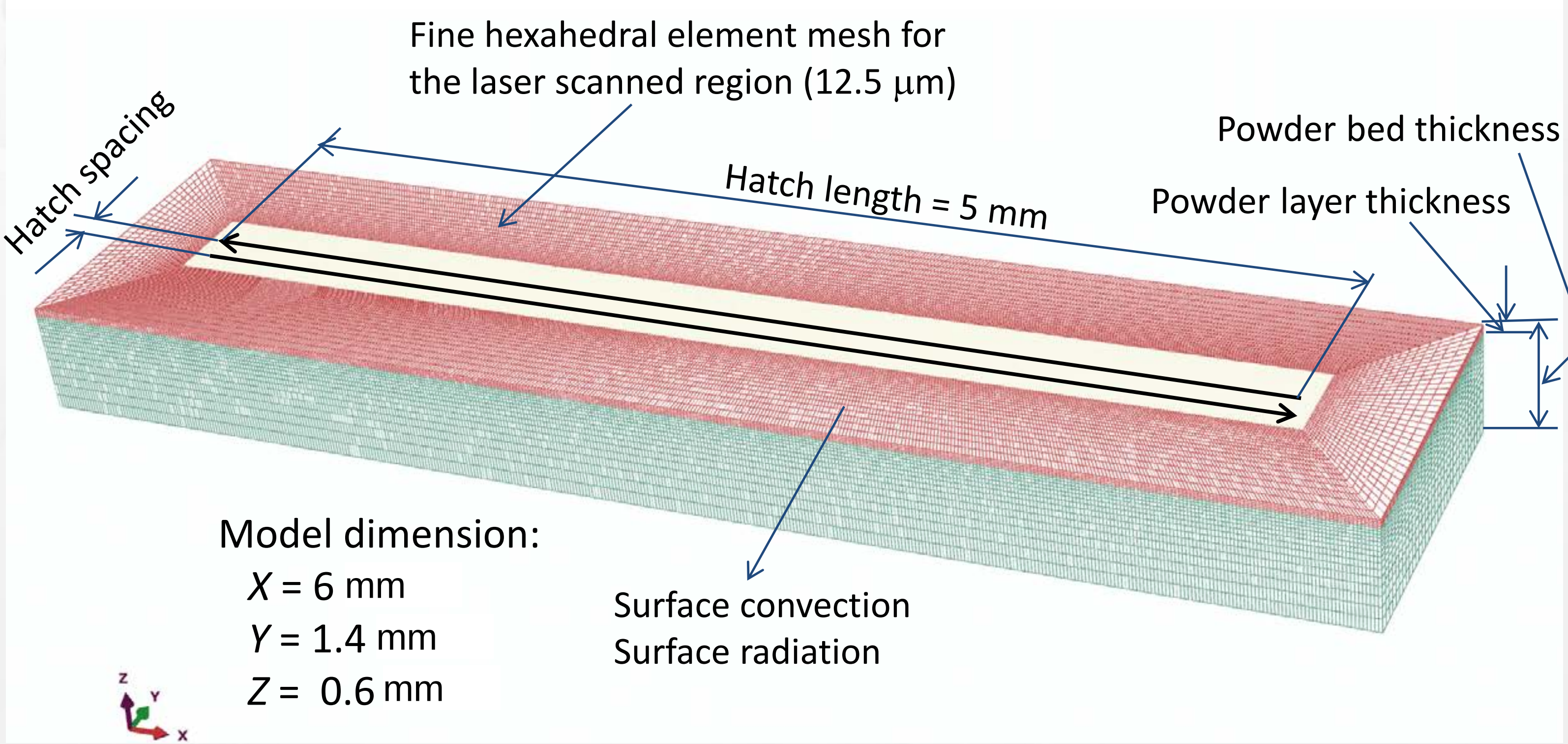
Laser source: Gaussian

Laser power: 195 W

Scan speed: 800 mm/s

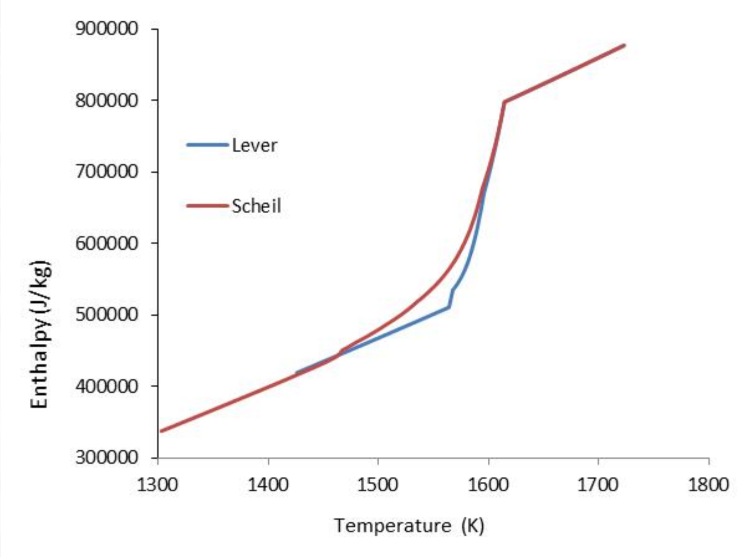
Spot size diameter: 100 μm

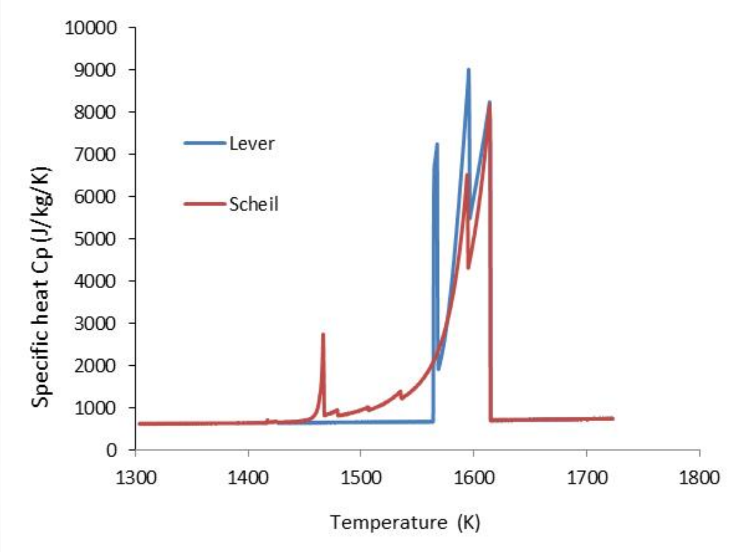
Hatch spacing: 100 μm



FE Simulation

Enthalpy Prediction from Thermodynamics Calculation (CALPHAD)





