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Investigating Surface Topography Effects on Directional Emissivity of Metallic Additively Manufactured Parts

Samantha Taylor

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Purpose

To improve the accuracy of in-situ monitoring by accounting for the effects of extreme surface roughness of as built metallic additively manufactured parts has on the thermal emissivity

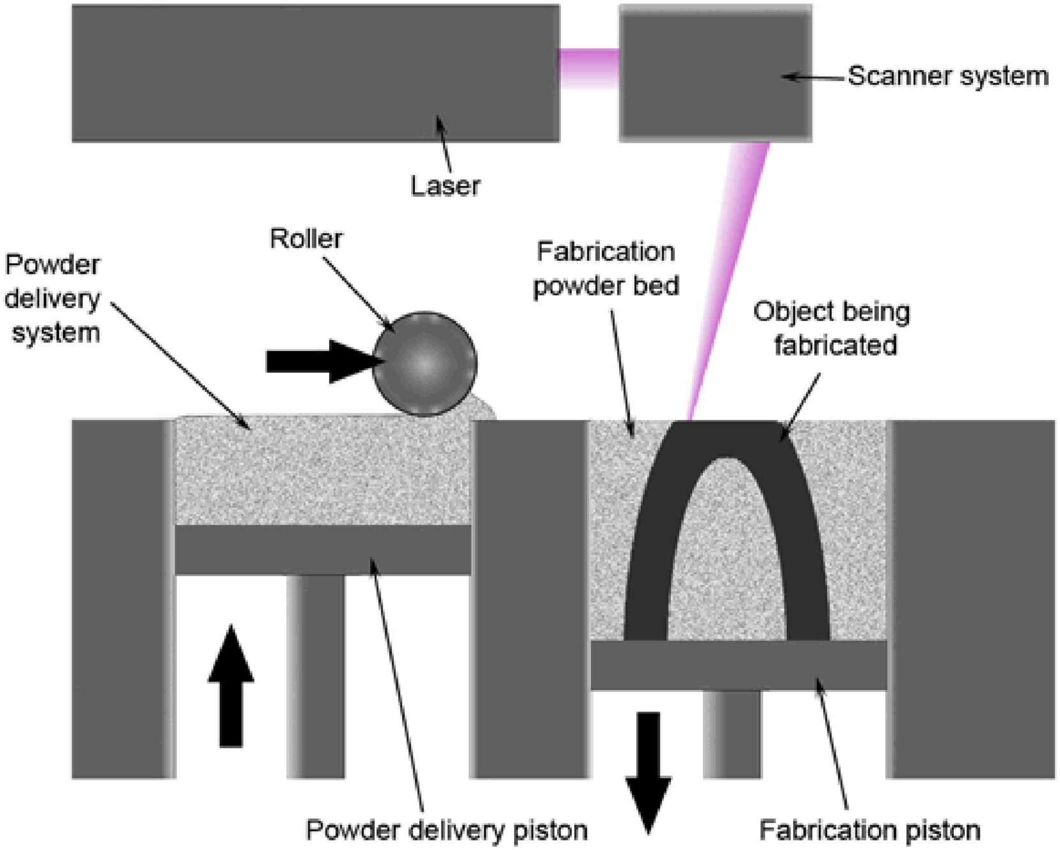
Agenda

- Background
- Investigating Surface Characteristics that affect Emissivity
  - Simulations
  - Experimental Measurements
- Investigating View Angle and Temperature Effects on Emissivity
- In-Situ Surface Roughness Measurement Testing
- Conclusions
- Future Work

Background

- Direct Metal Laser Sintering
- Thermal Monitoring in Additive Manufacturing
- Radiation/Emissivity
- Surface Roughness Definitions
- Surface Roughness in Additive Manufacturing
- Surface Roughness and Emissivity

Direct Metal Laser Sintering (DMLS)



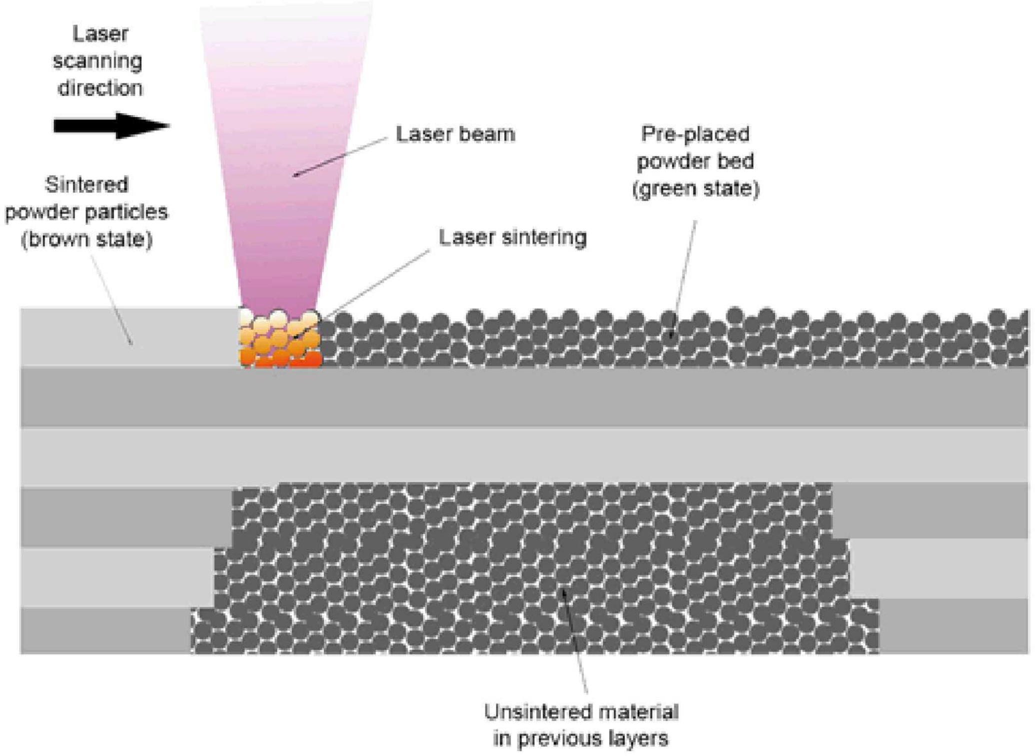


Image from: SPI Lasers

Thermal Monitoring in AM

- Pre-heat in EBAM
- Melt pool measurements in DMLS and LENS
- Cooling rate monitoring in DMLS and LENS
- IR camera wavelength ranges
  - 1-3
  - 3-5
  - 7.4-13

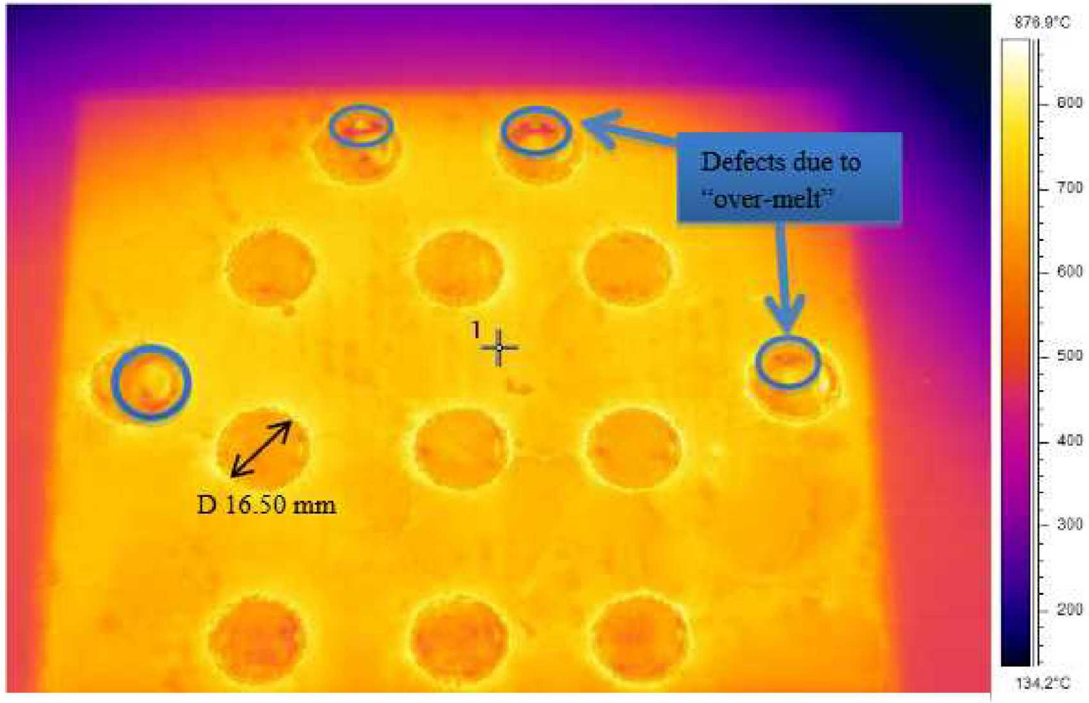


Image from: Rodriguez et al.

Radiation/Emissivity

- Black body
- Gray body
- Emissivity
  - Material dependent
  - Wavelength dependent
  - Temperature dependent
- A + R + T = 1

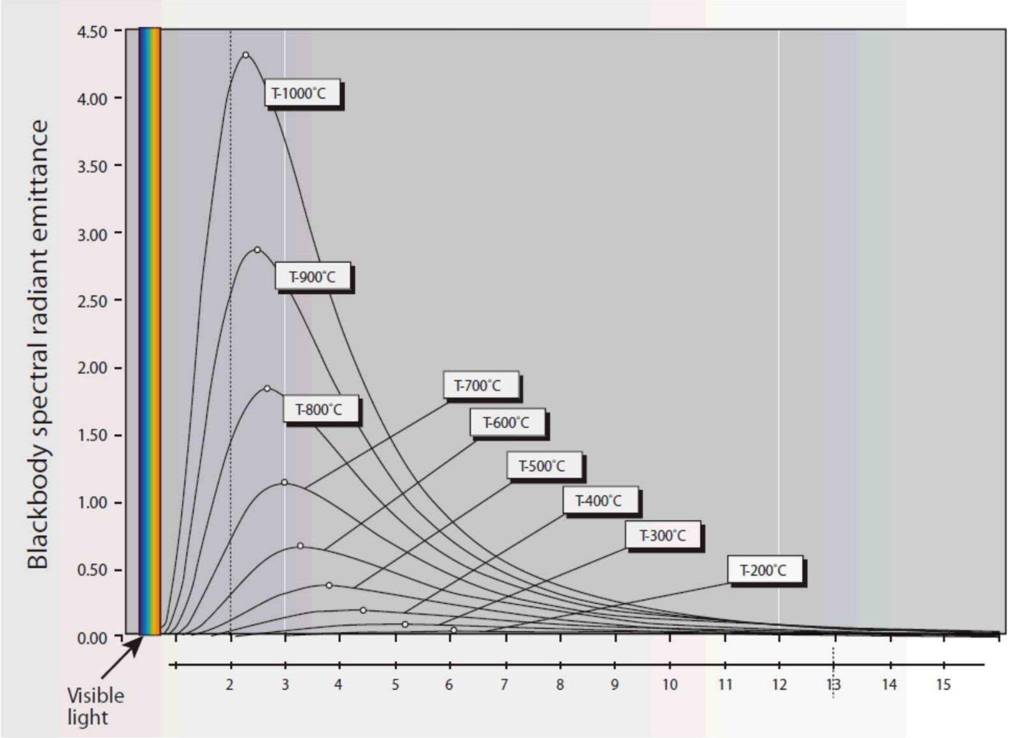
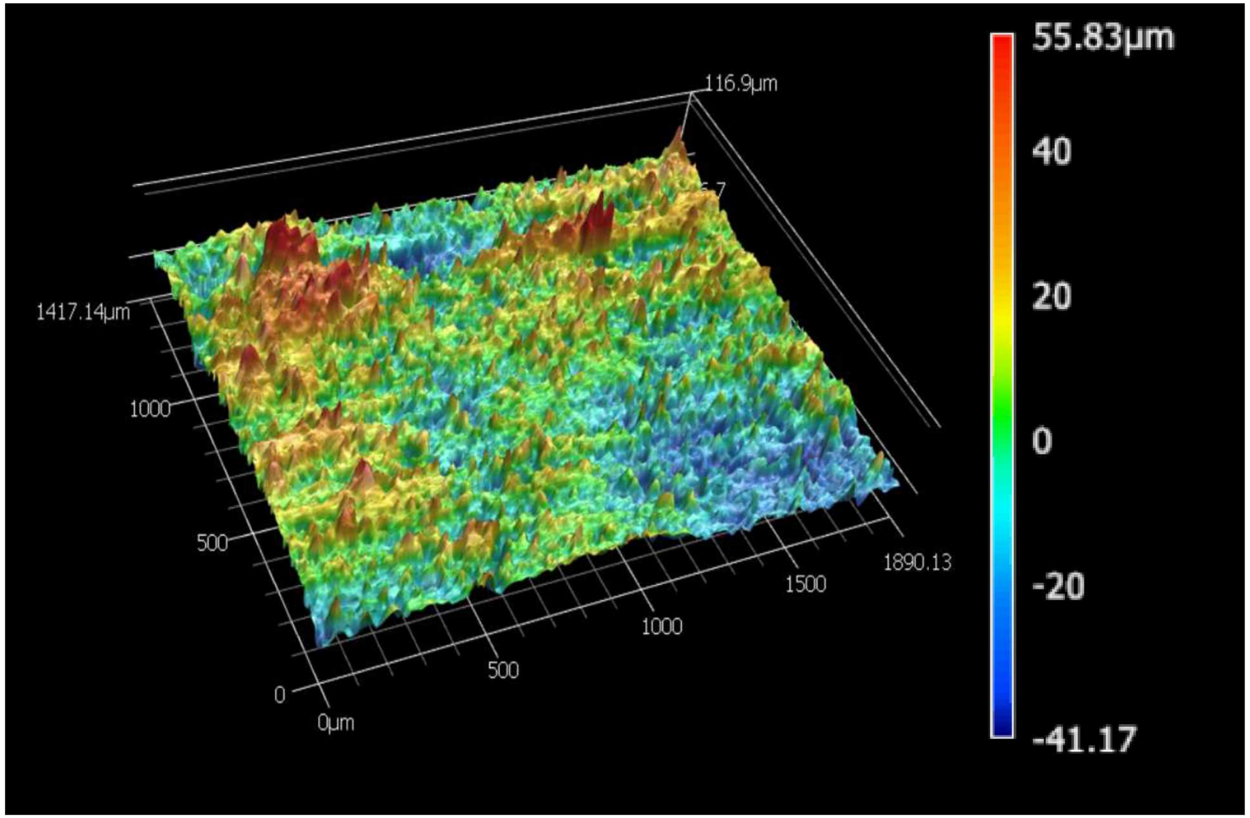


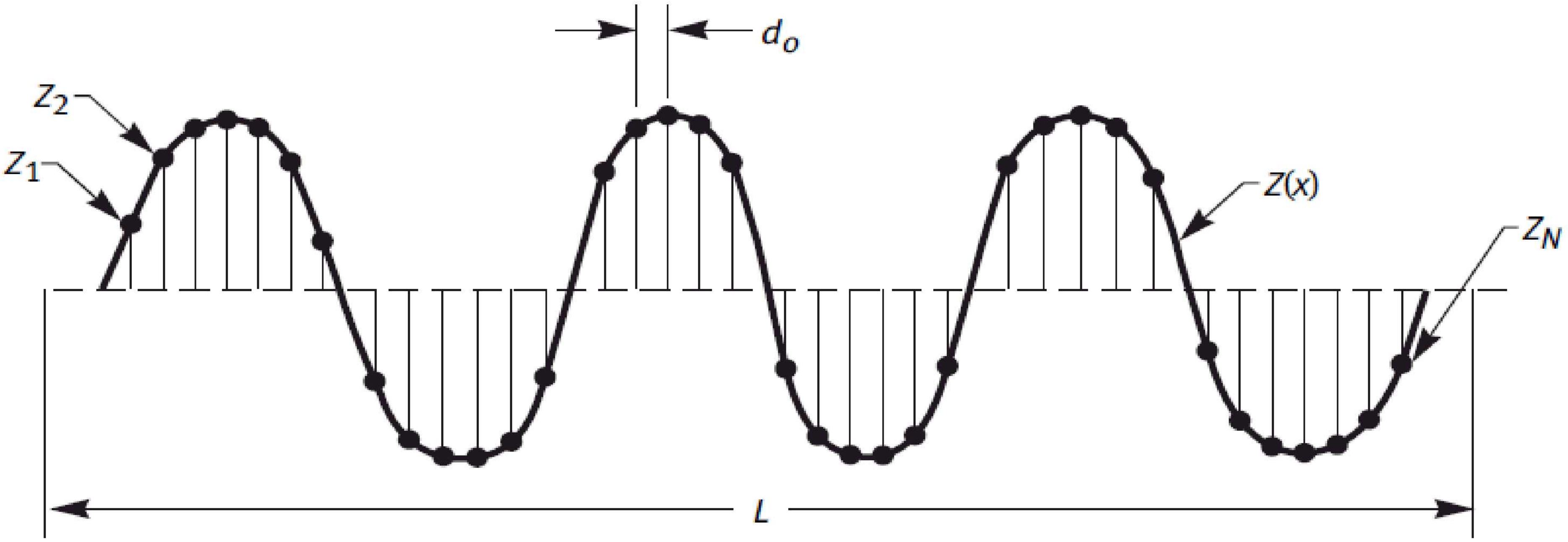
Image from: FLIR Systems, "Ultimate Infrared Handbook for R&D Professionals"

Surface Roughness

- ASME B46.1
- ISO 4287
- R_a is dominant in literature (90% of AM literature references this when discussing surface roughness)



Arithmetic Mean Roughness

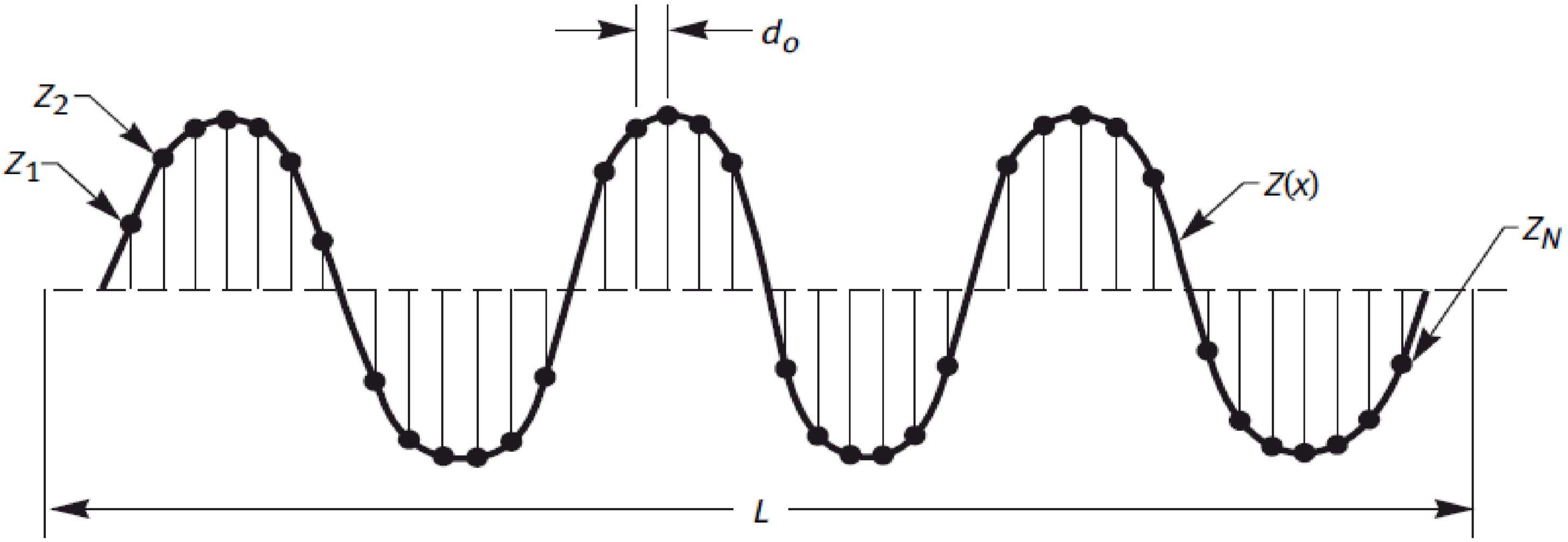


$$R_a = \frac{1}{L}\int_0^L |Z(x)|dx$$

$$S_a = \frac{1}{A}\int_0^{L_y}\int_0^{L_x} |Z(x,y)|dxdy$$

Sourced from: ASMBE B46.1

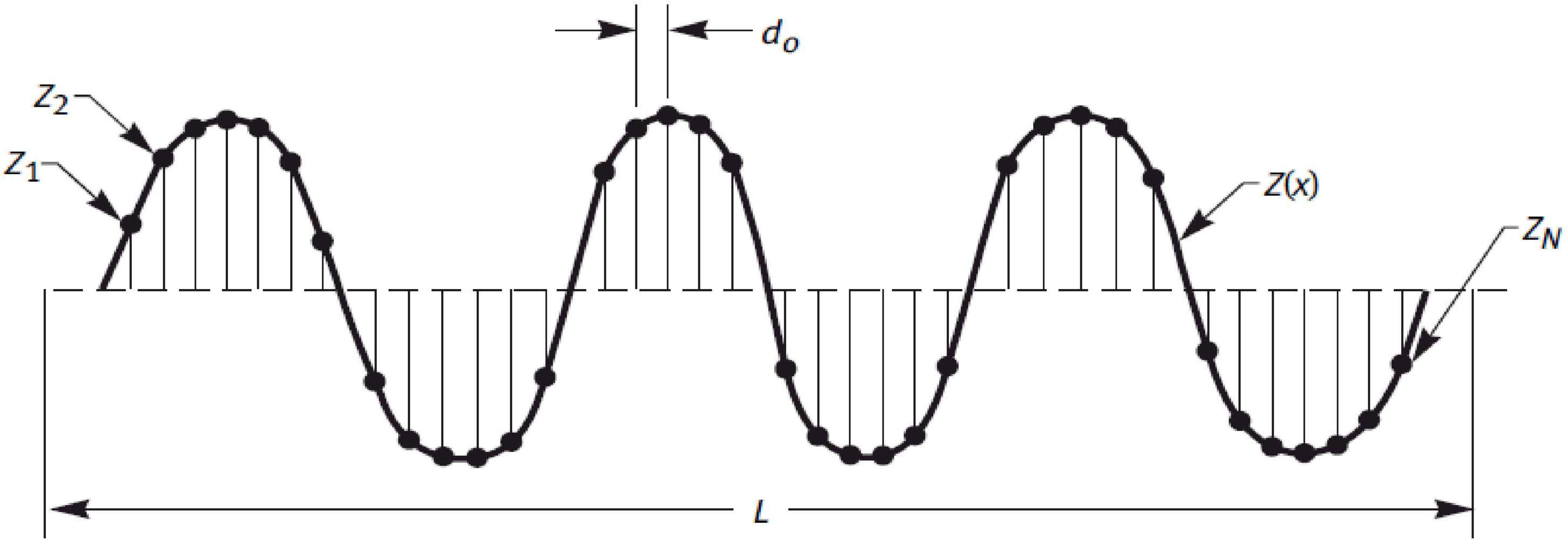
Root Mean Square Roughness



$$R_q = \sqrt{\frac{1}{L}\int_0^L Z(x)^2 dx}$$

Sourced from: ASMBE B46.1

Root Mean Square Slope

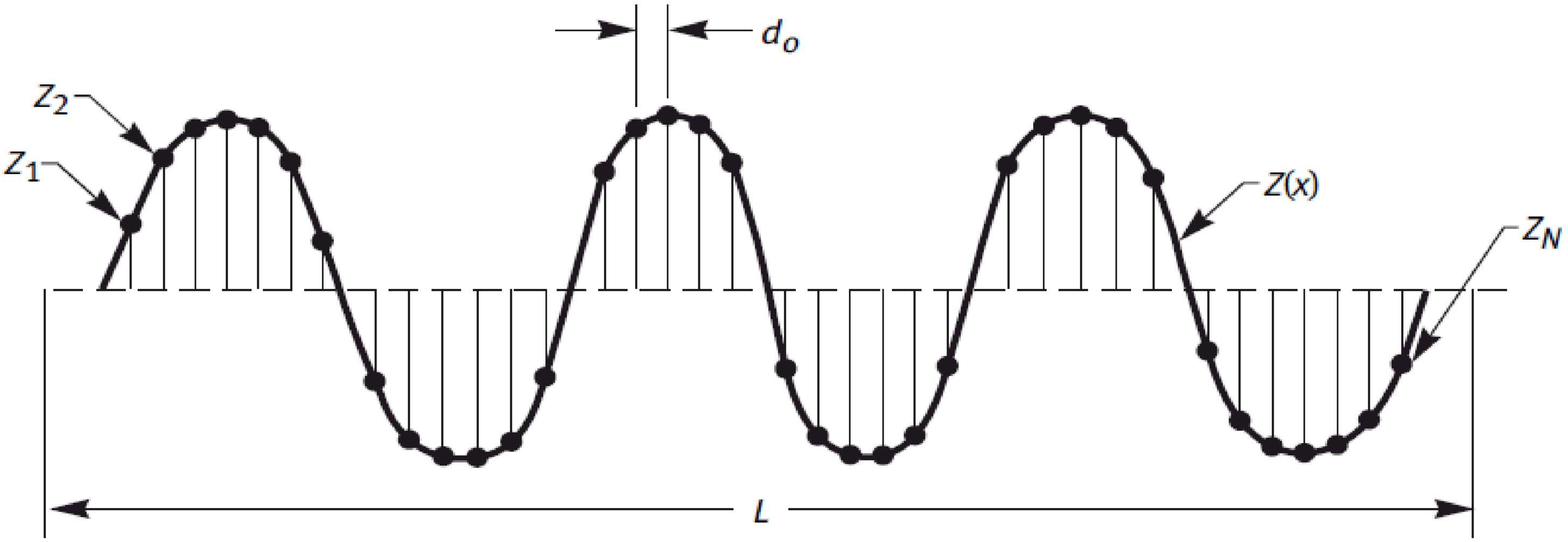


$$R\Delta q = \sqrt{\frac{1}{L}\int_0^L \left(\frac{dZ}{dx}\right)^2 dx}$$

$$S\Delta q = \sqrt{\frac{1}{A}\int_0^{L_y}\int_0^{L_x} \left(\frac{dZ(x,y)}{dx}\right)^2 + \left(\frac{dZ(x,y)}{dy}\right)^2 dxdy}$$

Sourced from: ASMBE B46.1

Arithmetic Tilt Angle



$$R\Delta a = \frac{1}{L}\int_0^L \frac{|dZ|}{|dx|}dx$$

Sourced from: ASMBE B46.1

Surface Roughness in Additive Manufacturing

- Build-to build and position variability
- Shear forces in melt pool create ripple effect which is then frozen due to high processing speeds
- Balling
  - Laser power too high causing currents where outward forces exceed surface tension in melt pool and material is ejected
  - Raleigh Instability: scan speed too fast compared to laser power so balling occurs due to long melt pool breaking up

Surface Roughness Relationship with Emissivity

Case 1: $R_q/\lambda << 1$

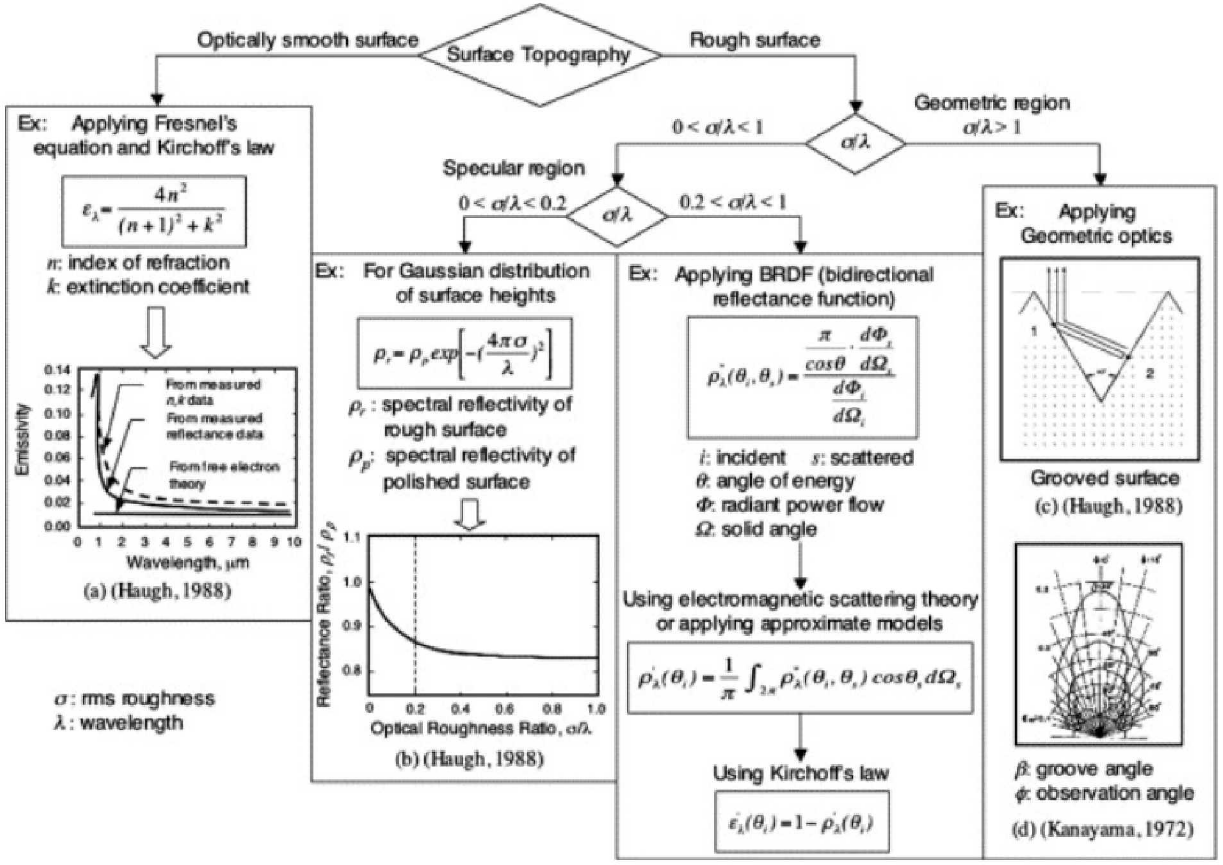
- Optically smooth surface, where the roughness of the surface does not contribute to the thermal emissivity of the object.

Case 2: $0.2 < R_q/\lambda < 1$

- Intermediate region where there is no easy defined relationship between emissivity and surface roughness. The roughness of the surface does contribute but is not solely responsible for affecting the emissivity.

Case 3: $1 < R_q/\lambda$

- The geometric region, where it is suggested that the slope of the peaks and valleys of the surface can play a key role in emissivity trends.



Sourced from: Wen and Mudawar, "Modeling the Effects of Surface Roughness on the Emissivity of Aluminum Alloys"

Problem Statement

- Additive manufacturing has large values and ranges of surface roughness
- Wavelengths used for monitoring are at same length scales as surface roughness of additive parts
- Emissivity can be affected by extremely rough surfaces
- Accuracy of thermal monitoring is paramount for quality control of process and parts in metal AM processes

Research Plan

- Defining surface parameter(s) that affect thermal emissivity
- Determine range of emissivity values seen during in build AM conditions and sensitivity of view angle
- In-situ surface texture measurement for the purpose of in build adjustment of emissivity for thermal monitoring instruments

First Task: Define Surface parameter(s) that affects emissivity

- Simulation Work
  - Discover surface characteristics that affect emissivity
  - Discover phenomena behind emissivity trends
- Experimental Measurements
  - Fabricate metallic AM sample with a range of SR
  - Correlate measured surface roughness with measured emissivity
  - Discover which new and pre-existing surface roughness parameters best describe emissivity behavior

Simulation Strategy – Lumerical FDTD

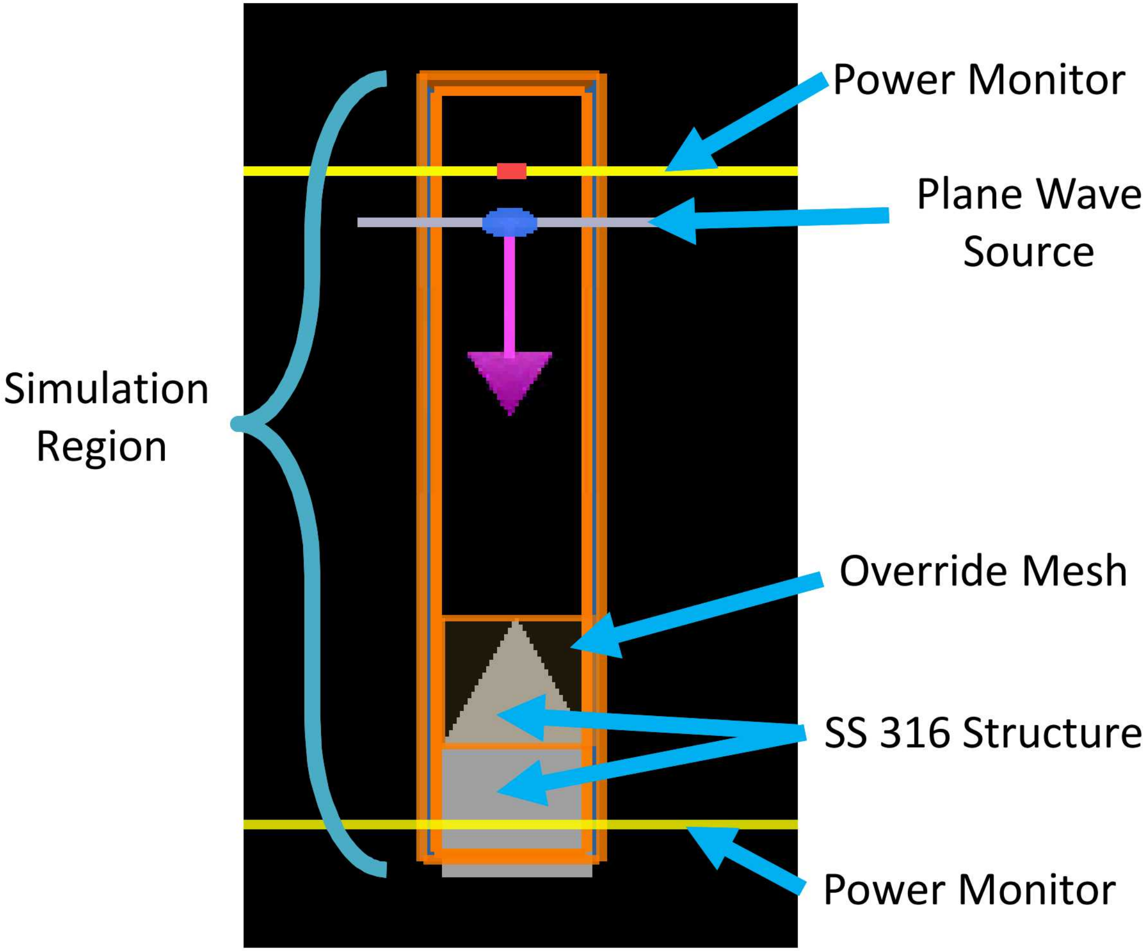
- Finite Difference Time Domain (FDTD)
  - Calculates electric and magnetic fields at different time steps
- Maxwell solver
  - Electric field, magnetic field, electric flux, and magnetic flux are calculated for Yee Cell (fundamental spatial unit)
- Chosen over ray tracing due to surface features on same length scale as light wavelength range
  - Ray tracing may not accurately capture all optical behavior

Simulation Strategy

- Basic 2D periodic geometries were chosen for initial simulations
  - Less computation time and memory requirements
  - Geometries chosen to observe effects of certain SR parameters and various characteristics of surface topography
- Parameter sweeps
- Wavelength Range: 1-14 microns
- Material – 304 Stainless Steel

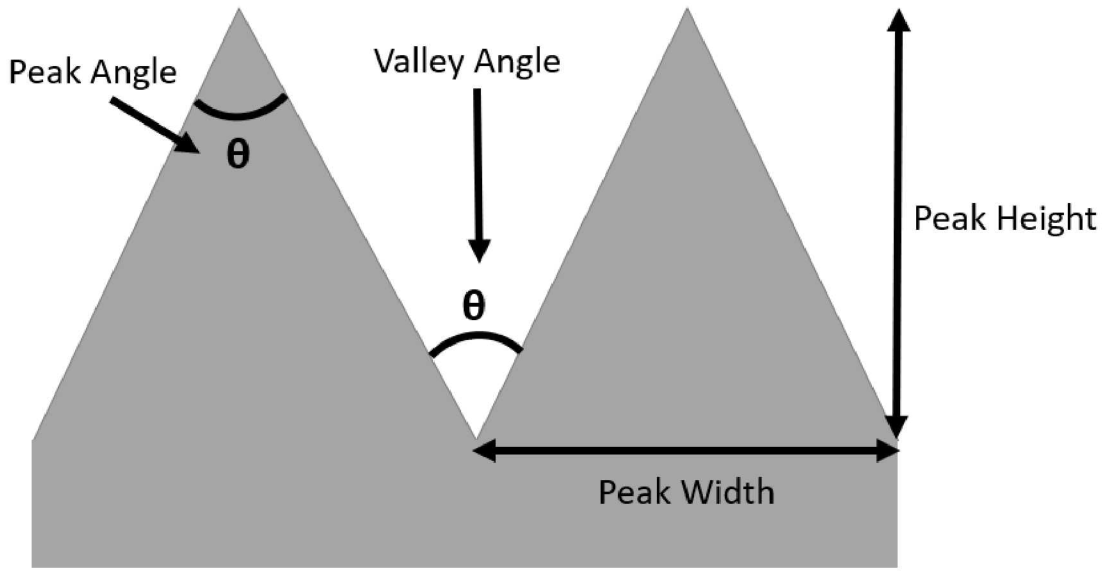
Overall Simulation Set Up

- 2D geometry (z plane goes to infinity)
- X axis boundary conditions: periodic
- Y axis boundary conditions: perfectly matched layer (PML)
- Plane wave source
- Power monitors above and below surface to measure reflection and transmission



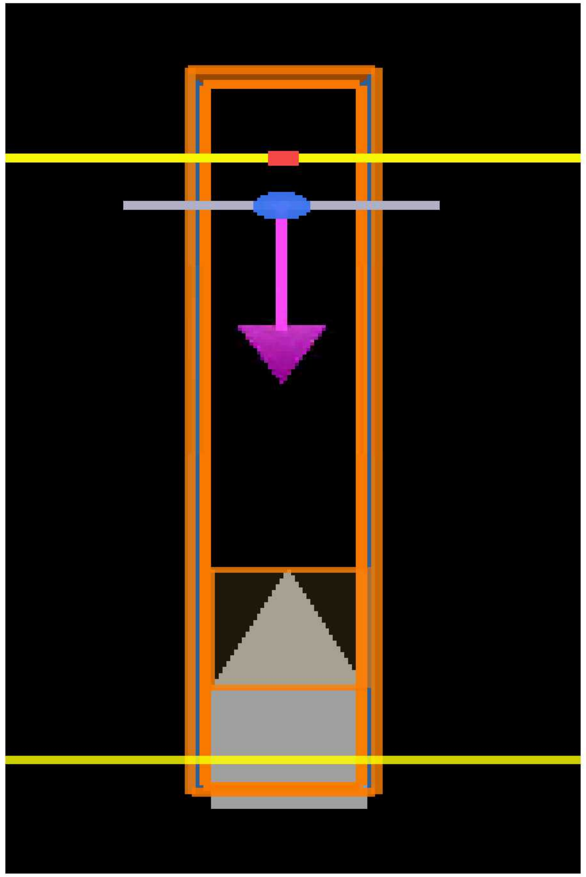
Simulation Surface Roughness Exploration

- Looked into existing SR parameters’ ability to describe emissivity trends
  - R_a and $R\Delta q$
  - Suggested in previous literature
- Looked at new surface roughness measurements
  - Peak or Valley
    - Height
    - Width
    - Angle

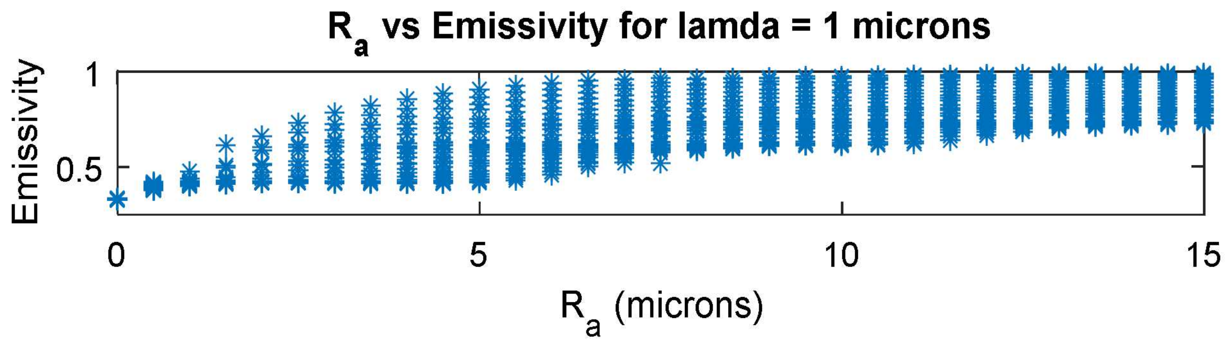


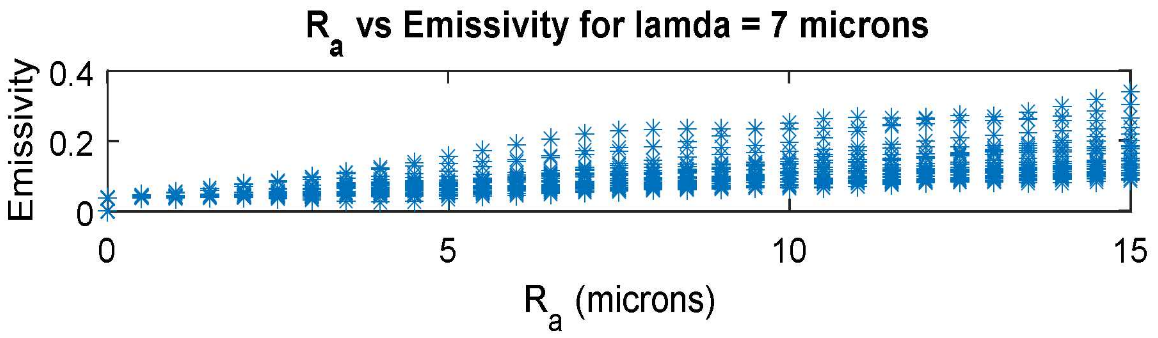
2D Triangle Set Up

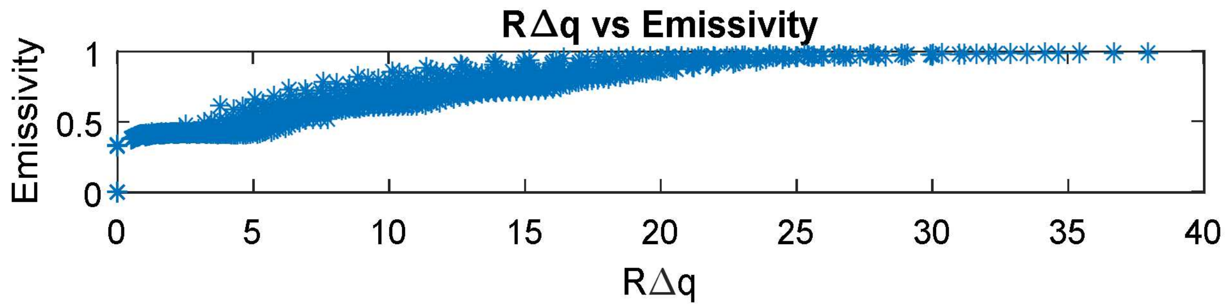
- Isosceles Triangle
- Periodic Boundaries
- Variables
  - Height of triangle: 0-30 microns
  - Width of Triangle: 1-30 microns