Courtesy of William Boettinger, NIST Fellow, MML

Two limiting cases of solidification behavior:

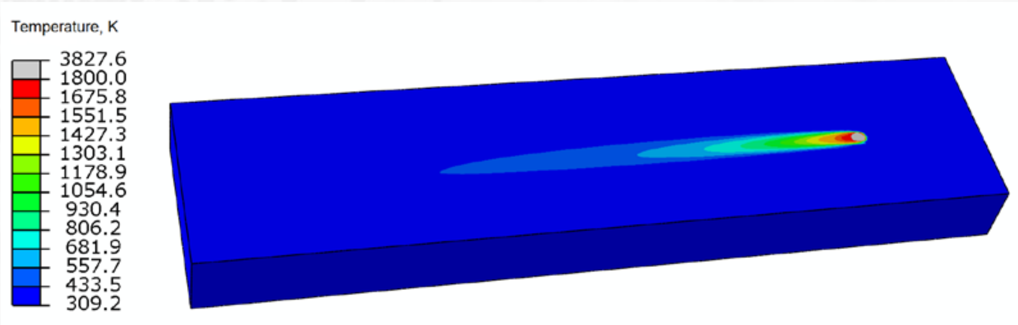
- Lever: complete diffusion, all phases are assumed to be in thermodynamic equilibrium at each T during solidification
- Scheil: diffusion in the solid is forbidden

AM Thermal modeling needs to include the data from thermodynamics calculation

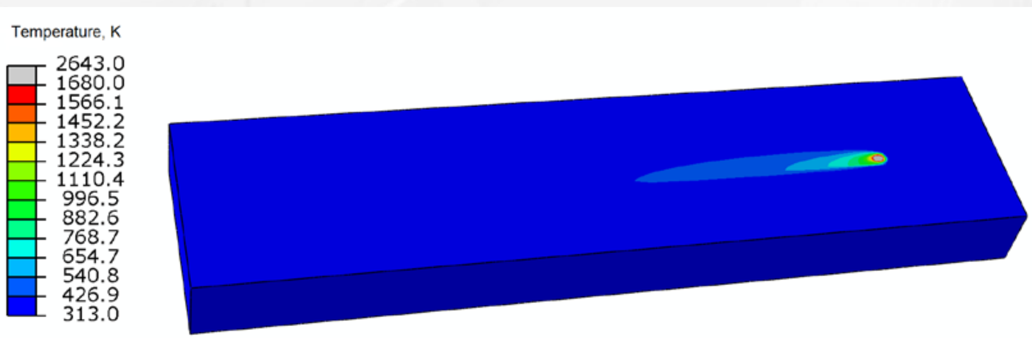
FE Simulation

Comparison of temperature after the 1st track scan (a) on one layer of powder on the solid substrate and (b) on solid substrate

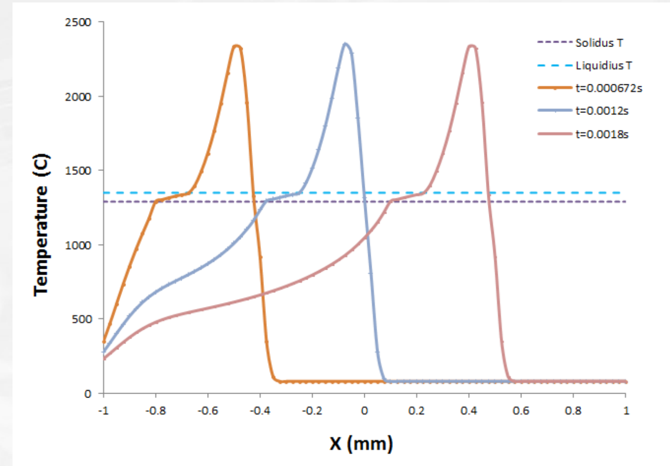
(a) On one layer of powder



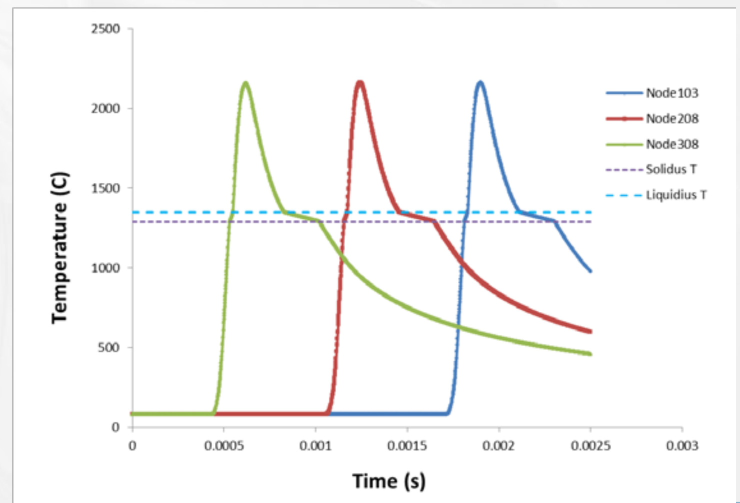
(b) On the solid substrate (surrounding material is powder)