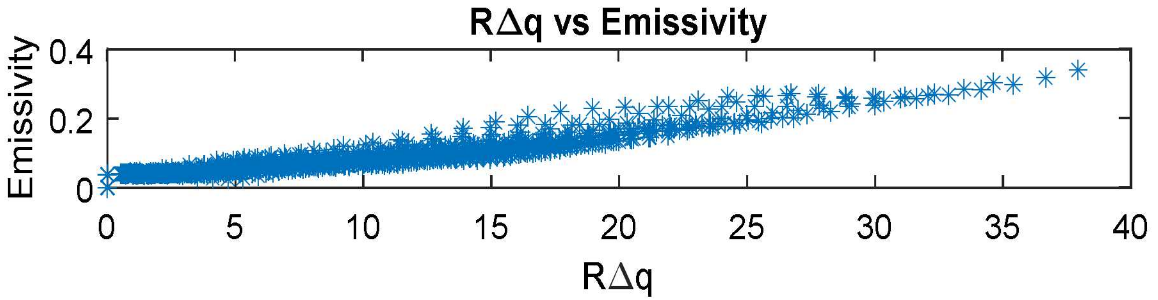


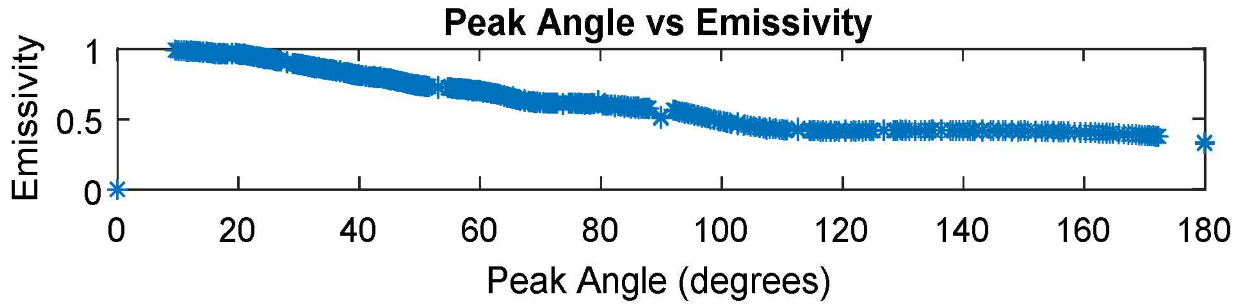
2D Triangle Results

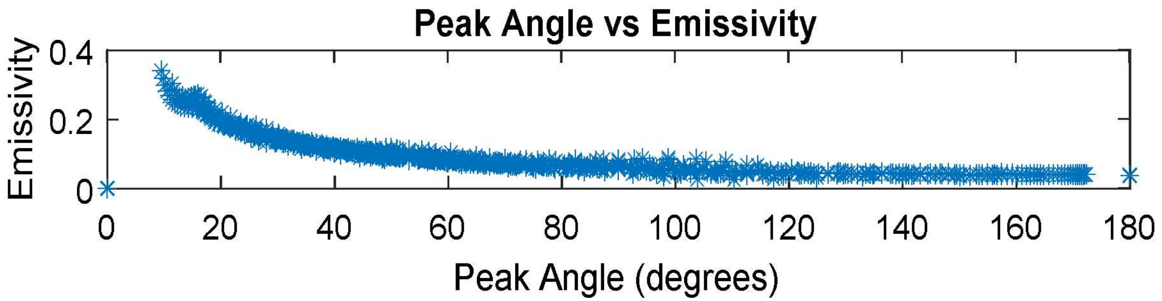






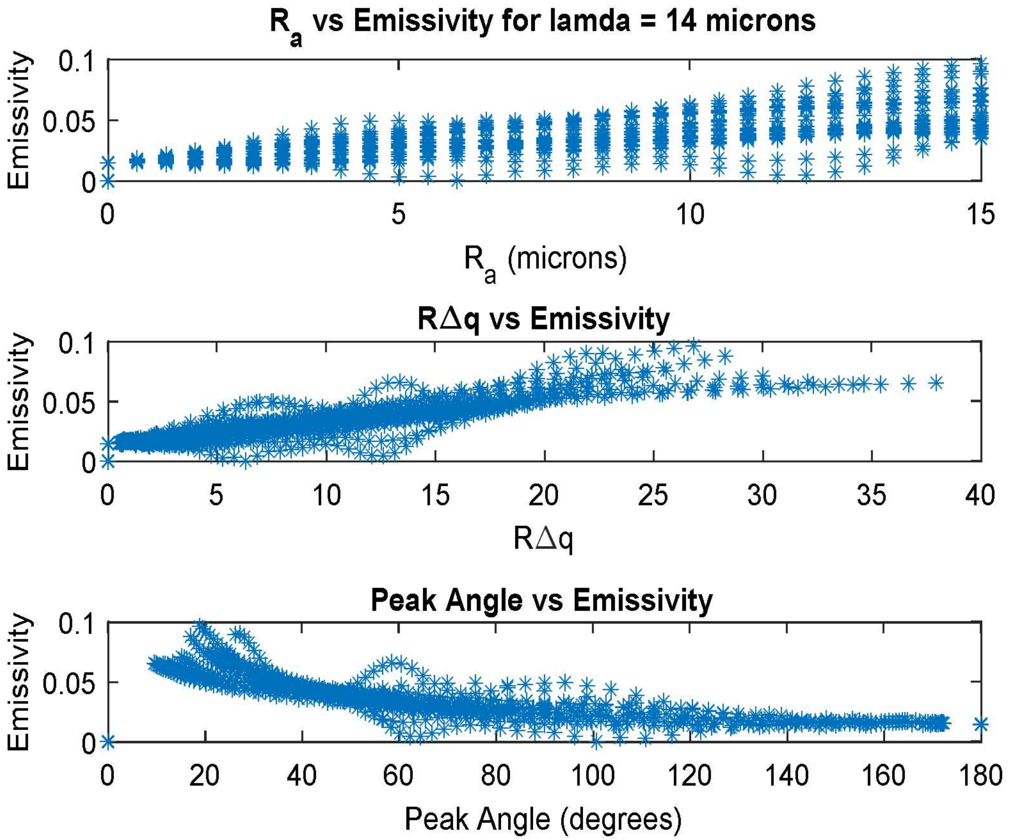






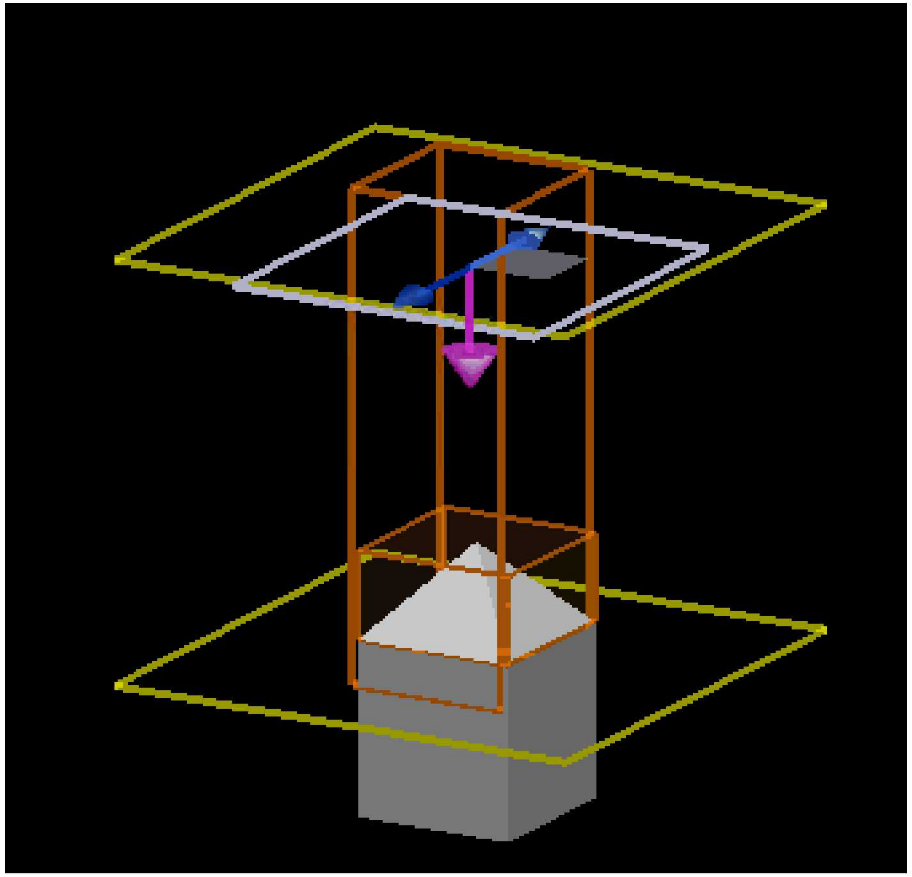
2D Triangle Results

- As observation wavelength increases, trends fall apart
- Ratio of R_q/λ falls below 1
  - Intermediate optical region
  - Emissivity not dominantly dependent on surface roughness

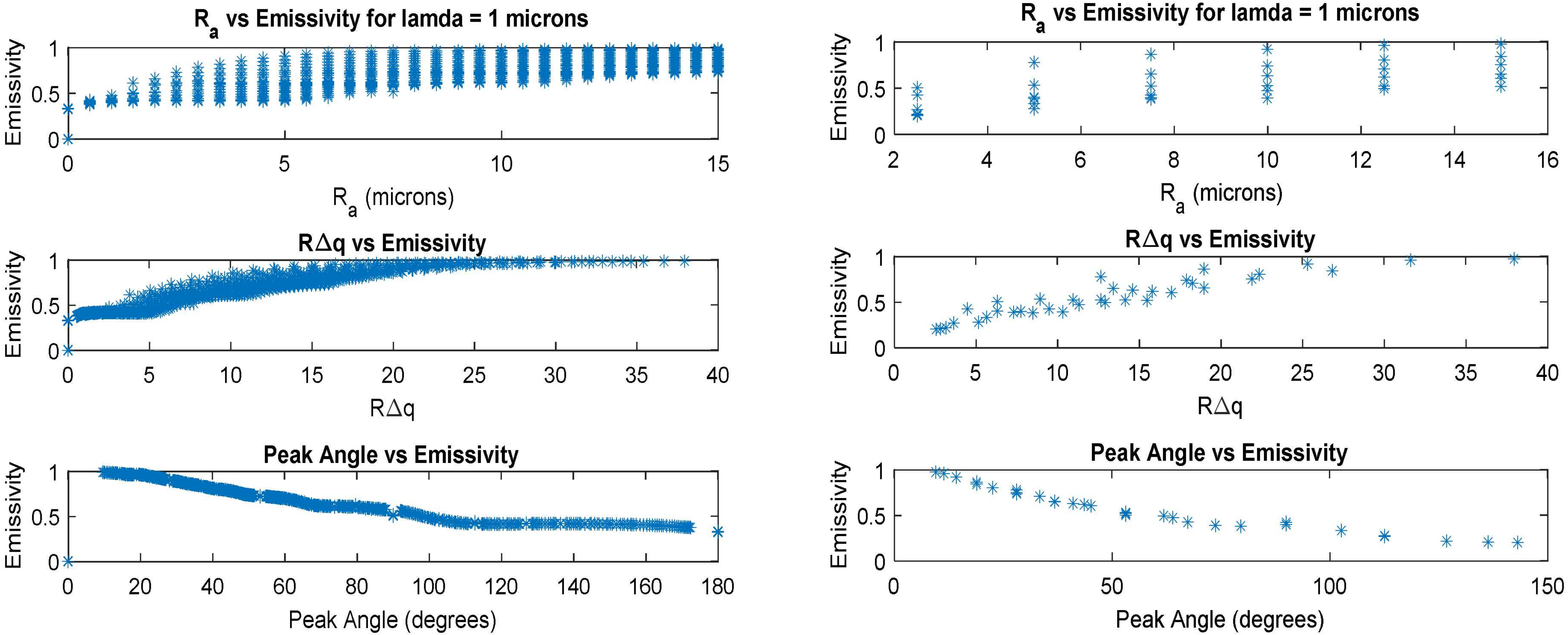


3D Pyramid Set Up

- 3D pyramid with identical geometry to 2D periodic triangle
- Periodic Boundaries
- Symmetry assumption used to reduce simulation space
- Variables
  - Height of pyramid: 5-30 microns
  - Width of pyramid: 5-30 microns

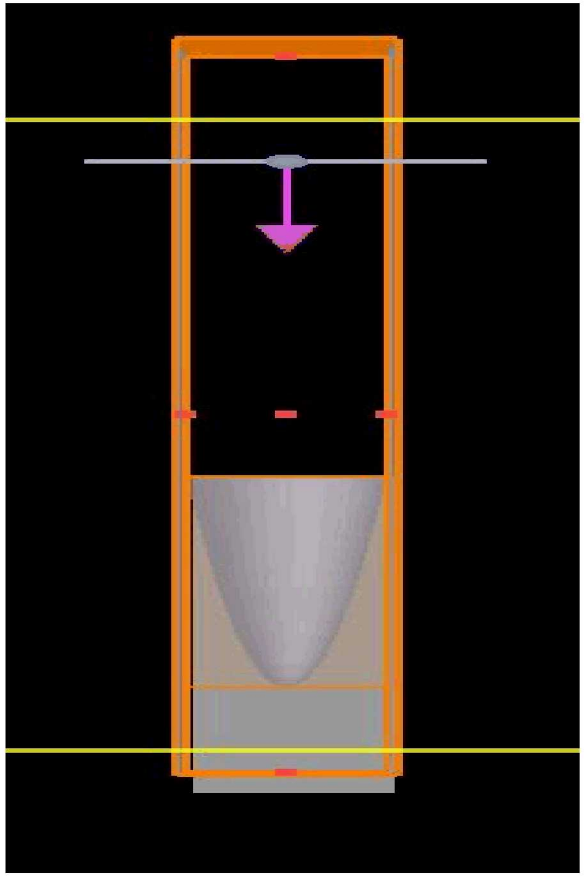


2D Triangle vs 3D Pyramid Results

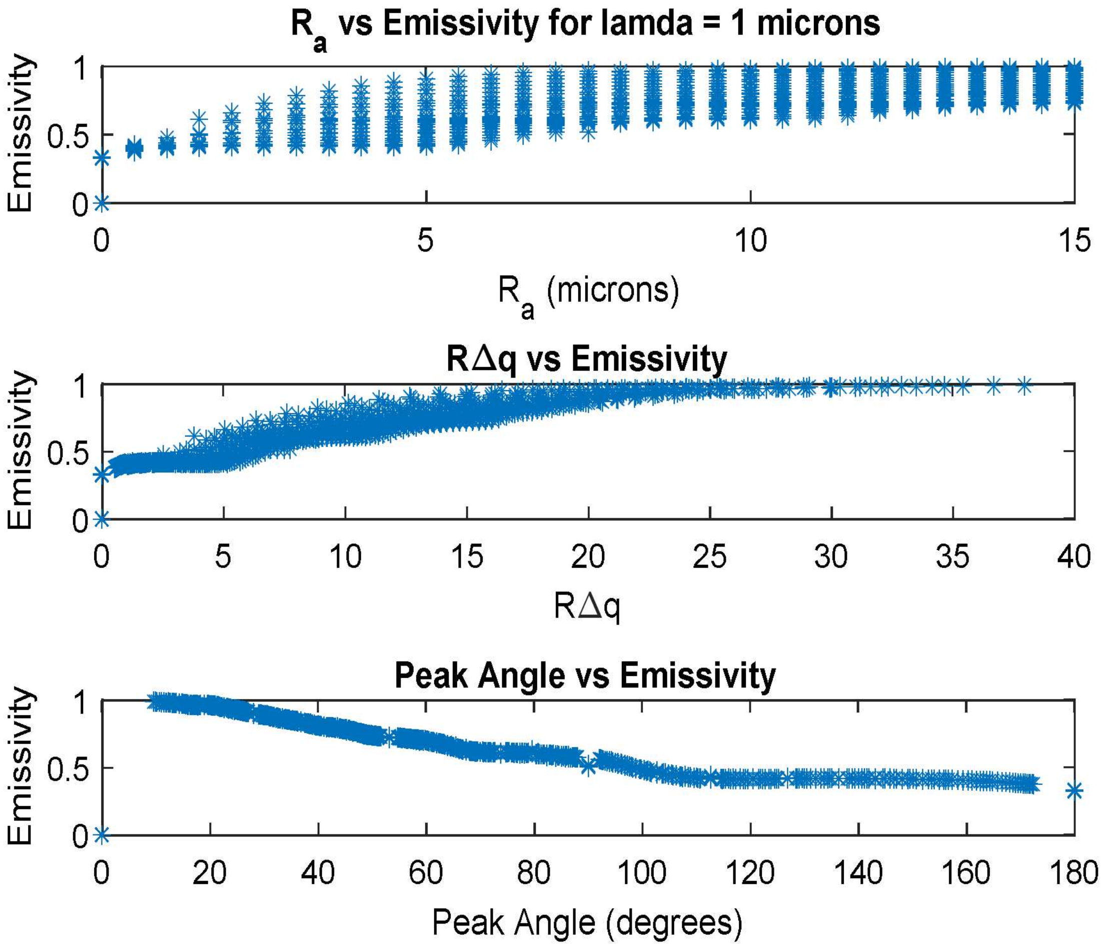


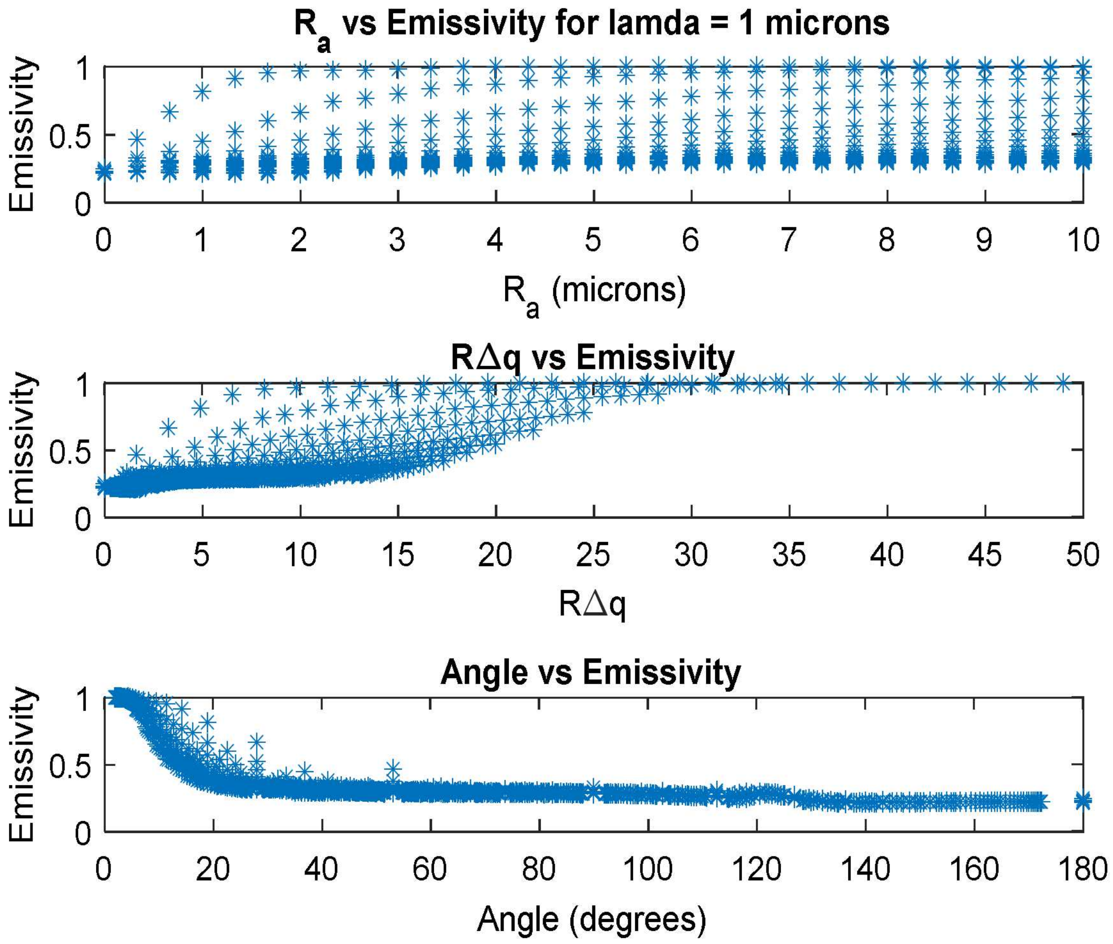
Parabolic Valley Set Up

- Similar dimensions to triangle
- Periodic Boundaries
- Observe effects of more life-like surface shape
- Variables
  - Height of valley: 5-30 microns
  - Width of valley: 5-30 microns

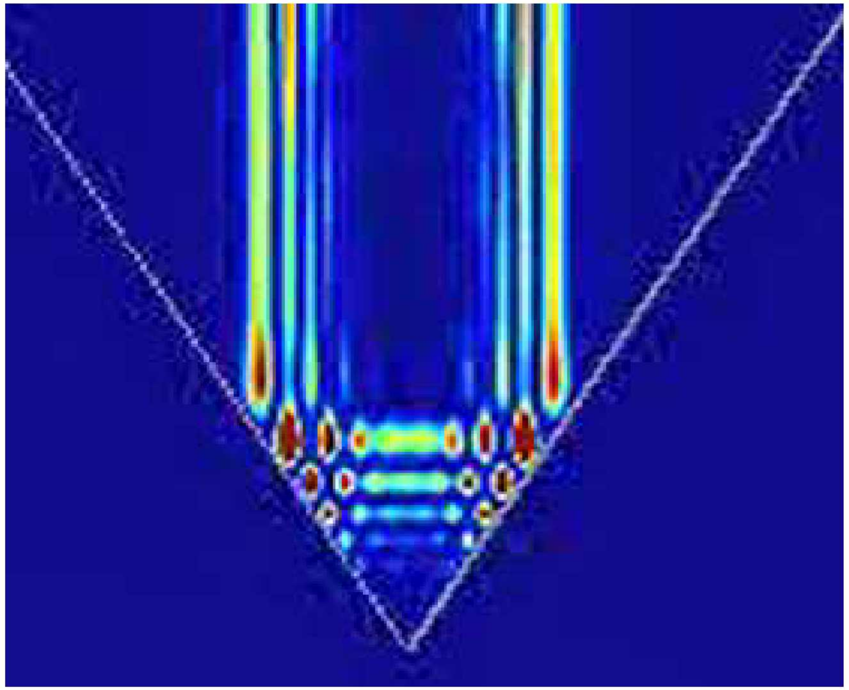


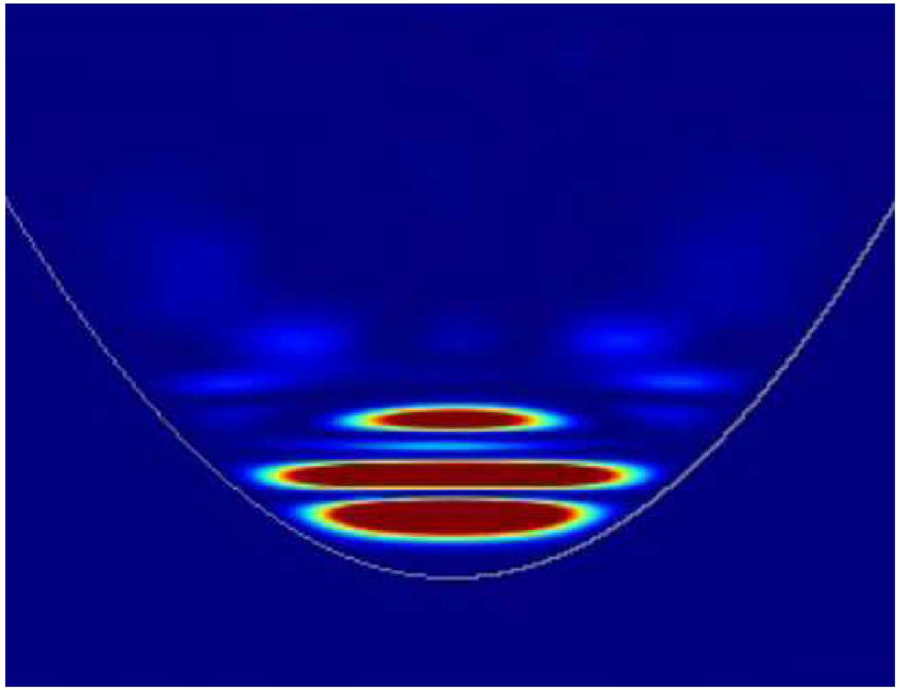
Triangular vs Parabolic Valley





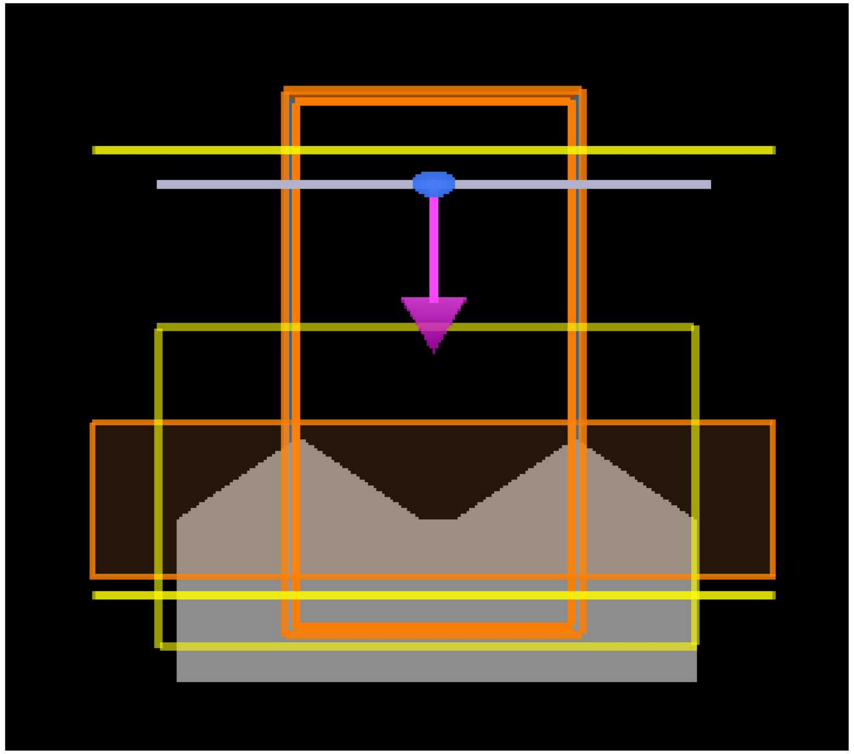
Triangular vs Parabolic Valley



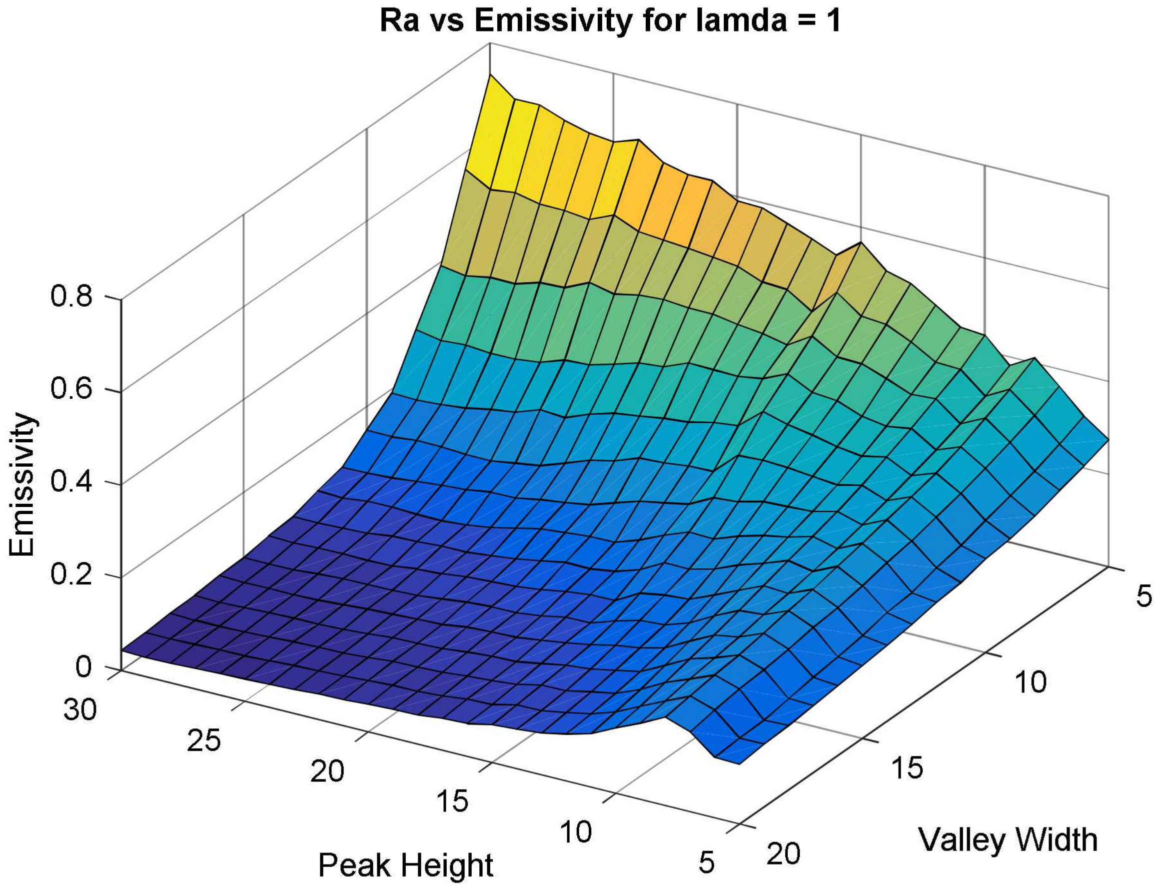


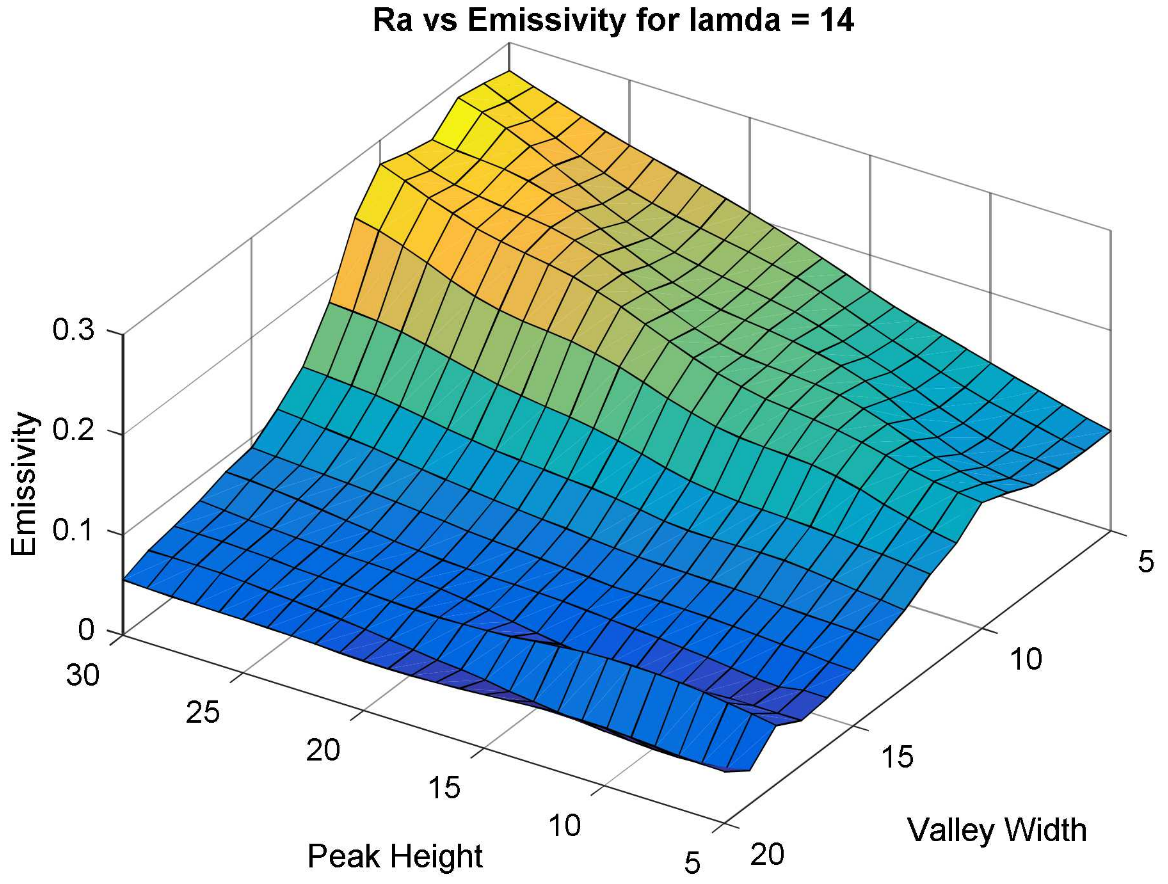
Flat Valley Set Up

- 2 isosceles triangle + flat valley in between
- Periodic Boundaries
- Variables
  - Height of triangles: 5-30 microns
  - Valley width: 5-20 microns



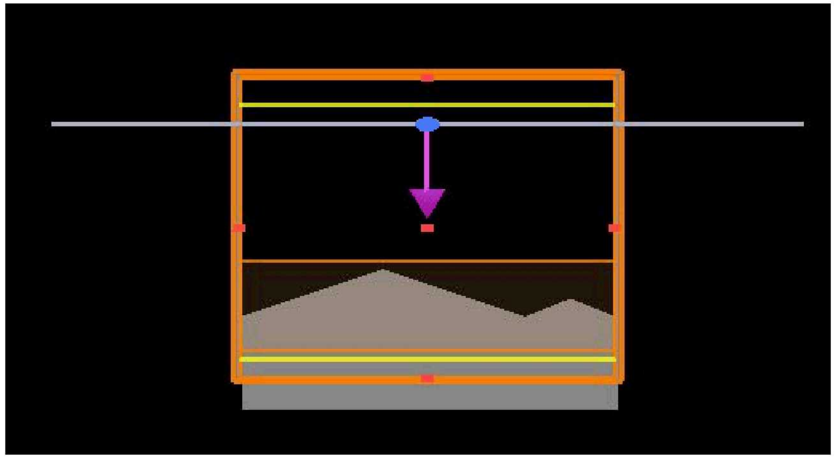
Flat Valley Results

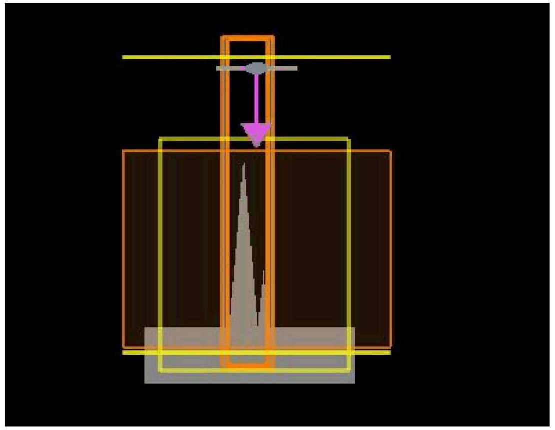




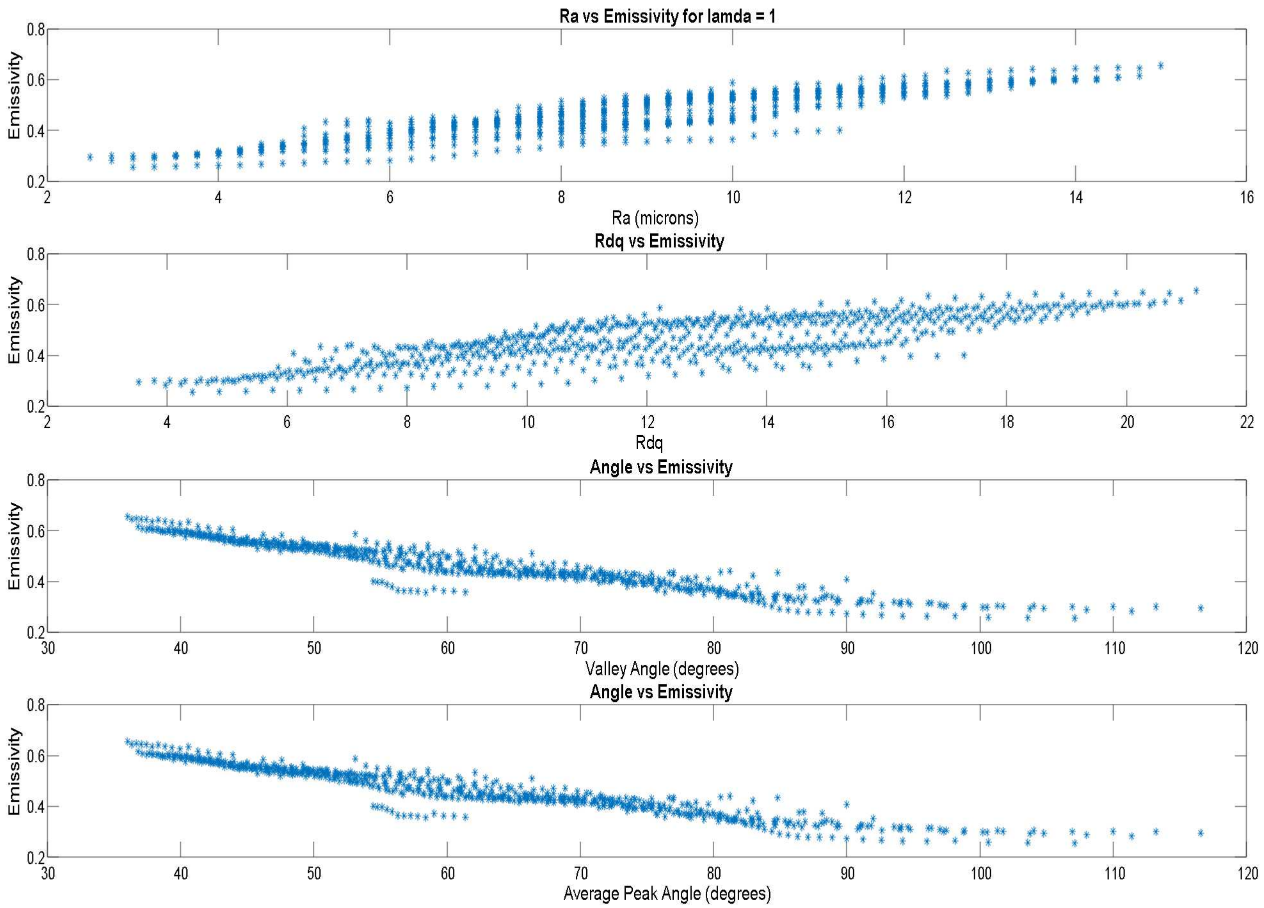
Multi-Sized Triangle Set Up

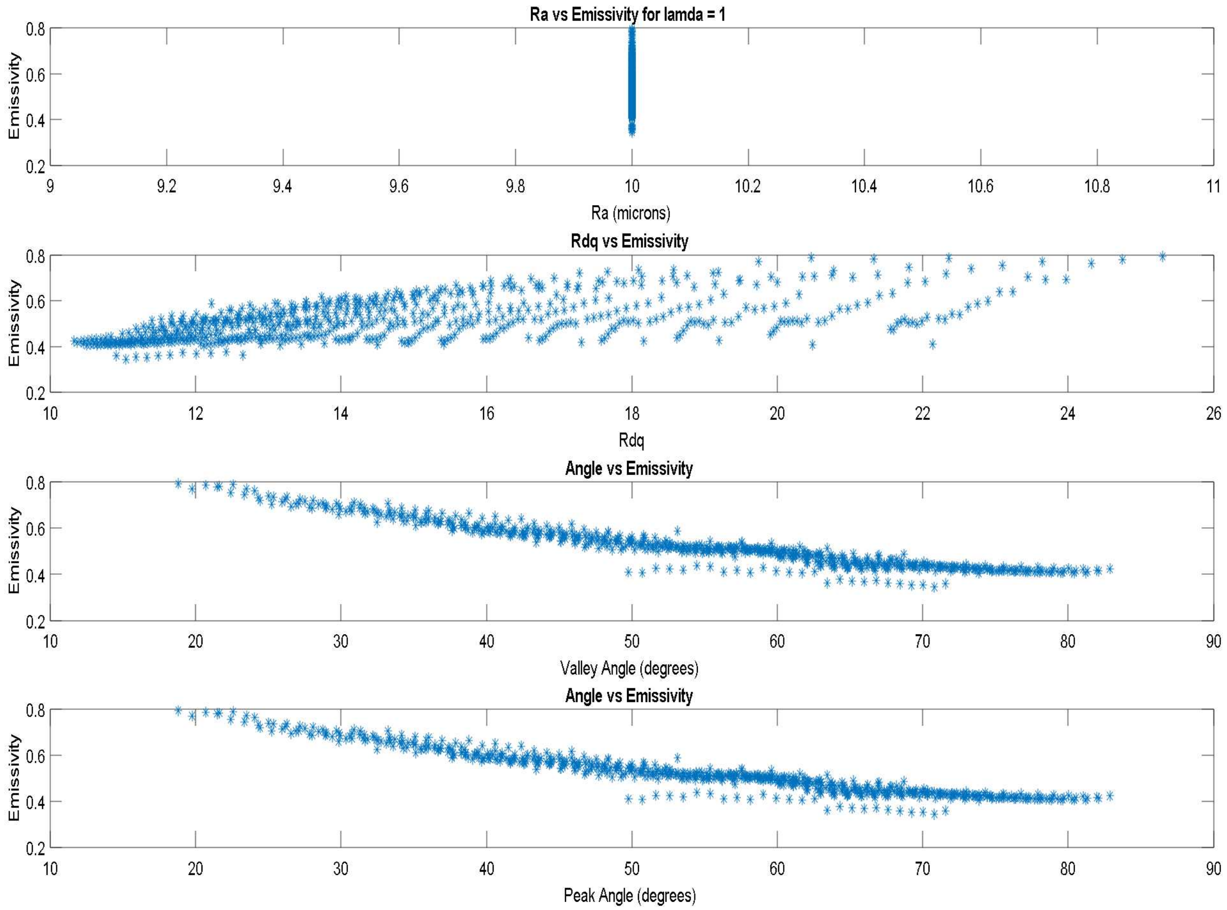
- 2 isosceles triangle with difference heights and widths
- Periodic Boundaries
- Variables (Height or Width)
  - Large triangle: 5-30 microns
  - Small triangle: 5-30 microns
  - Constant Width/Height
    - Small triangle: 10 microns
    - Large triangle: 10 microns





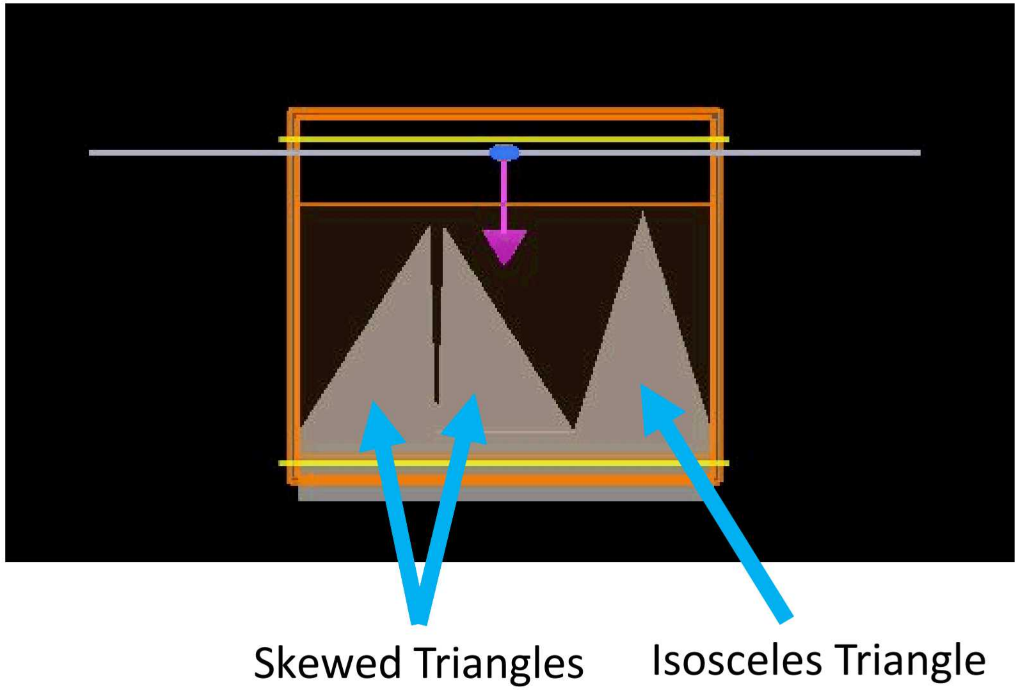
Height Change vs Width Change



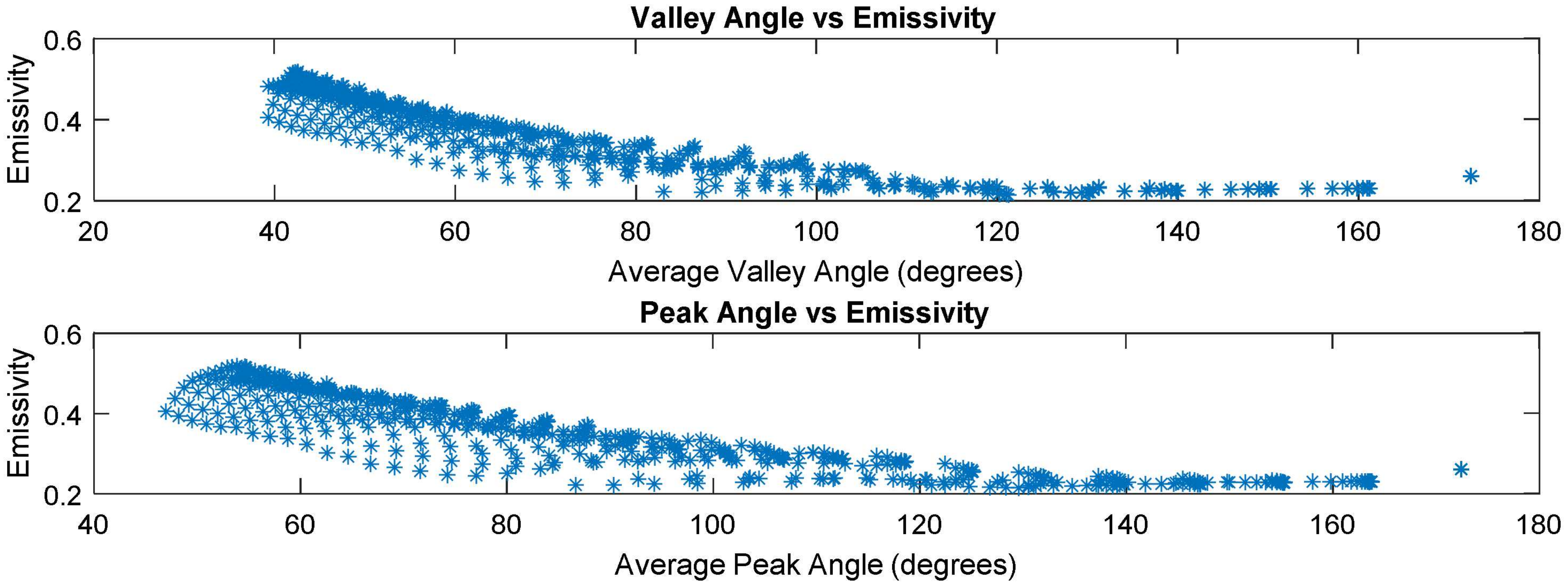


Skewed Triangle Set Up

- 2 Skewed Triangles + variable height isosceles triangle
- Periodic Boundaries
- Variables
  - Height: 0-25 microns
  - X position of skewed triangle peaks: 0-20 microns



Skewed Triangle Results

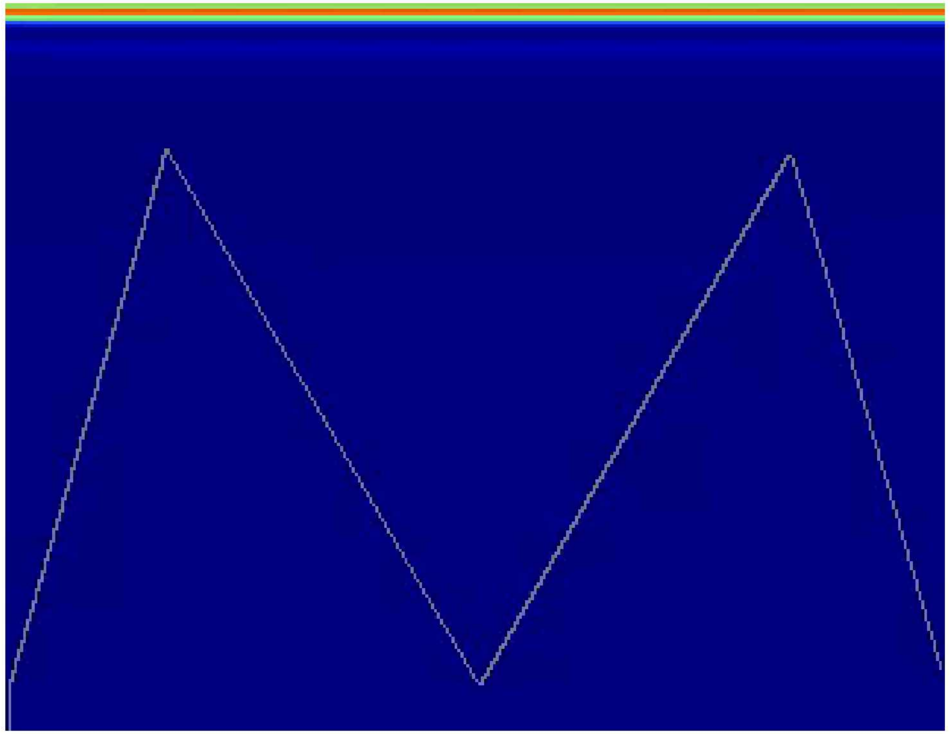


Simulation Conclusions

- R_a is related to underlying surface aspects that affect emissivity, but is not a good indicator
- RΔq has a better relationship to emissivity changes, but still not best indicator
- Average valley angle has best relationship with emissivity changes due to phenomena of internal reflections being the cause for increased emissivity