Temperature as a function of x distance at top surface at three scanning time

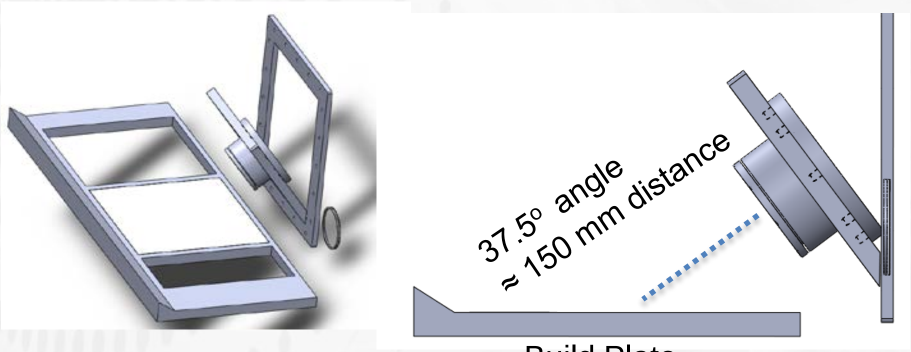


Temperature as a function of time at three surface node



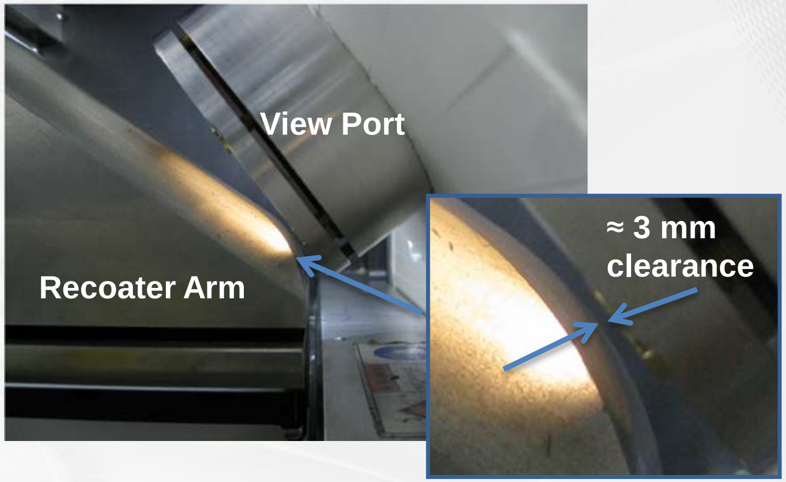
Experiment Setup

- EOS door
  - Objective: get the camera as close as possible (for highest magnification)
  - Custom built door for EOS machine

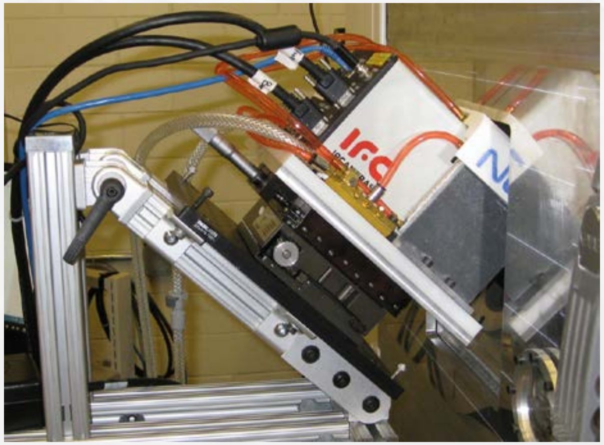


Build Plate

Solidworks model of EOS build chamber + custom viewport



Checking clearance of the viewport



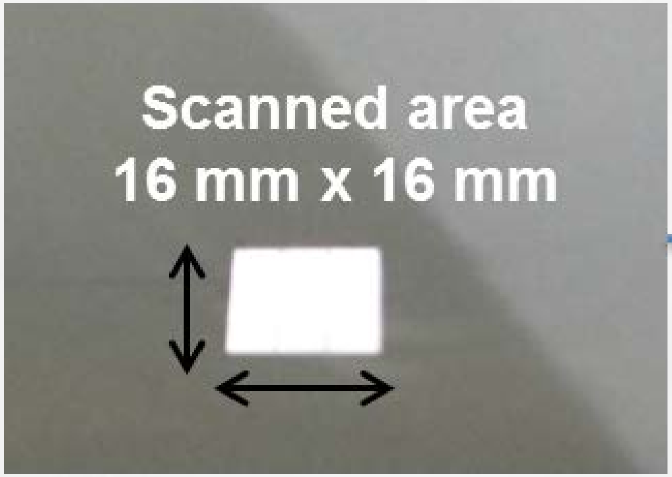
Thermal camera looking into the viewport

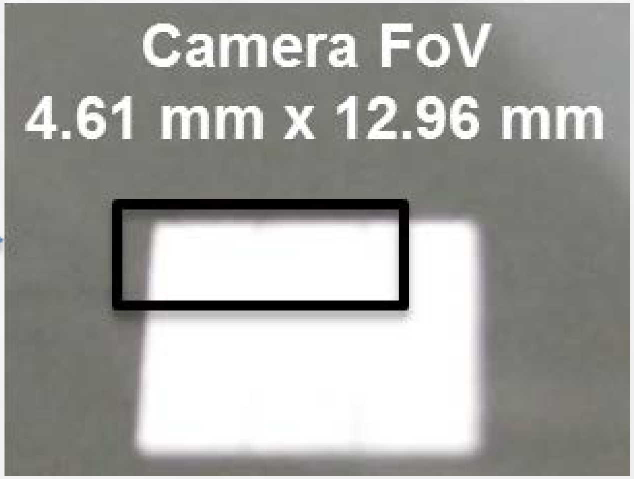
Results – Test 11 'Intensity'

- What are we looking at?