Phenomenological Explanation

- Internal reflections increase as angle of valley decreases
- Mendenhall Wedge Effect (1911) – narrow wedges formed from a strip of material that cause black body-like behavior
- "By forming a wedge one is causing incident radiation to undergo more reflections, and hence more absorption, and hence approaching more and more closely what is called a 'blackbody'"(Taylor 1987)



Phenomenological Explanation

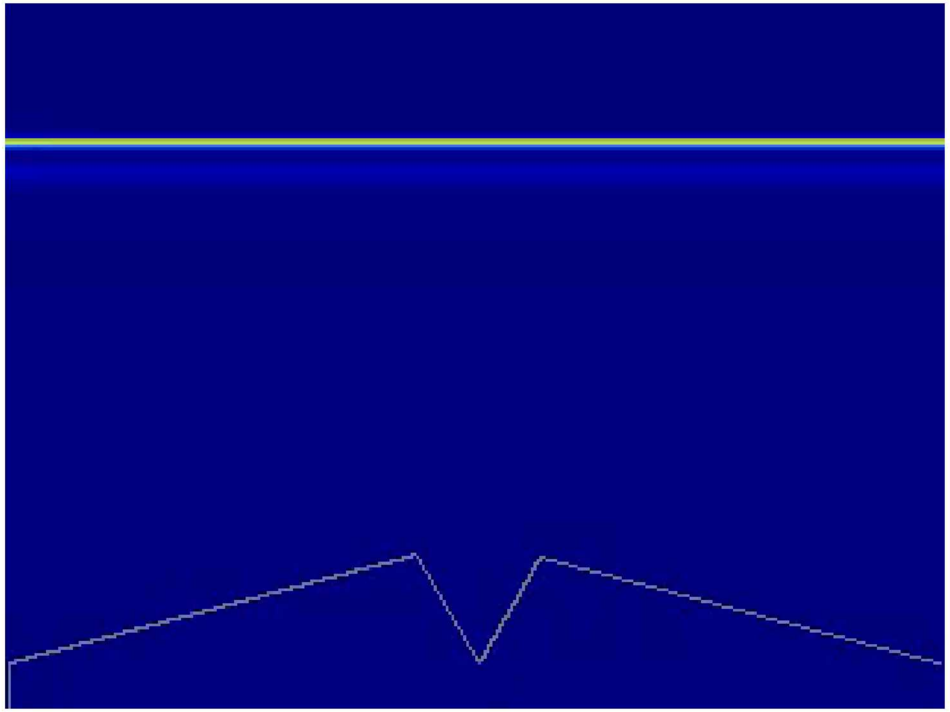
$$E \approx A = 1 - r^{\frac{180}{\theta}}$$

E = emissivity

A = Absorption

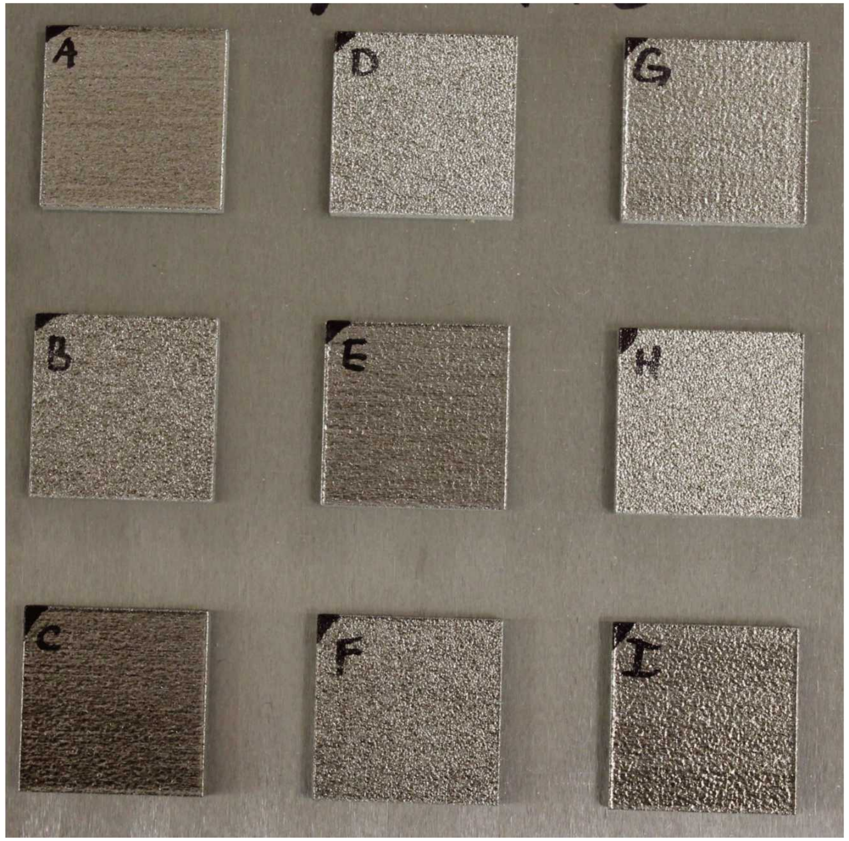
r = reflection power of the material surface

θ = internal wedge angle



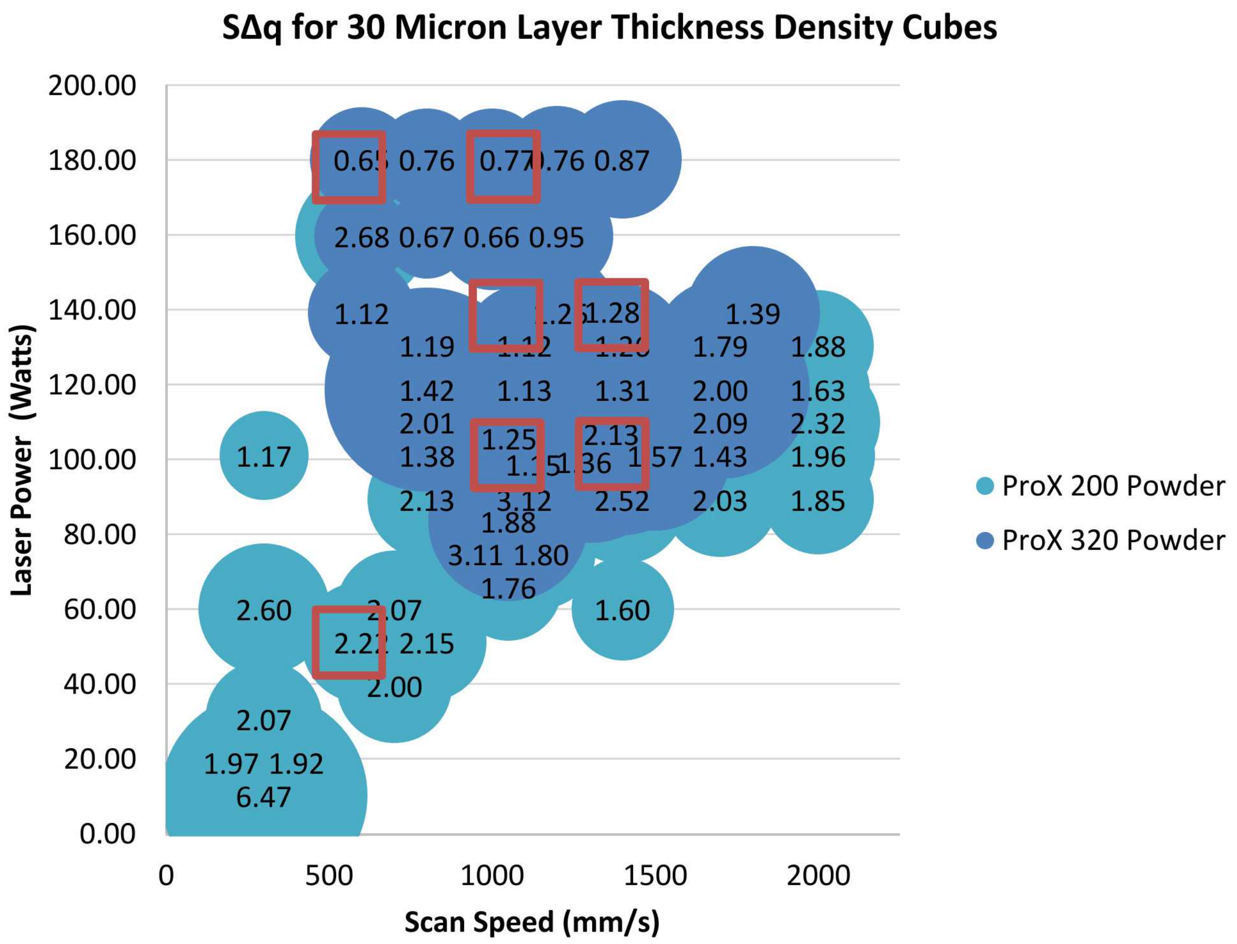
Experimental Evaluation of Surface Roughness Effects on Emissivity

- Build Parameter Selection
- Part Fabrication
- Surface Roughness Measurements
- Emissivity Measurements
- Correlation between emissivity and surface roughness parameters

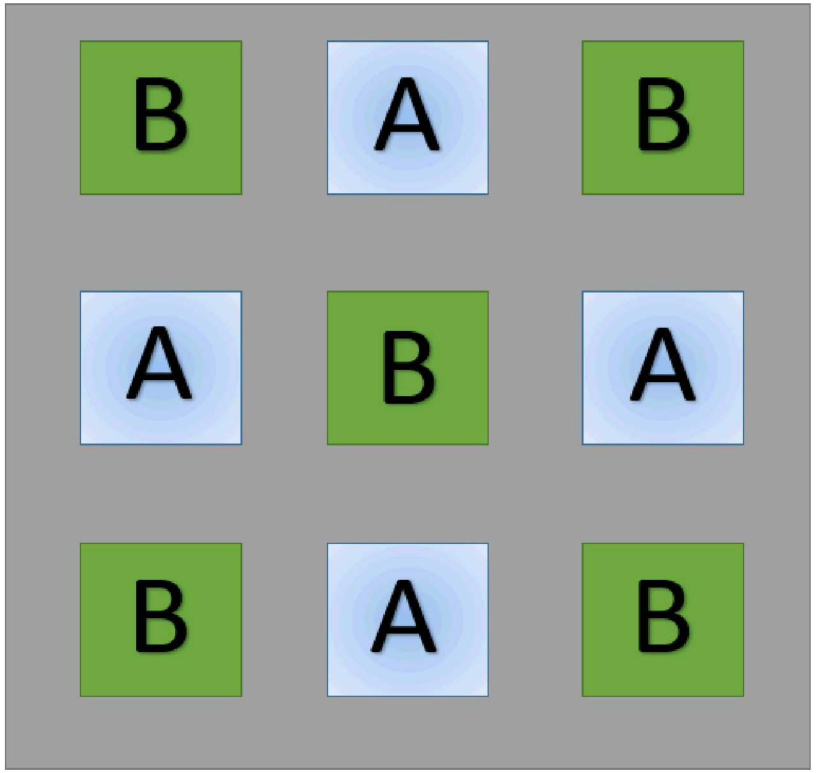


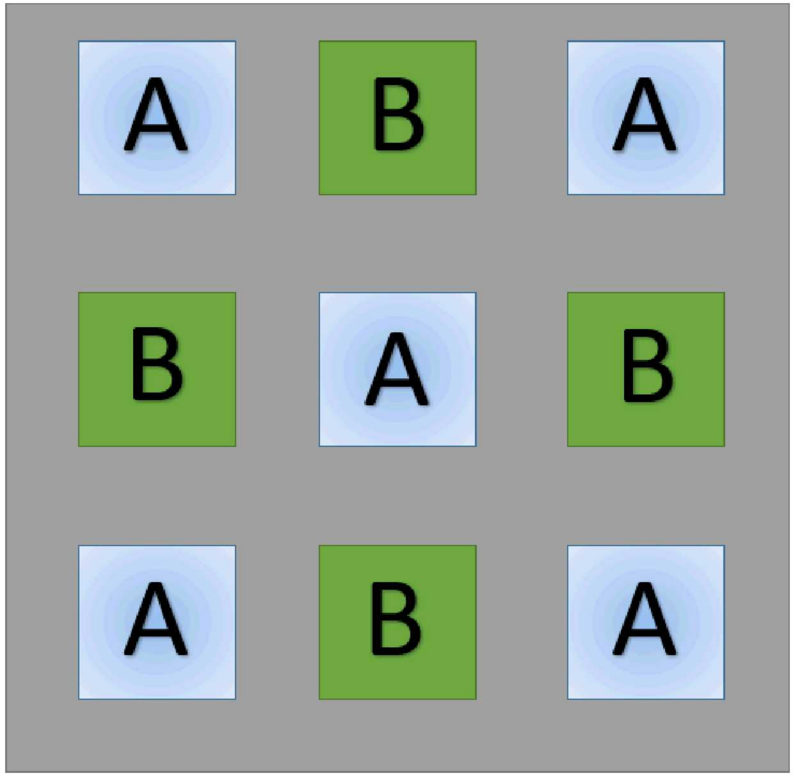
Sample Build Settings

- Geometry: 25mm square, 6mm thick
- Scan Strategy: 0/90
- Layer Thickness: 30 microns
- Hatch Spacing: 50 microns
- Laser Spot Size: 100 microns
- Powder: ProX 320 316 SS
  - Mean particle size: 25 microns



Build Layouts

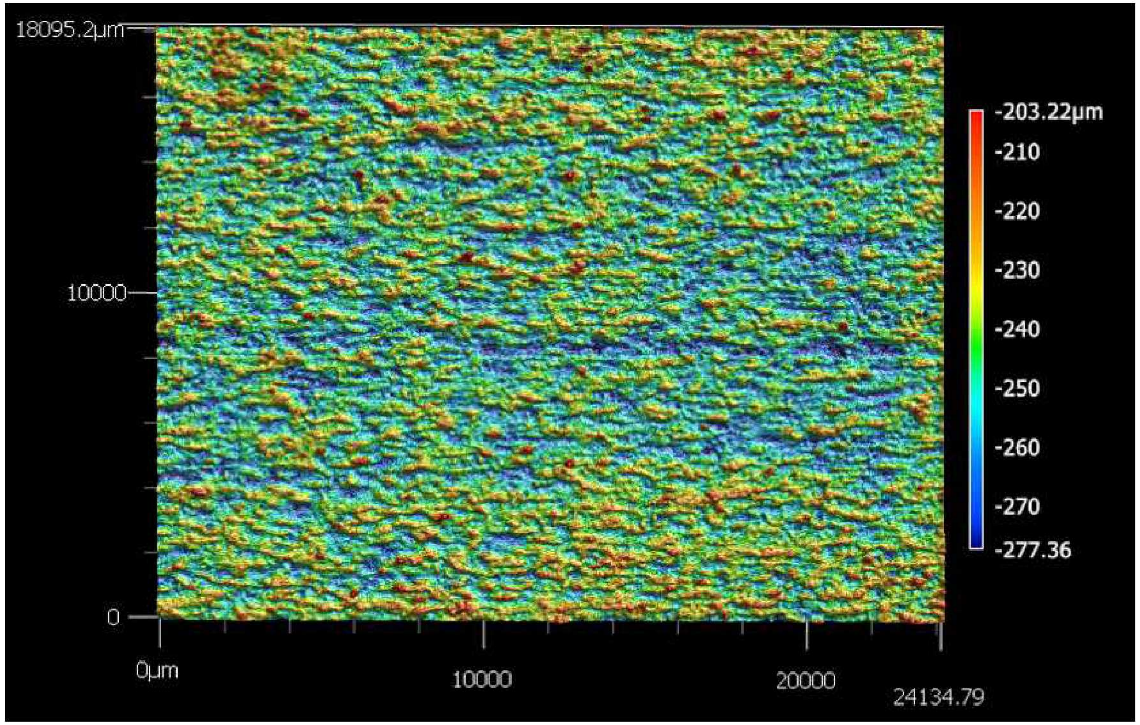




Completed Builds – 72 parts

Potential Surface Roughness Measurement Techniques

- X-ray Coherence Tomography (XCT)
  - Insufficient resolution for entire area of part
  - Surface detection issues (grayscale images)
- White light interferometry
  - Surface too rough
- Stylus-based contact profilometry
  - Possible aliasing
  - Possible damage to equipment
- Fringe pattern projection microscopy
  - Large areas of measurement
  - High resolution
  - Non-contact



Keyence VR3100 Microscope

- Uses light triangulation to measure height of samples
- Light bands are illuminated onto surface and CMOS sensor looks at light distortion to calculate height map
- Can measure height differences up to +/-5 mm
- Can measure up to 3 cm square with no distortion due to specialized lenses
- Raw surfaces output in excel spreadsheet for further analysis

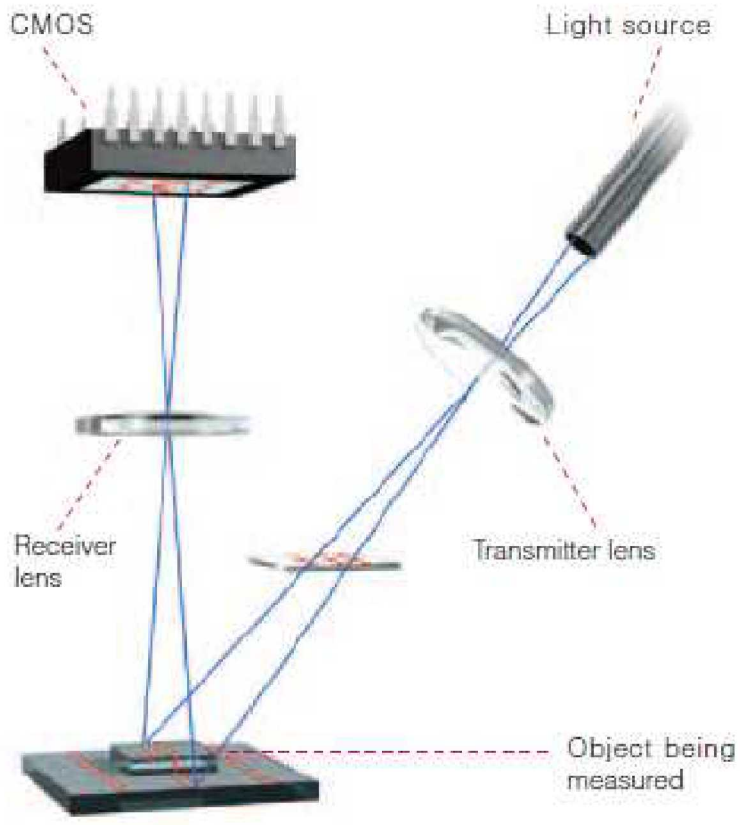
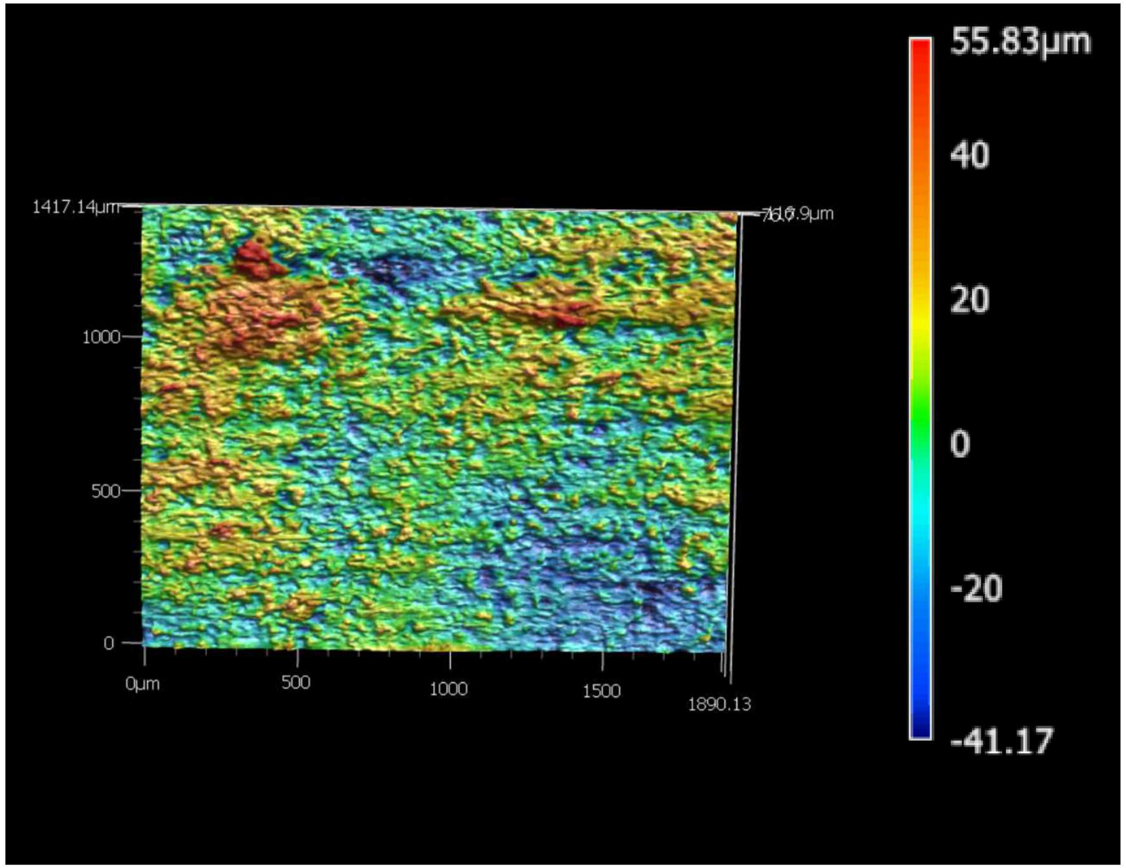