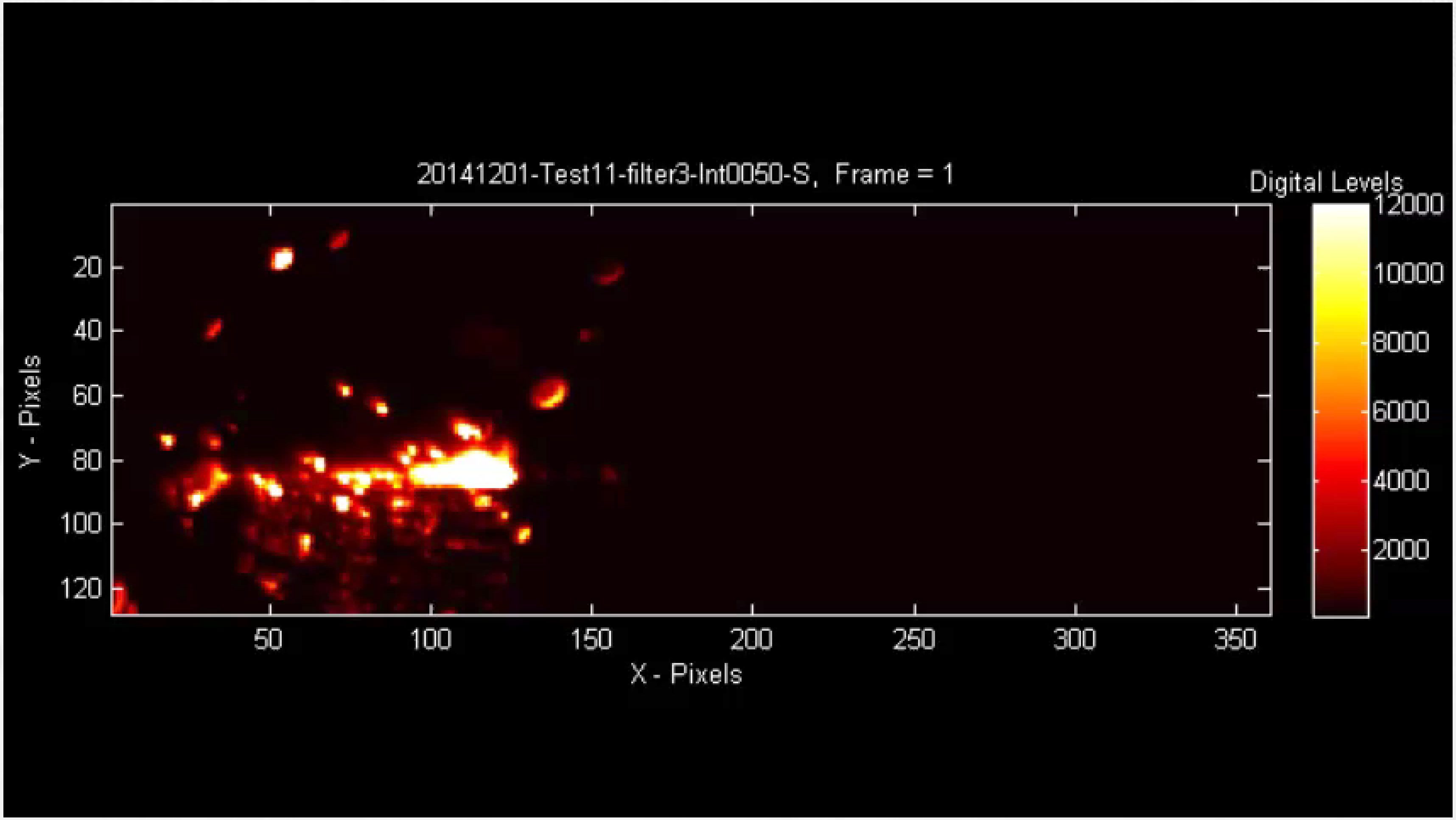
Camera Parameters:
iFoV: 36 μm/pixel
FoV: 128 pixel x 360 pixel
(4.61 mm x 12.96 mm)
Frame Rate: 1800 fps
Integration time: Test 11: 0.05 ms
Test 15: 0.02 ms
Spectral range: 1640 nm to 2400 nm

Build Parameters:
Material: EOS PH1 Stainless Steel
Mean Particle Size: 35 μm
Hatch Spacing: 100 μm
Hatch Width: 5 mm
Laser Power: 195 W
Scan Speed: 800 mm/s



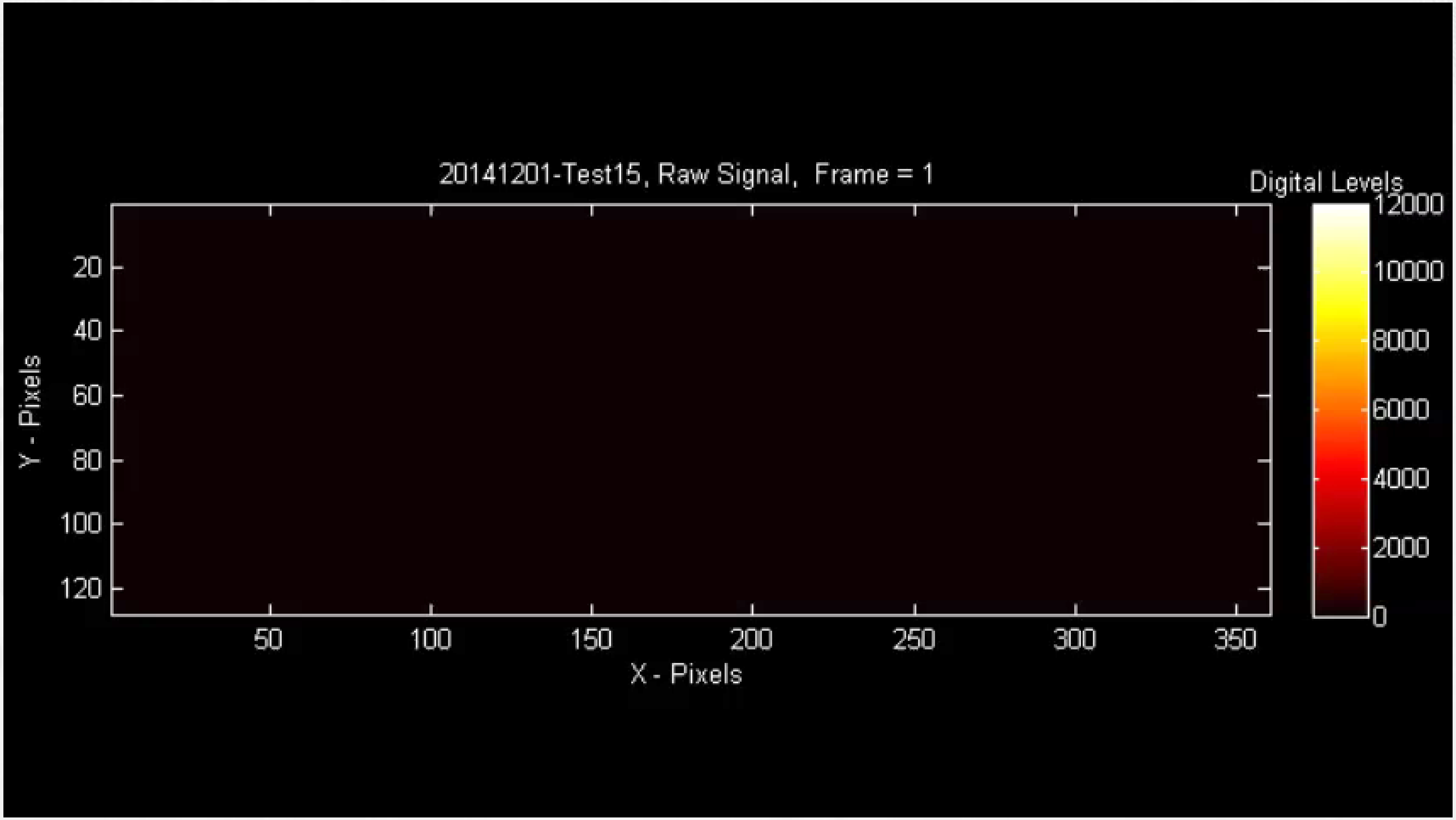


Results – Test 11 'Intensity'



Note: Video should only be used for qualitative analysis. Inference of temperature, radiance, or other quantitative measurements from this video is not endorsed by NIST.

Results – Test 15 'Intensity'



Note: Video should only be used for qualitative analysis. Inference of temperature, radiance, or other quantitative measurements from this video is not endorsed by NIST.

Calibration

- Why? Relate signal to temperature
- Signal is proportional* to spectrally integrated Planck's law (radiant flux)
- Calibration objective: Evaluate a function F that maps camera signal S_{bb} to blackbody temperature T_{bb}