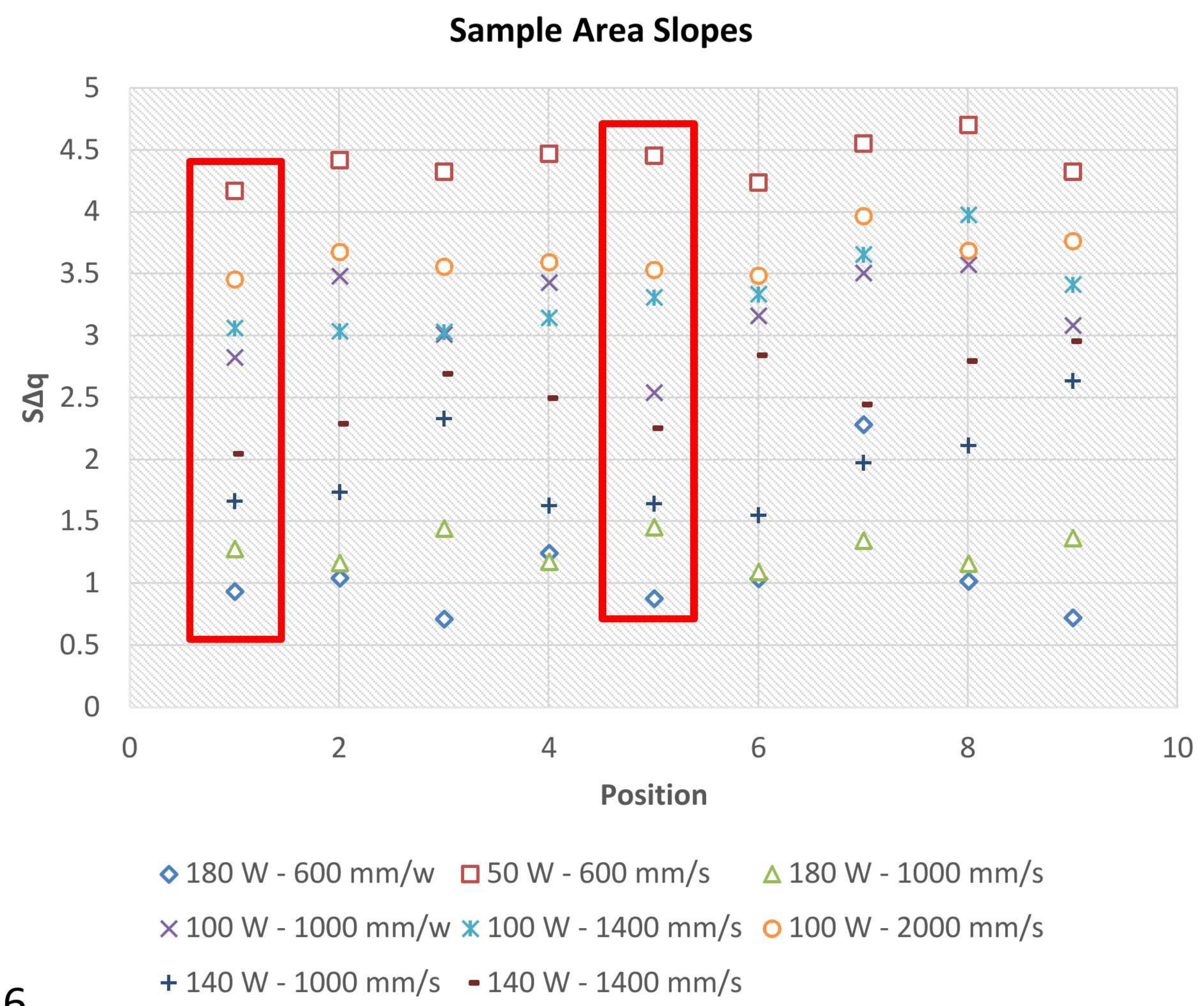
Image from: Keyence One-shot Measuring Macroscope VR-3000 Series

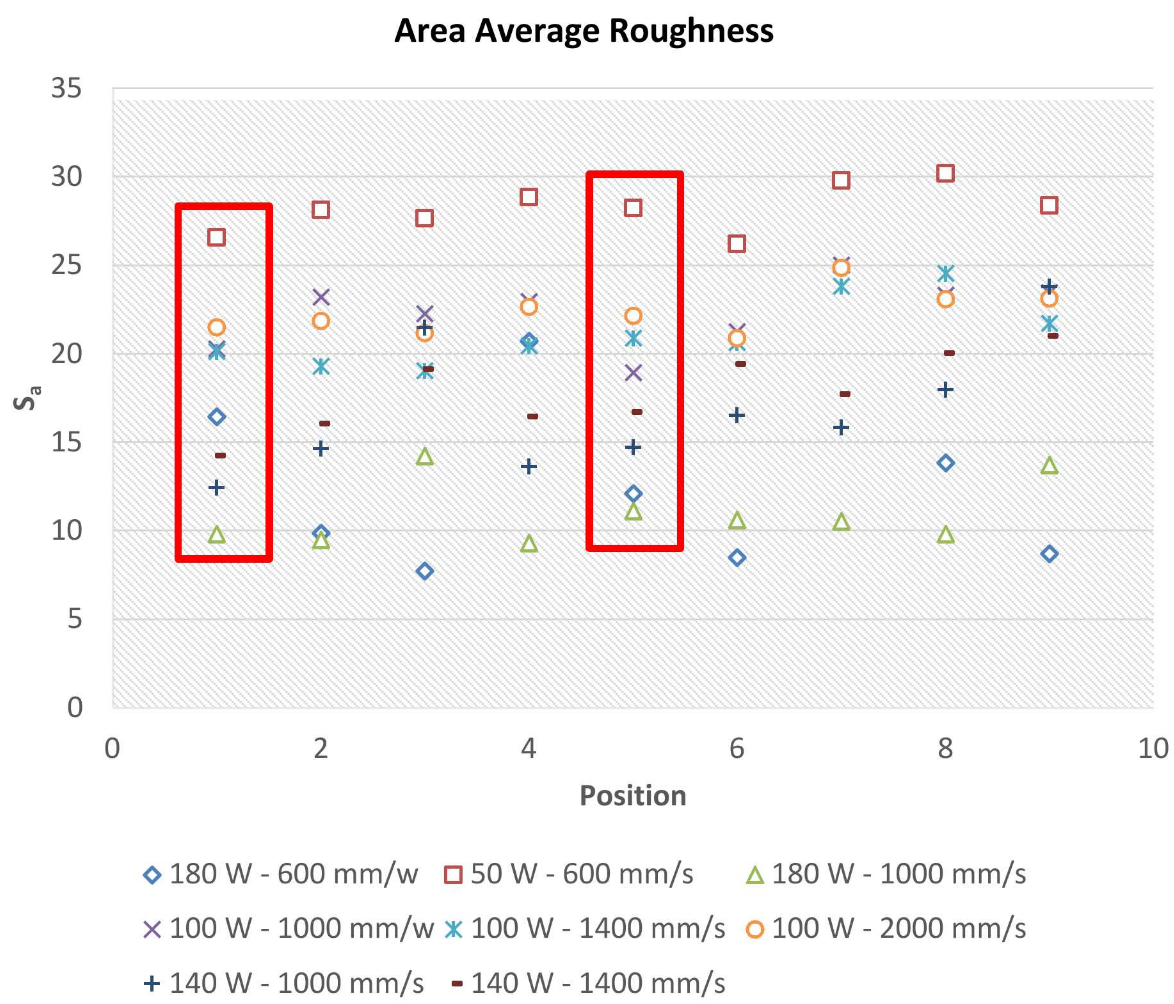
Surface Roughness Analysis

- Custom MATLAB program
- Input was raw height maps
- No filtering except plane removal
- Multiple zooms/resolutions used
- Standard and custom SR parameters calculated



Surface Roughness Results





Emissivity Measurements

- Hemispherical Directional Reflectometer (HDR)
  - Directional reflectance is measured at 5-10 degree increments
  - Radiation reflected from sample is directed by a mirror that directs radiation to the coupled FTIR
- Wavelength Range: 2.5-24 microns
- Baseline measurements performed on polished AM and stock samples

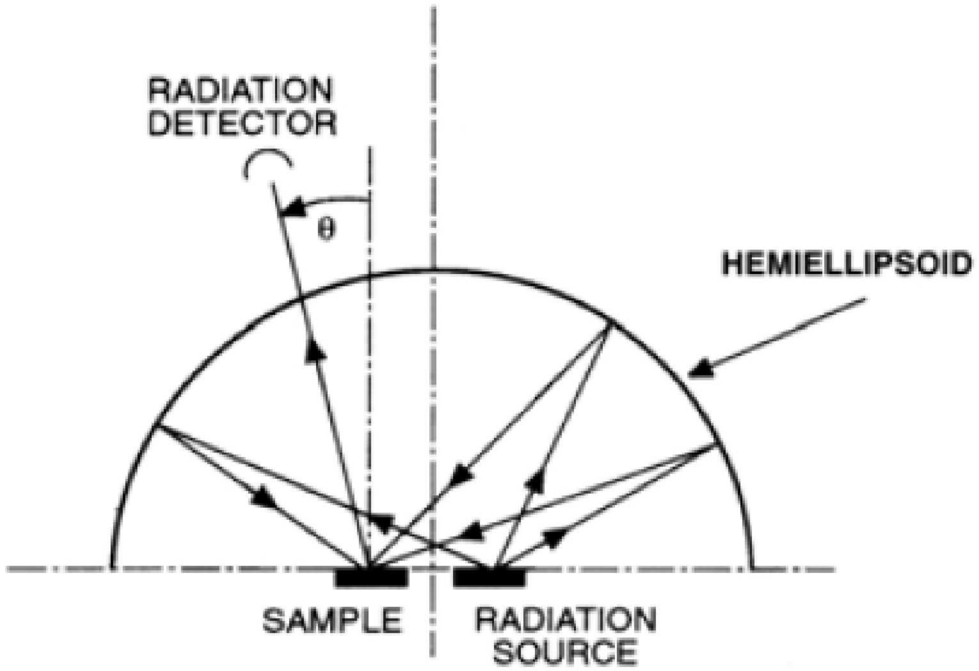


Image from: Surface Optics Corporation, SOC-100 HDR

Emissivity Measurements

- Fourier Transform Infrared Spectroscopy
  - Using interference of able to produce multiple spectra from broad band light source
  - Analyzes the various reflected spectrum off sample to determine reflection at specific wavelengths

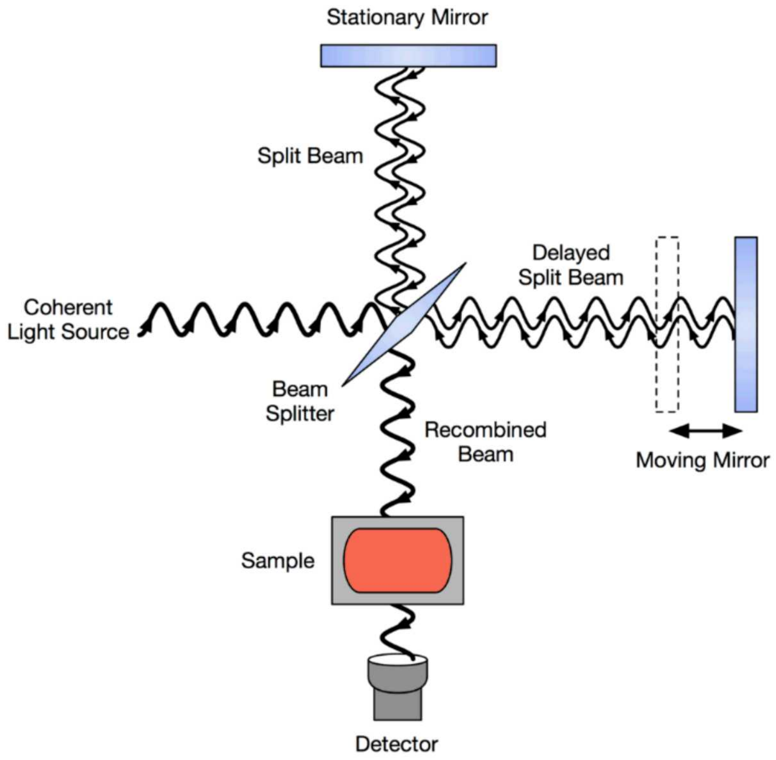
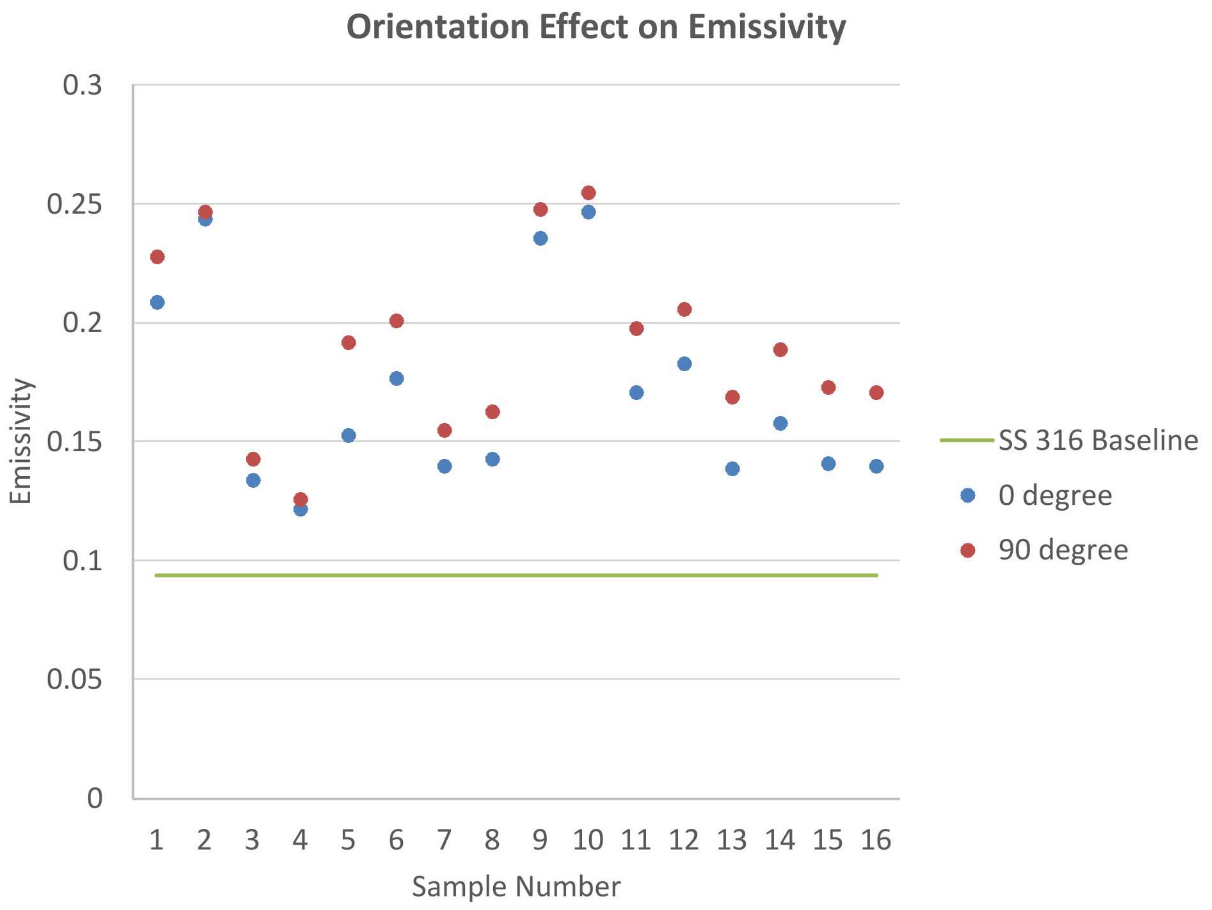
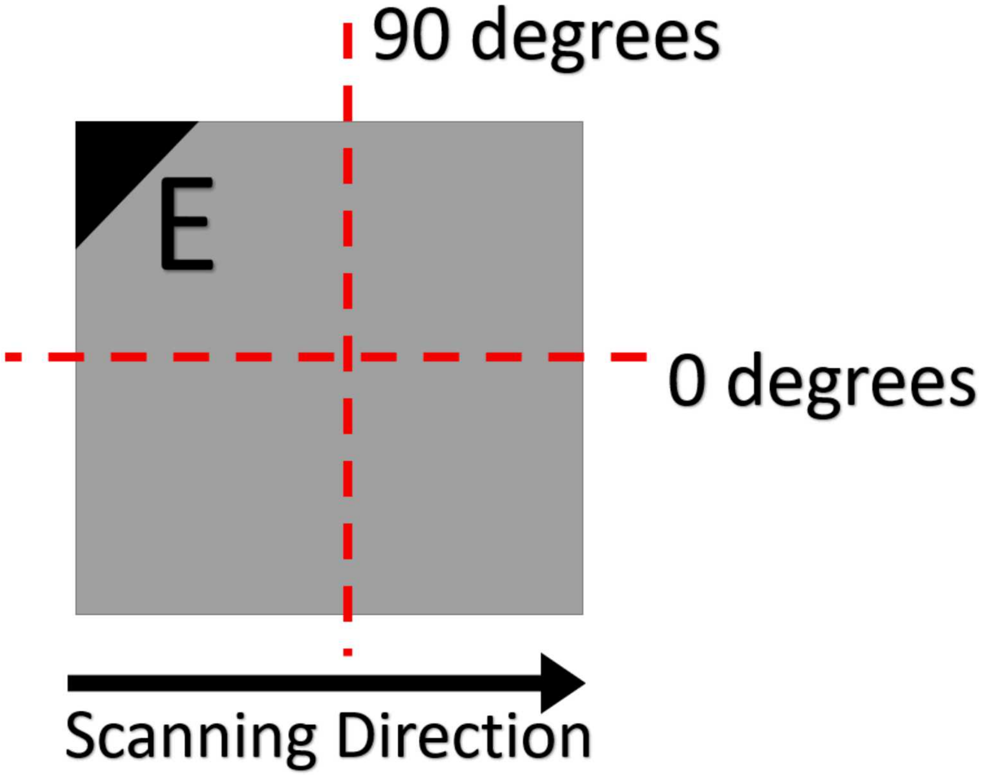


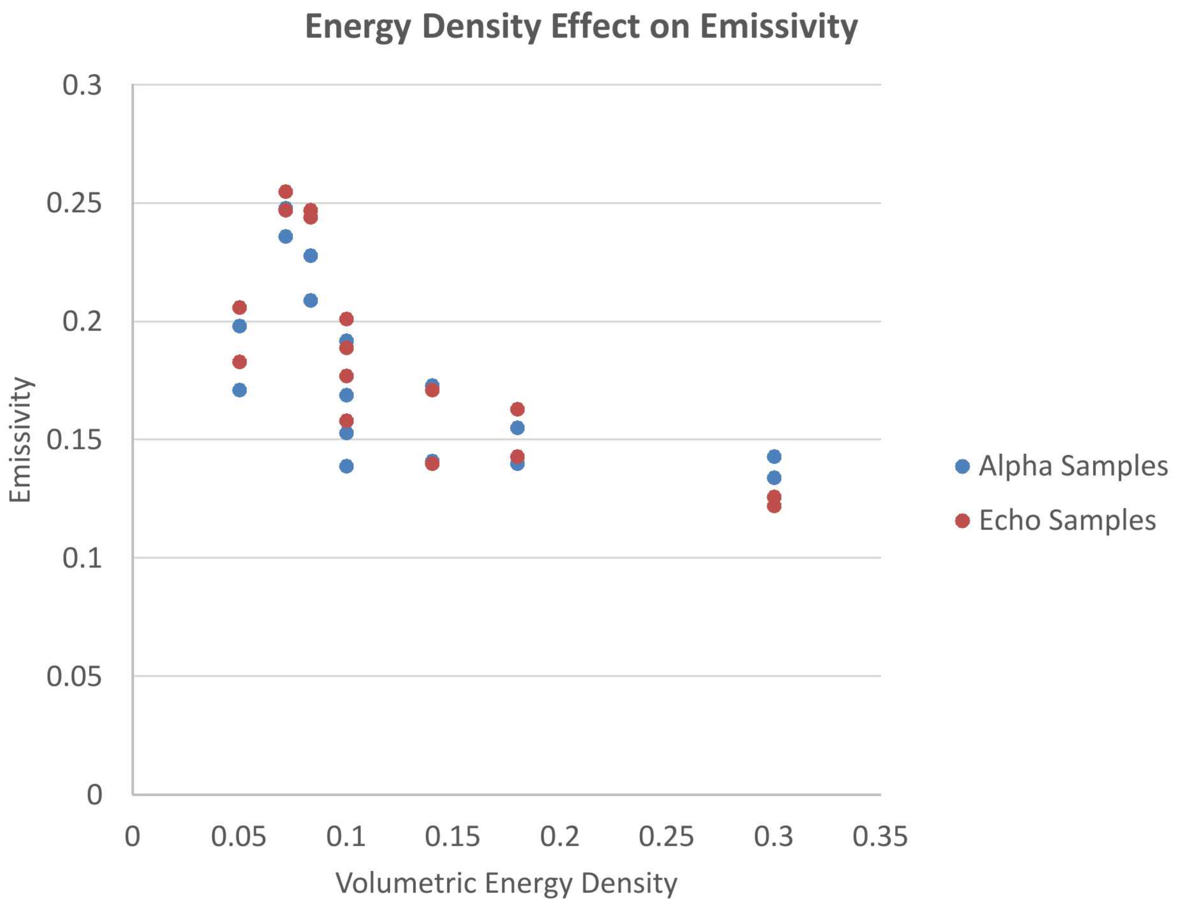
Image from: https://en.wikipedia.org/wiki/Fourier-transform_infrared_spectroscopy