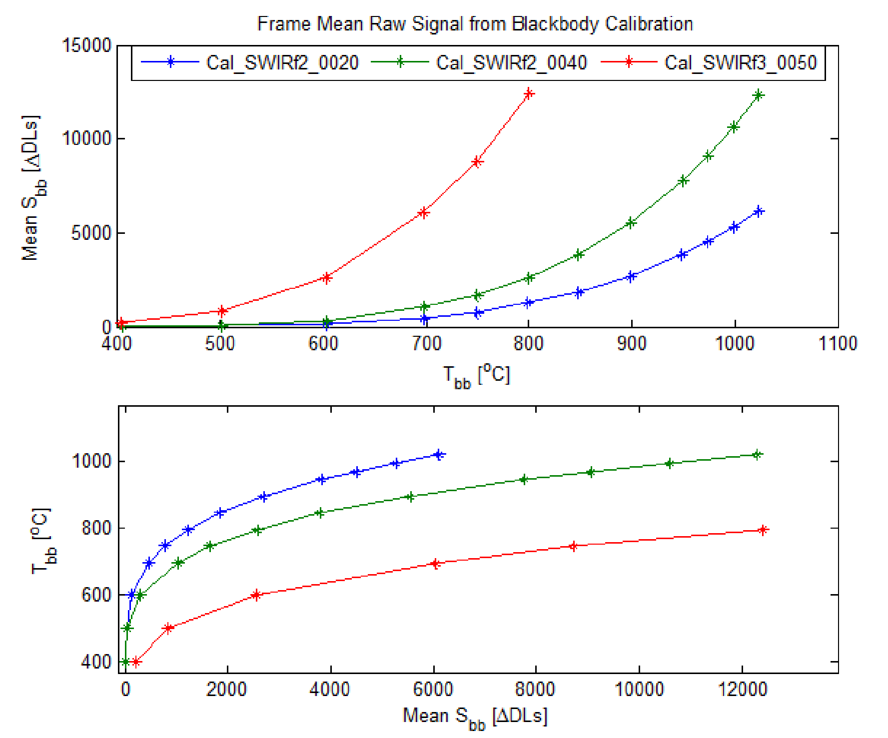
$$F : T_{bb} \leftrightarrow S_{bb}$$

Planck's Law of Blackbody Radiation

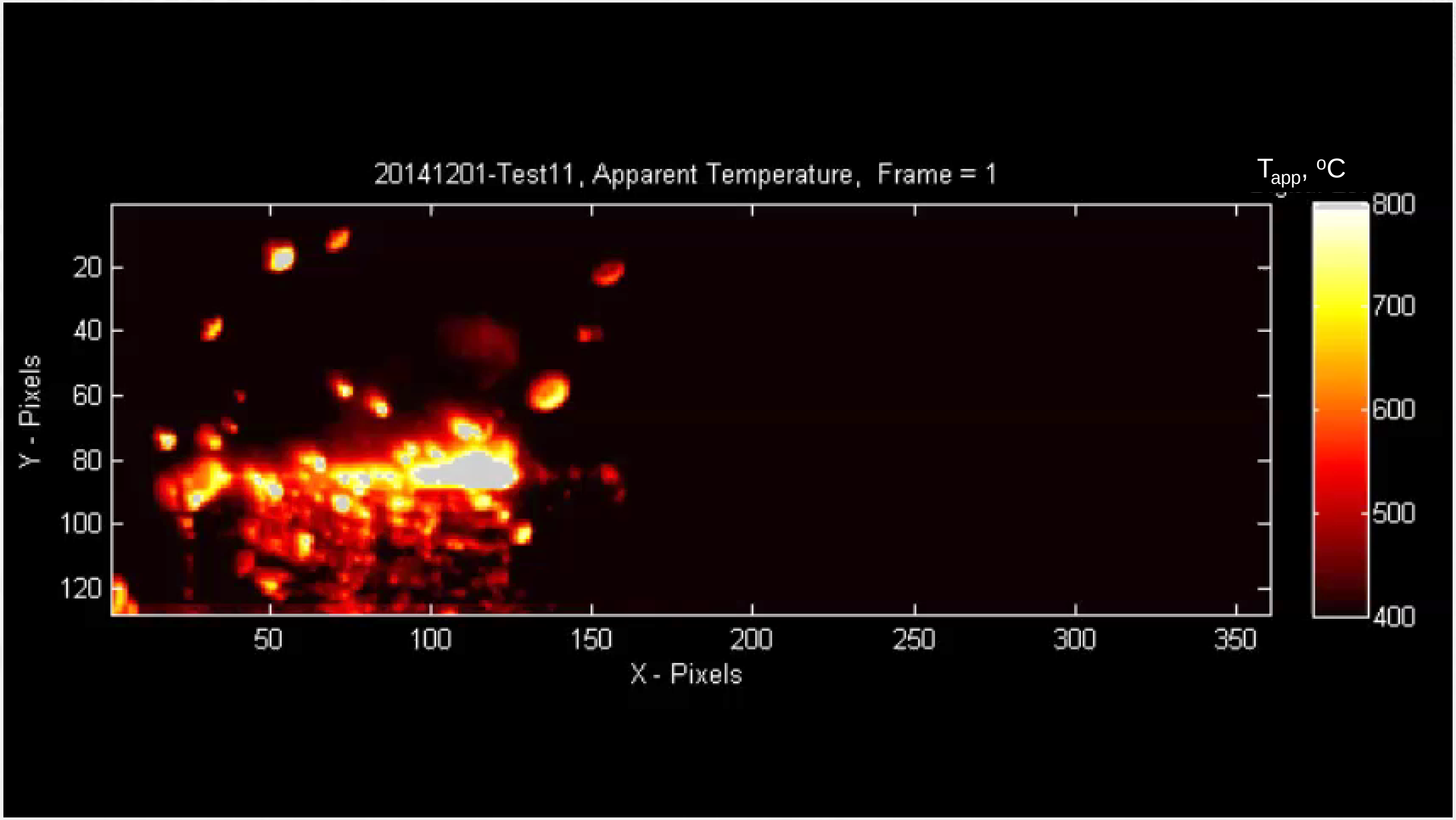
$$L_\lambda(T) = \frac{c_{1L}}{\lambda^5 [\exp(c_2 / \lambda T) - 1]}$$

Signal proportional to spectrally integrated Planck's law

$$S \propto \phi_{bb} = \alpha \cdot \int w_\lambda L_\lambda(T_{bb}) d\lambda + \beta$$



Results: Test 11 Apparent Temperature



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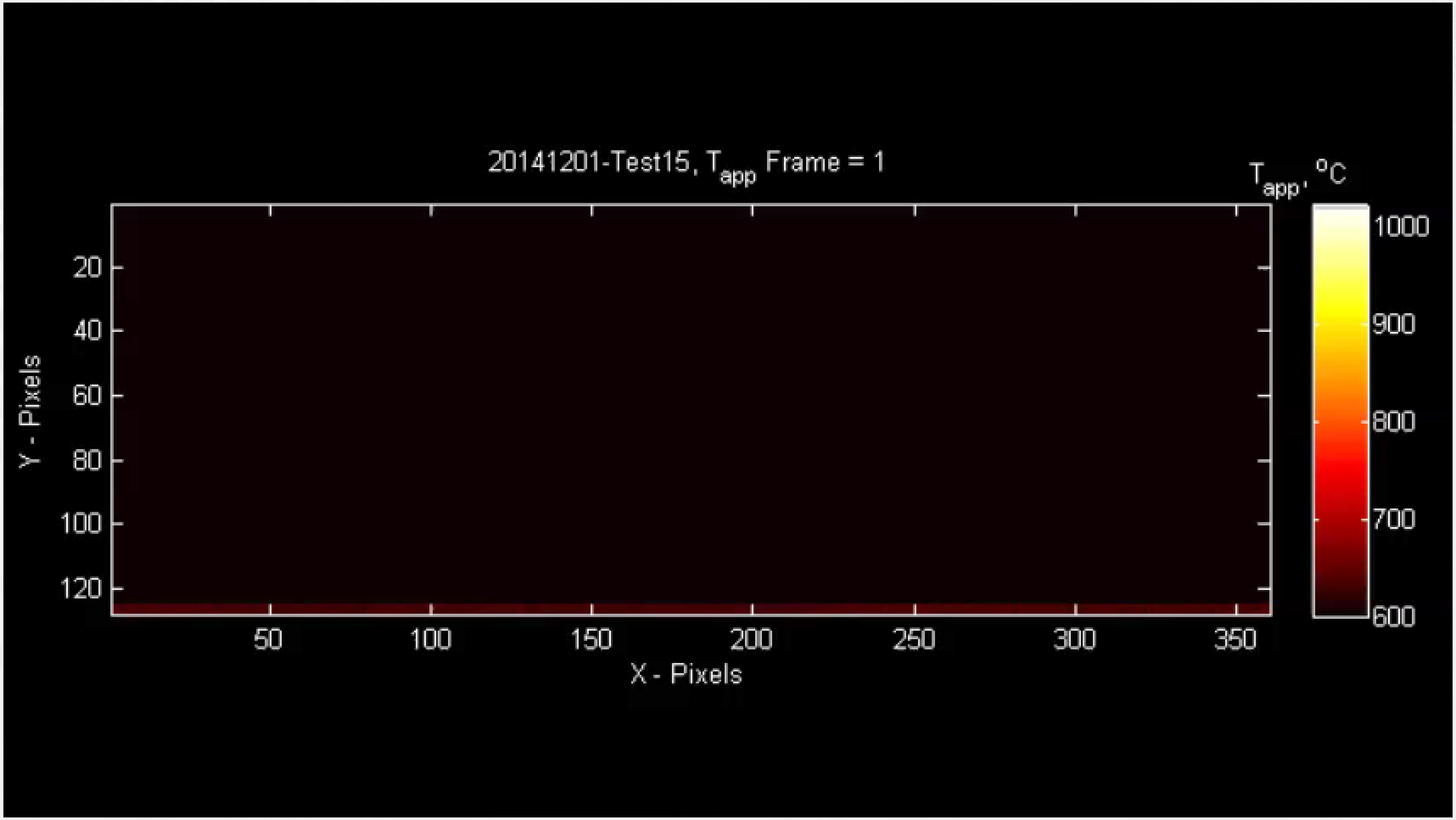
Results: Test 15 Apparent Temperature



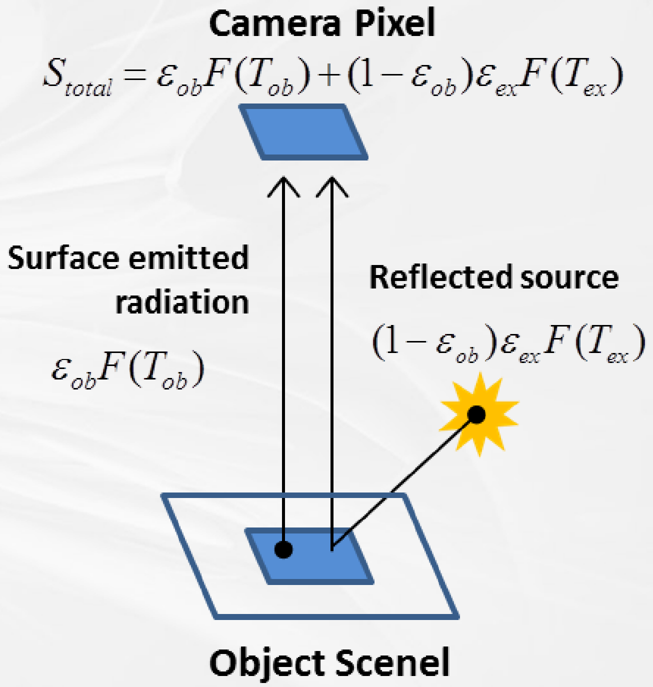
Note: Video should only be used for qualitative analysis. Inference of temperature, radiance, or other quantitative measurements from this video is not endorsed by NIST.

Discussion: Potential Measurands

- What is 'apparent' temperature?

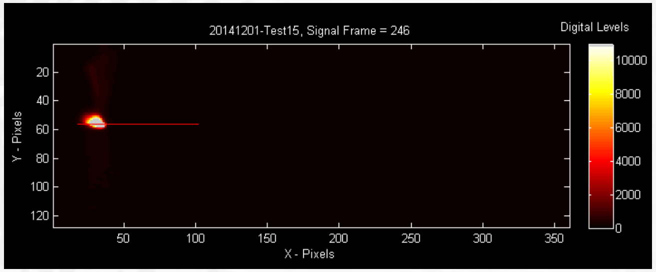
$$S_{total} = F(T_{app}) \qquad T_{app} = F^{-1}(S_{total})$$

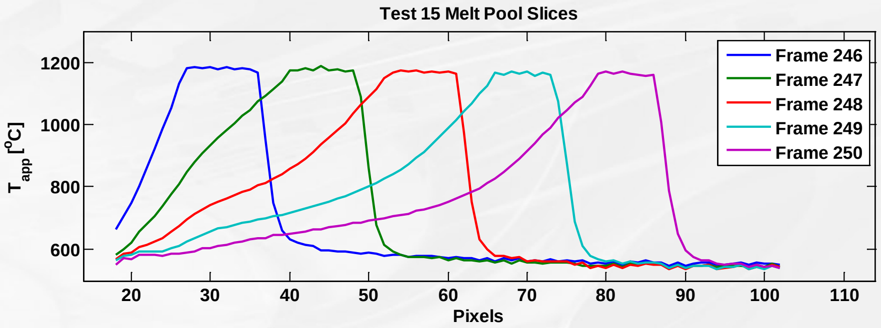
- Claiming T_{app} is 'minimum temperature'
  - 1.) Blurring reduces T_{app}: **$T_{app} < T_{true}$**
  - 2.) A real emissivity <1: **$T_{app} < T_{true}$**
  - If every effect decreased T_{app}, then **T_{app} is a 'minimum temperature'**
  - 3.) Reflections cause **$T_{app} > T_{true}$**
  - Reflections *may* affect 'minimum temperature' claim