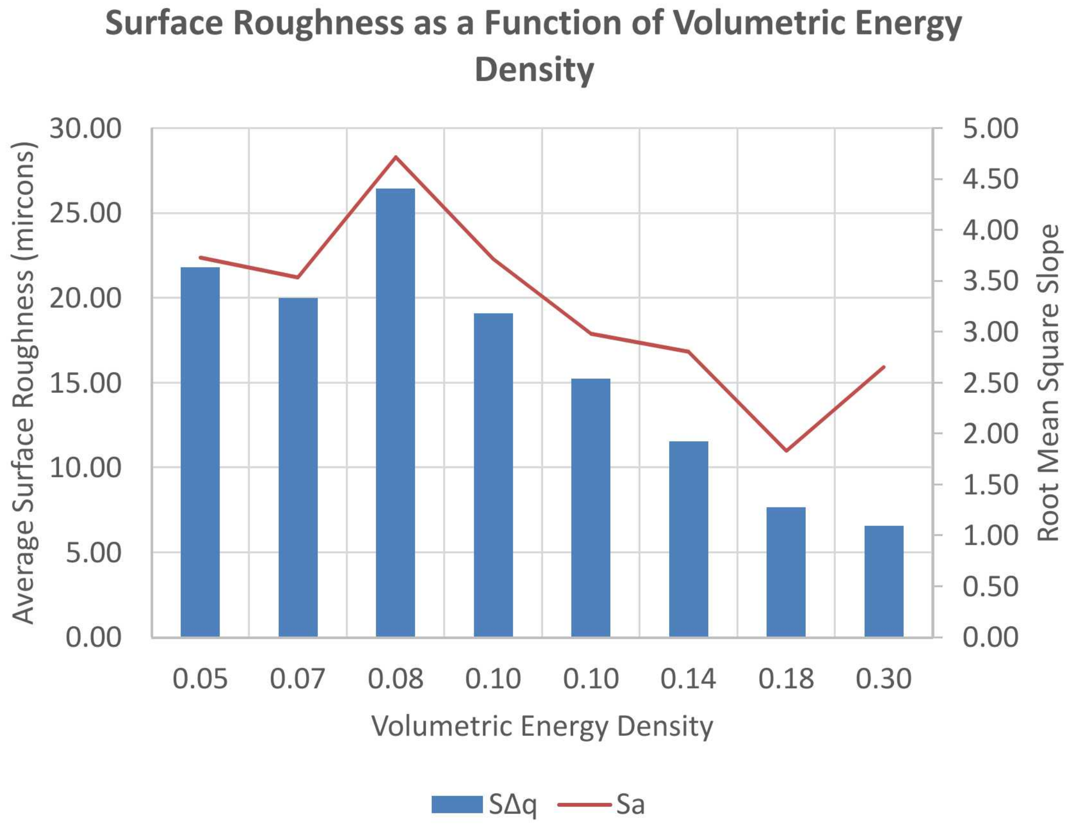
Emissivity Measurements



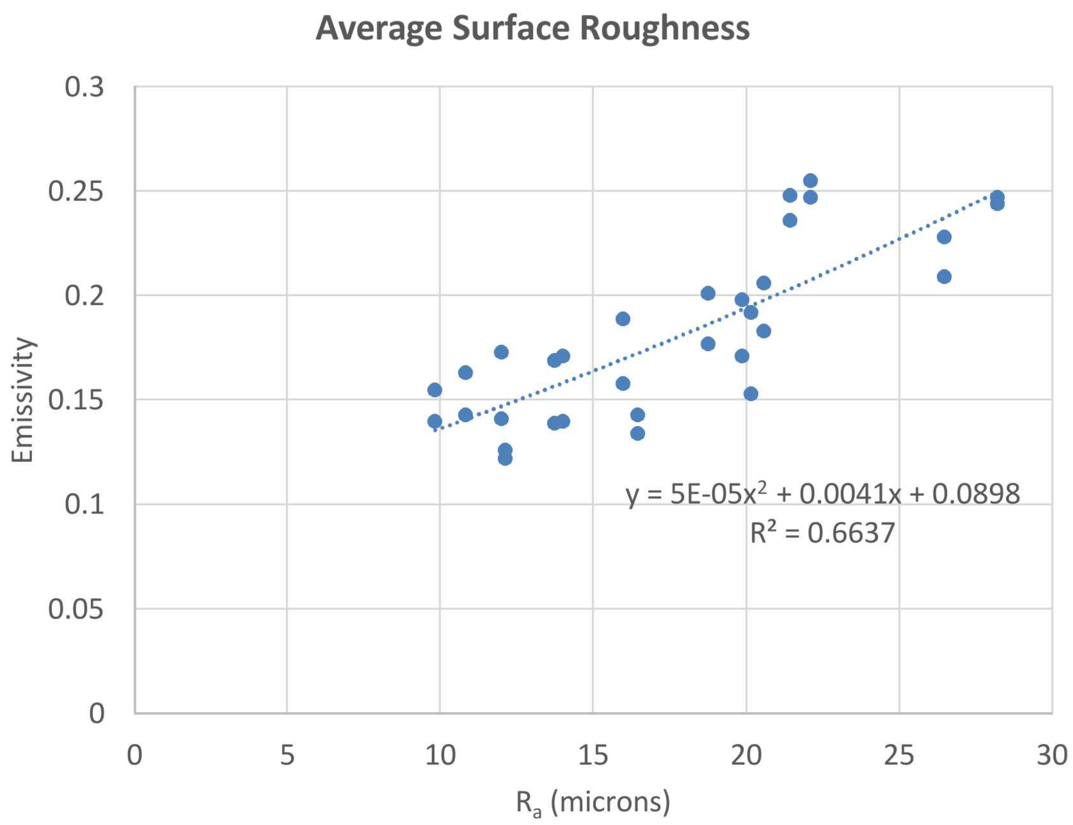


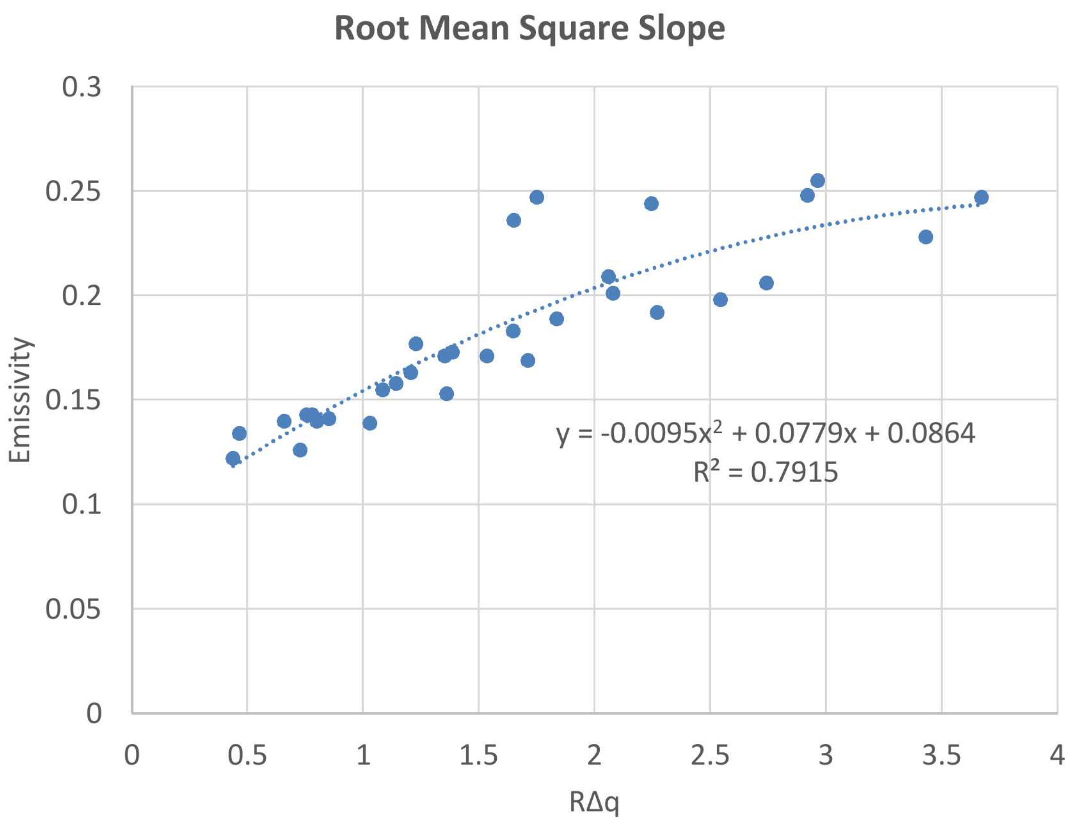
Emissivity Measurements



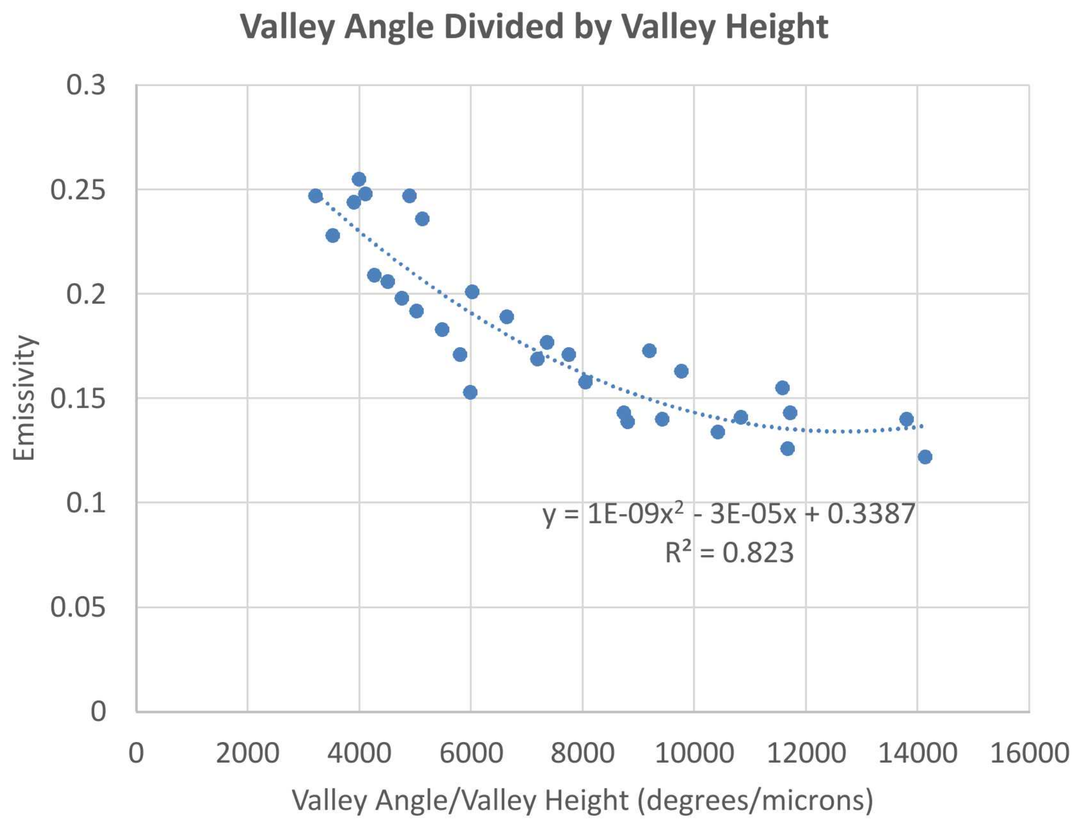


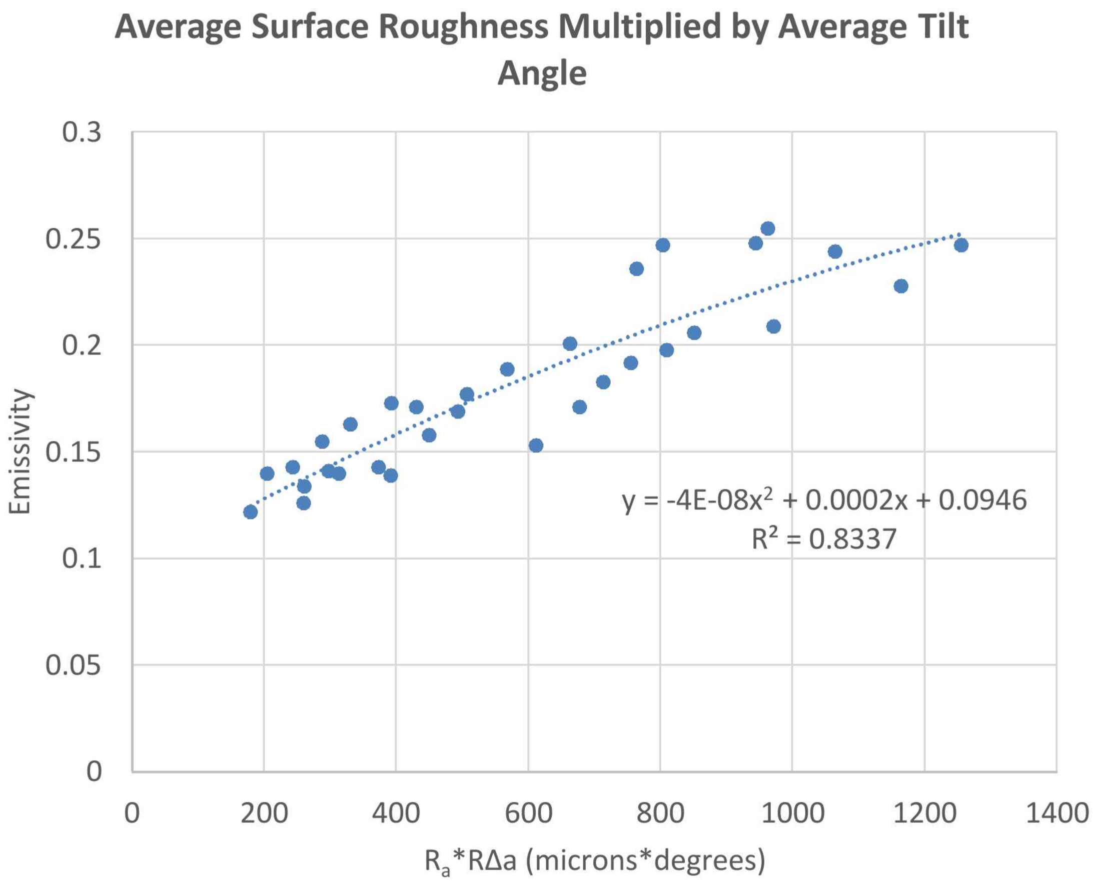
R_a and RΔq Correlations



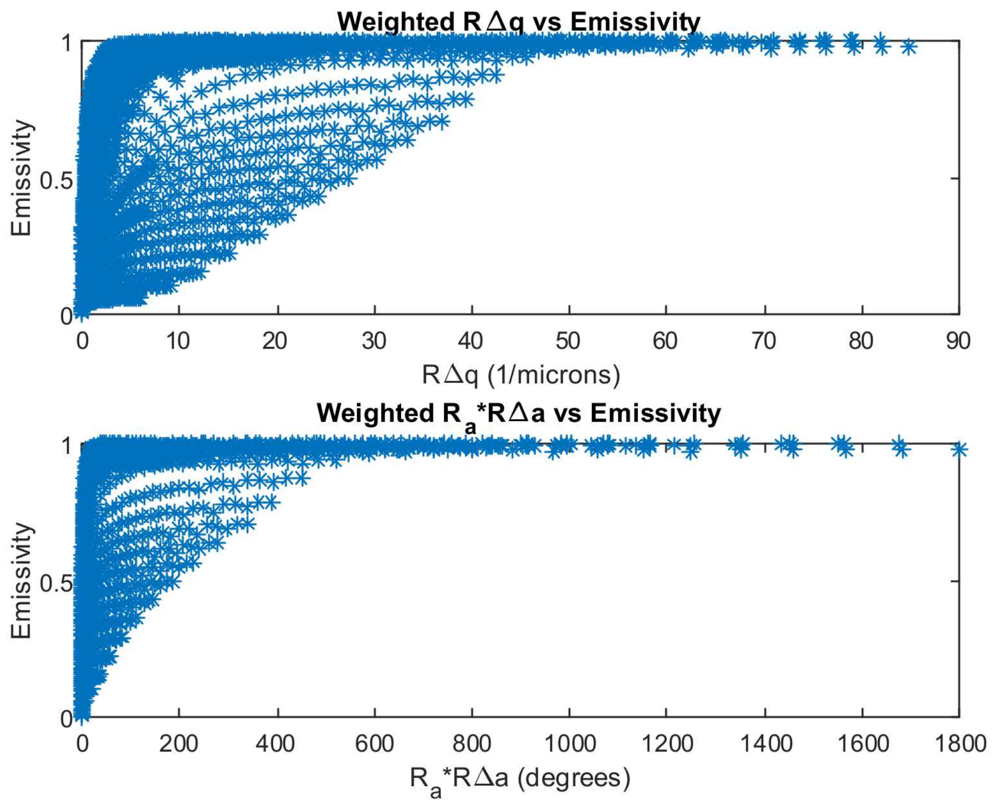


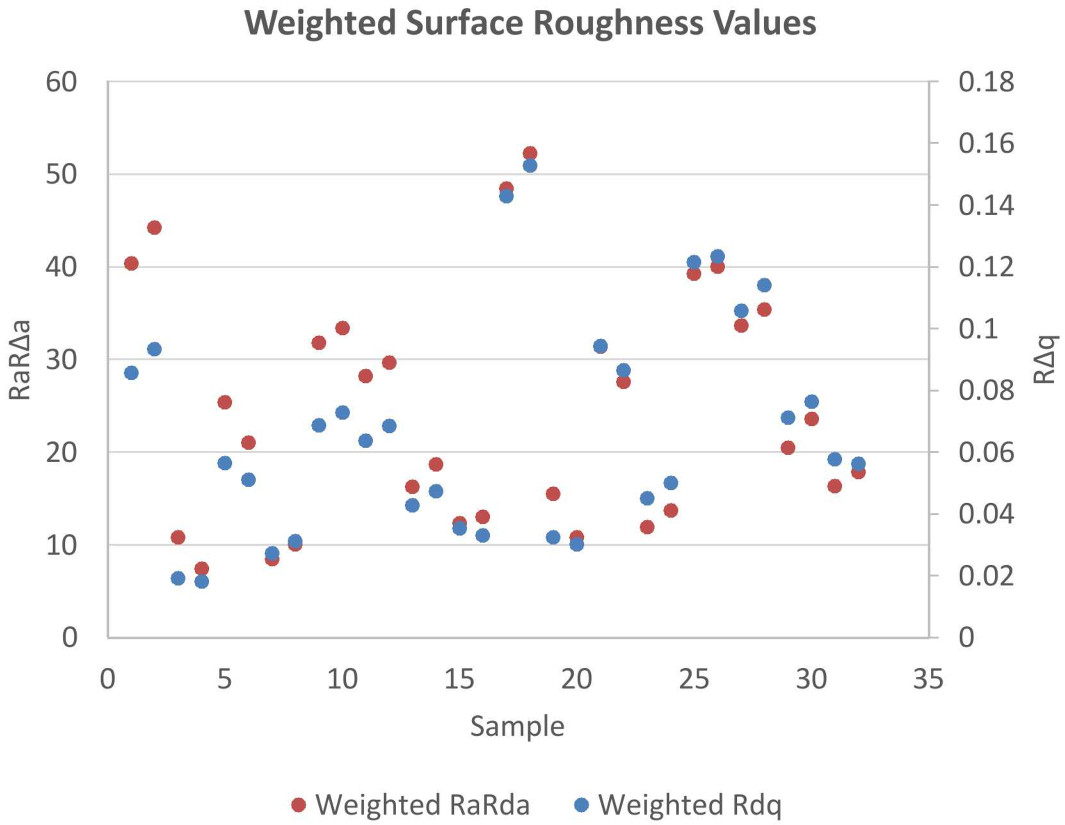
Best Correlations



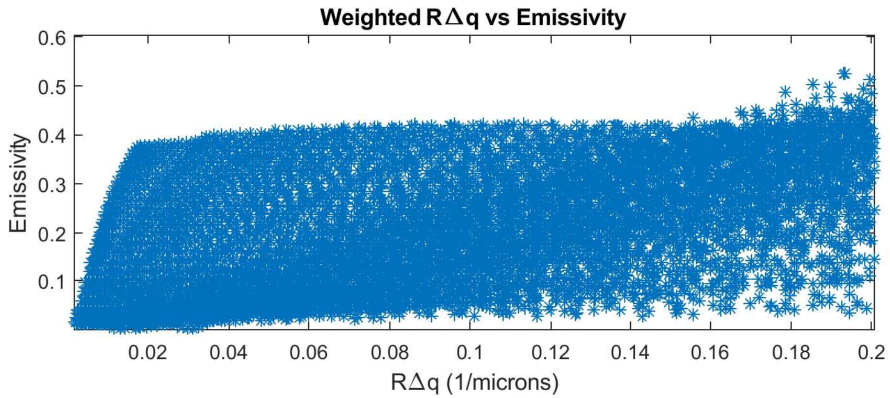


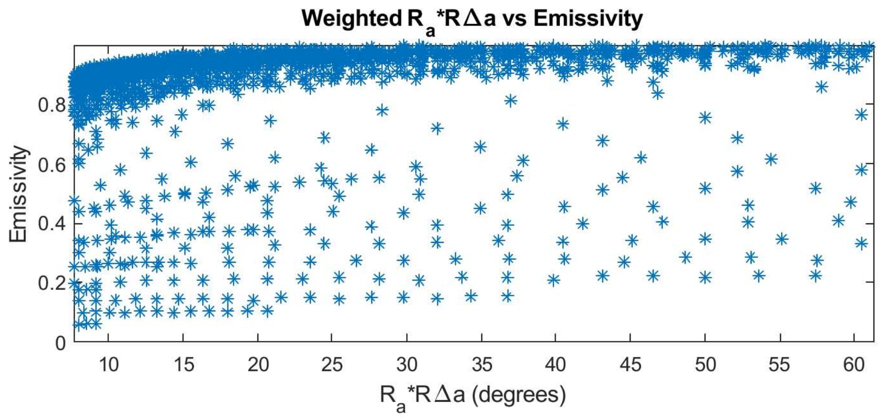
Non-dimensional SR parameters – Weighted by Wavelength