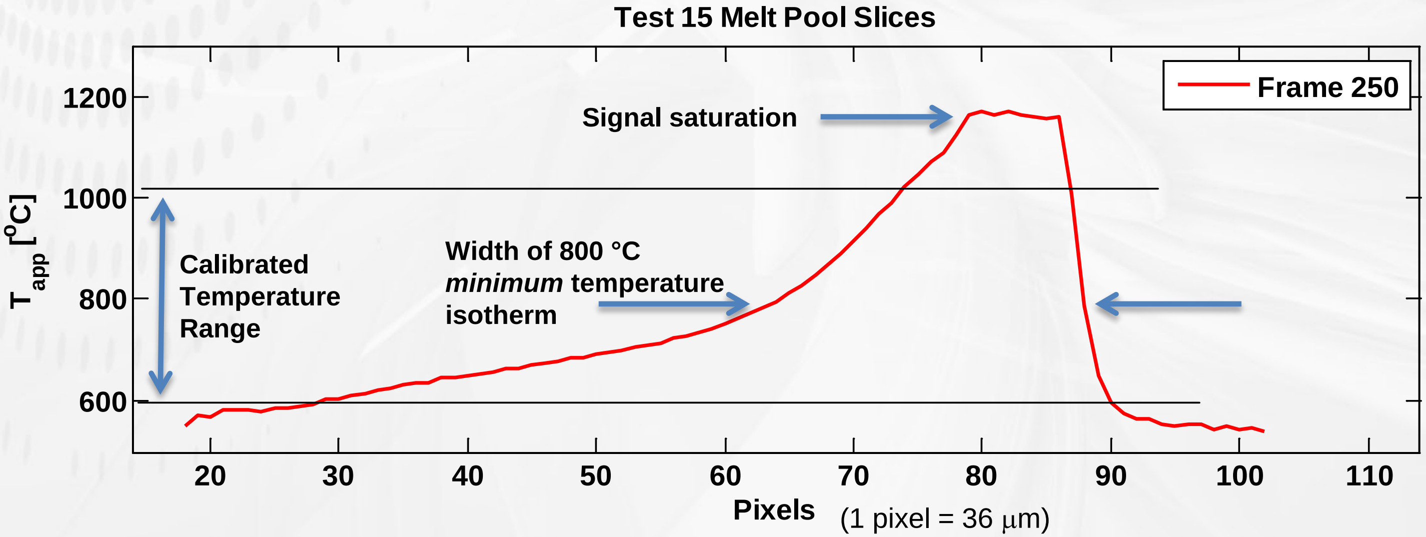


Discussion: Potential Measurands

- Example measurand: isotherm size





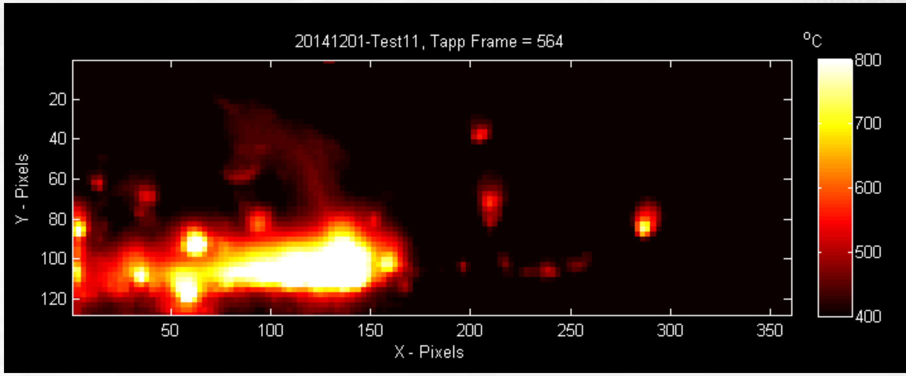


Example statement:
"Everything within this isotherm is greater than 800 °C and less than 24 pixels, or 0.86 mm in length"

- Motion blur? Optical blur? Effect of emissivity? Was the slice taken at the center of melt pool? Uncertainties need to be studied…

Discussion: Potential Measurands

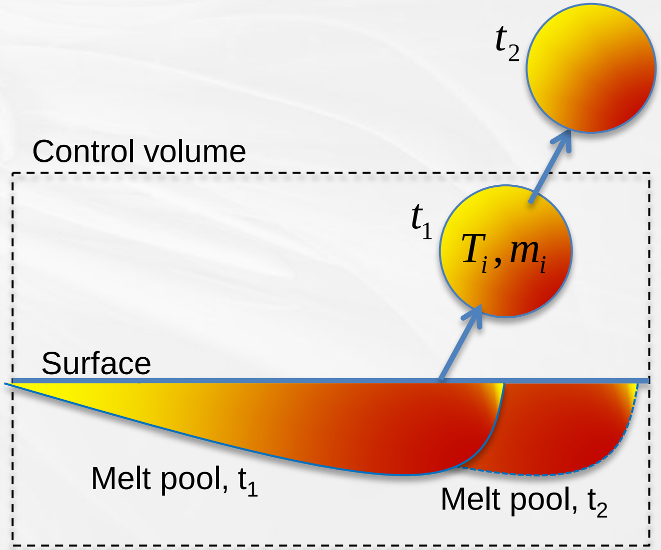
- Example measurand: Energy loss from spatter
  - Advection of discrete particles
  - Not accounted for in most PBF models
- Potentially measurable:
  - r_i = radius of particle i
  - T_i = temperature of particle i
  - Δt = time interval



$$m_i \approx \rho\left(\frac{4}{3}\pi r_i^{3}\right)$$ Mass of particle

$$Q_i \approx m_i c\left(T_i - T_{amb}\right)$$ Stored thermal energy

$$P \approx \frac{1}{\Delta t}\sum_i Q_i$$ Heat loss rate



These are initial thoughts, but this is apparently a significant heat/energy transfer process

Conclusions

- Current efforts in AM simulation + validation at NIST
- Simulations:
  - Material thermodynamics calculation through Calphad
  - Sensitivity analyses of process parameters + simulation parameters
  - Future: alloy phase and residual stress calculation
- Thermography:
  - Measurement system constructed, able to take images
  - Measurand definition / image analysis underway