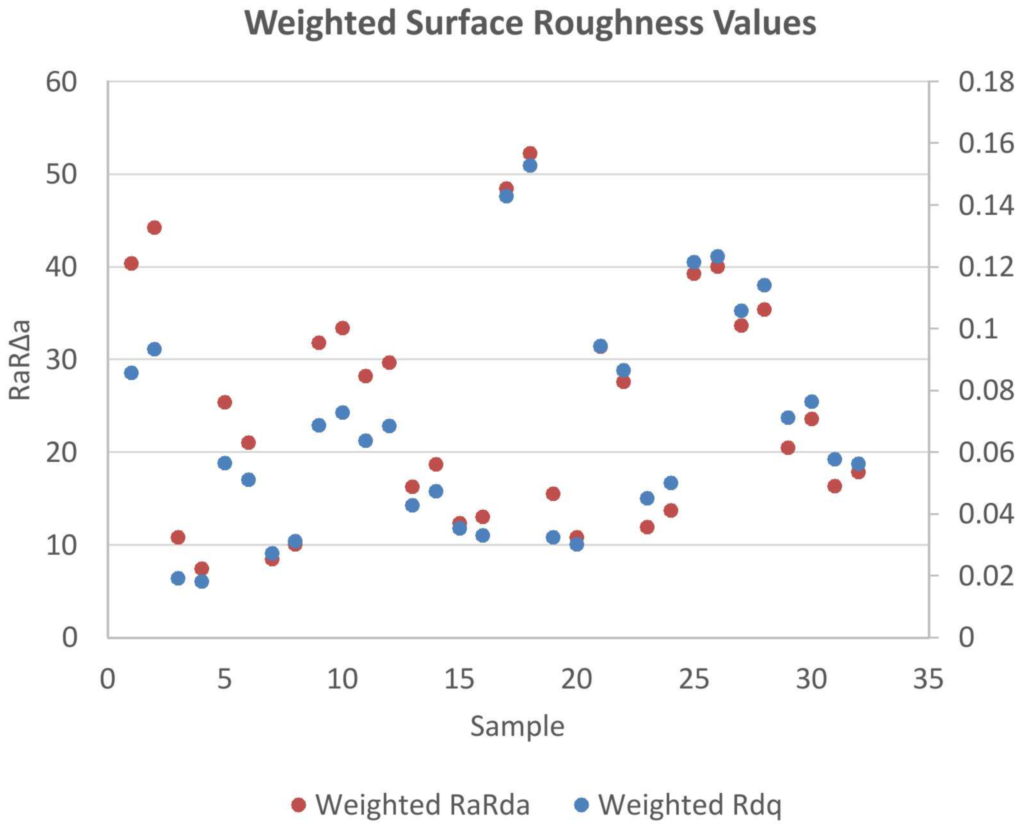




Difference between RΔq and R_aRΔa

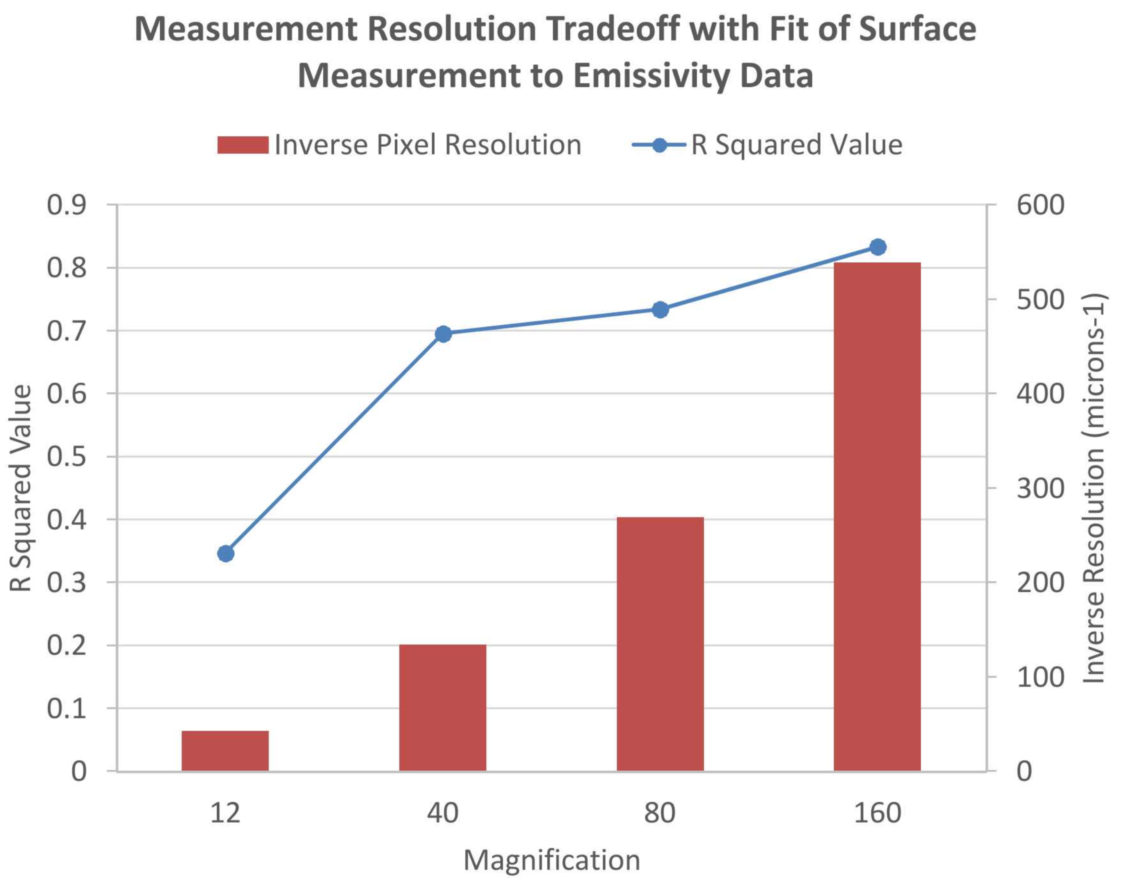




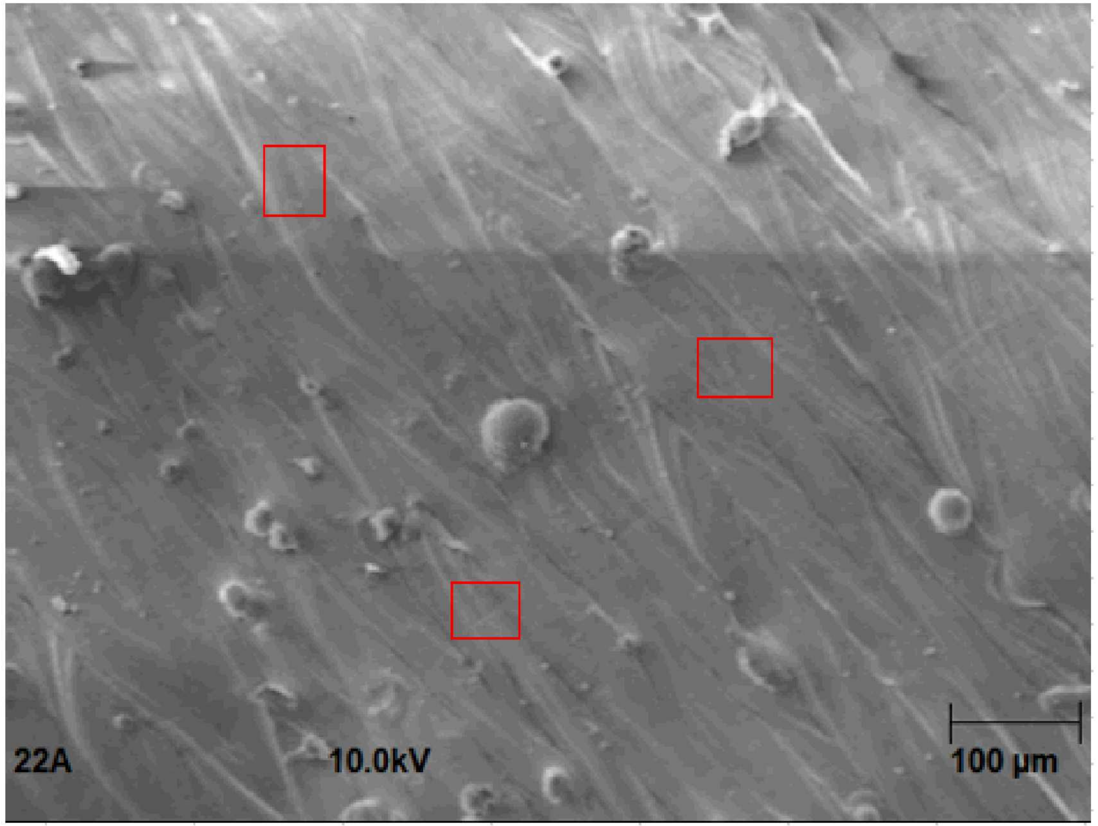


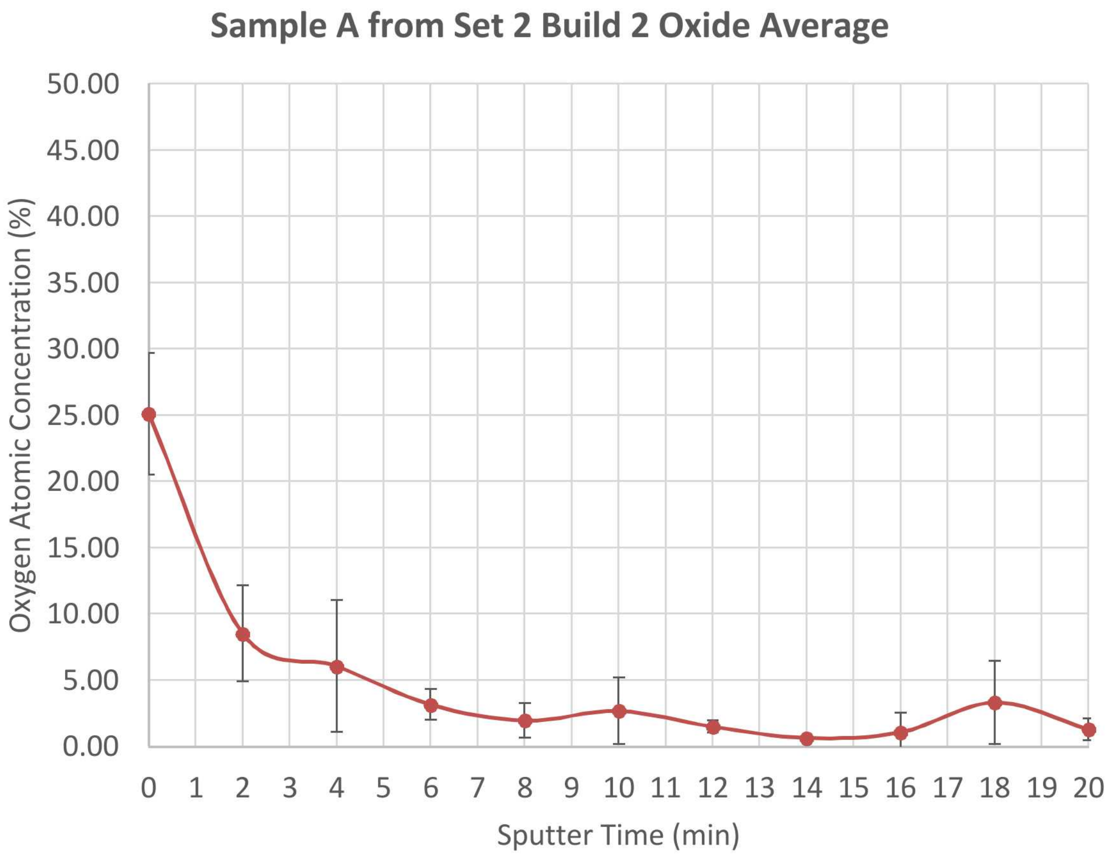
Measurement Resolution Importance

- Resolution of surface roughness measurements had a large effect on correlation strength to emissivity
- Measurement spacing did not affect correlation strength

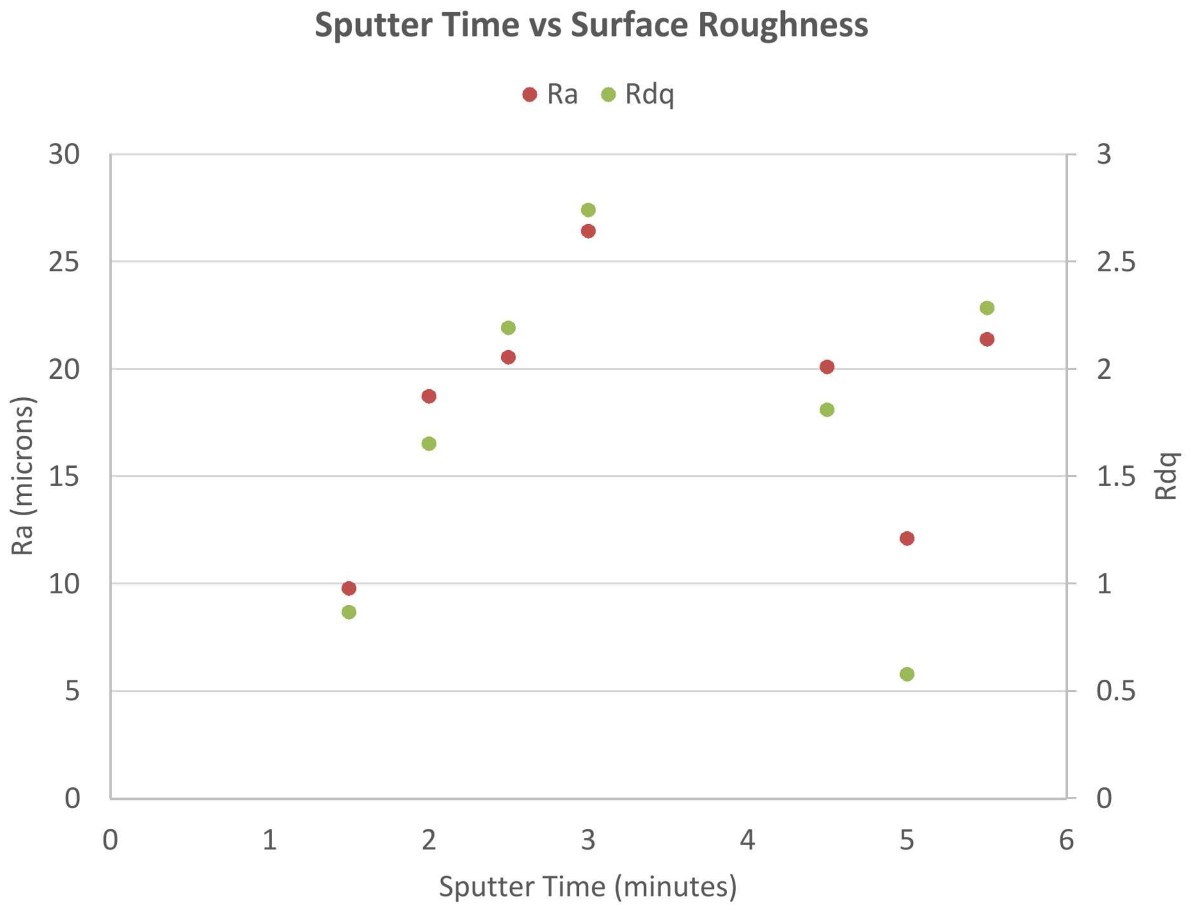


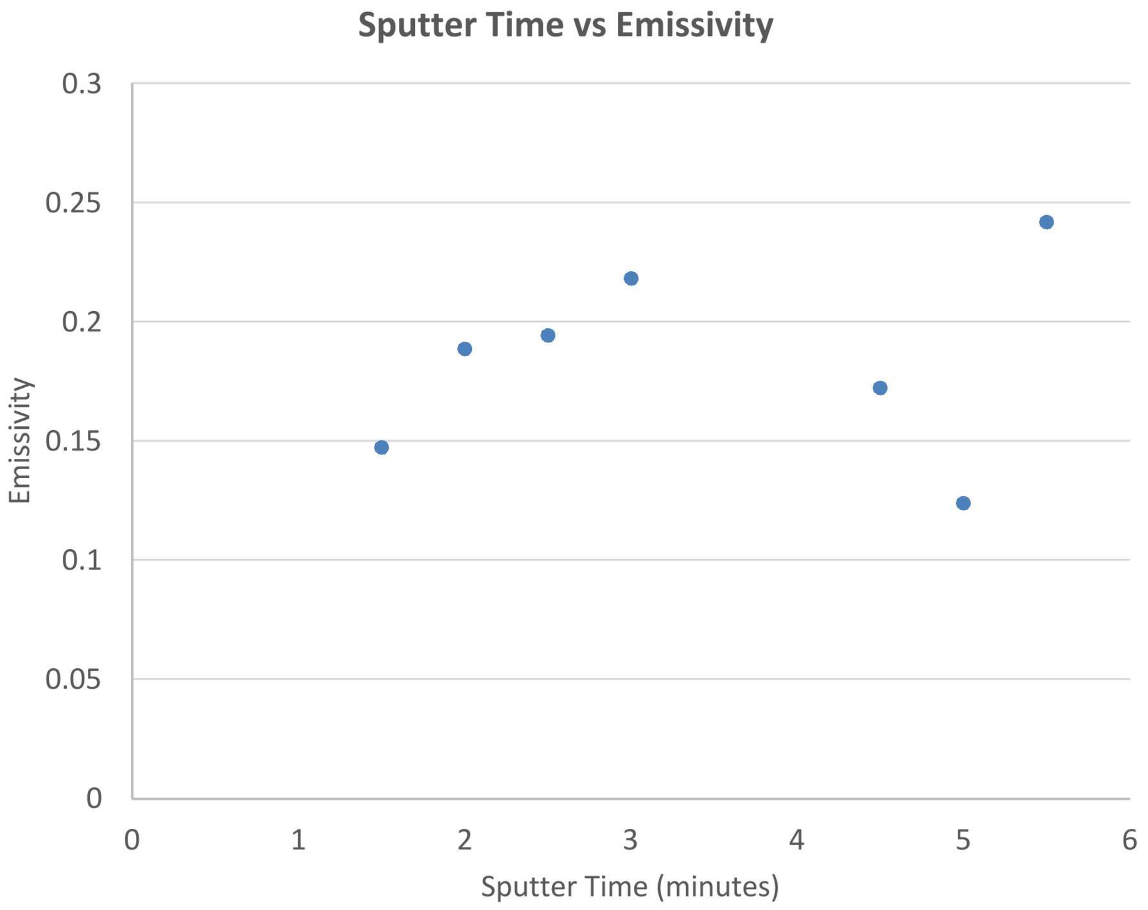
Oxide Layer Measurements - AES





Oxide Layer Measurement Comparison



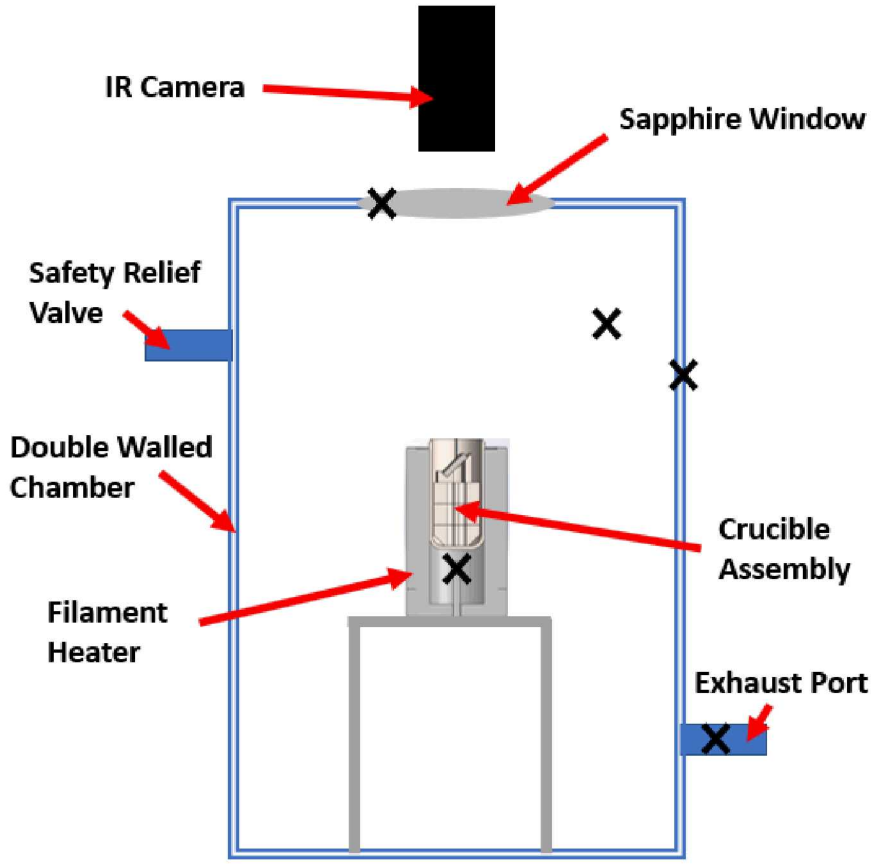


Second Task: Exploration of View Angle Sensitivity of Emissivity

- Purpose is to observe effects of view angle on emissivity for a range of sample roughness
- Angles will be 0, 30, and 45 degrees from normal (majority of literature had cameras that were 25-45 degrees from normal)
- Measurements will be taken at a range of temperatures to see if emissivity trends vary as temperature is increased

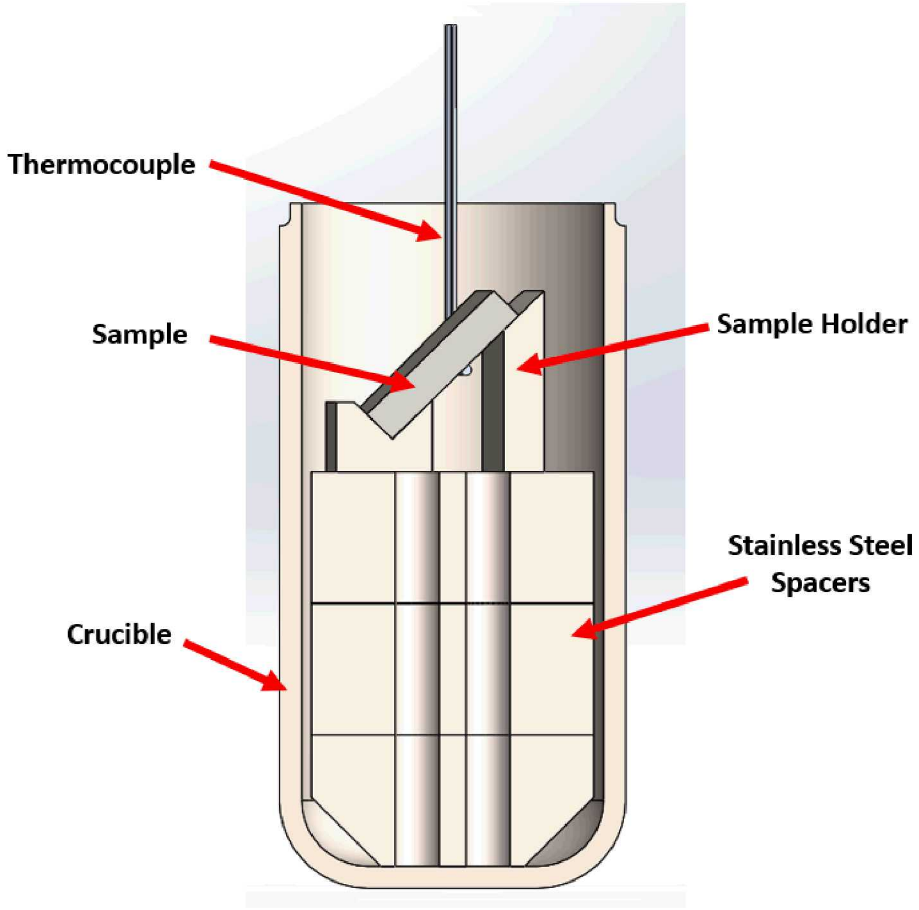
Vacuum Furnace Set Up

- Double walled chamber has cooling channels
- Argon atmosphere used to simulate in build conditions
- Sapphire viewing window limits camera options to SWIR or MWIR due to lack of transmission in the long-wave infrared range
- FLIR SC6811 MWIR camera used

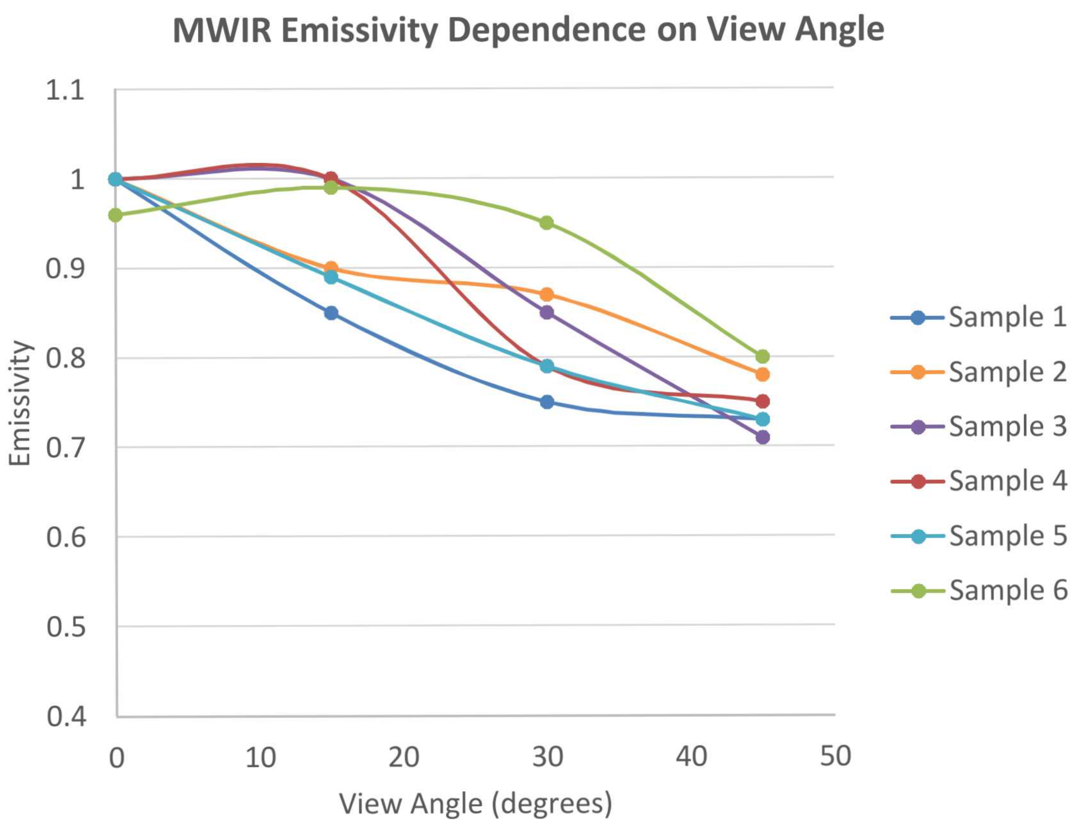


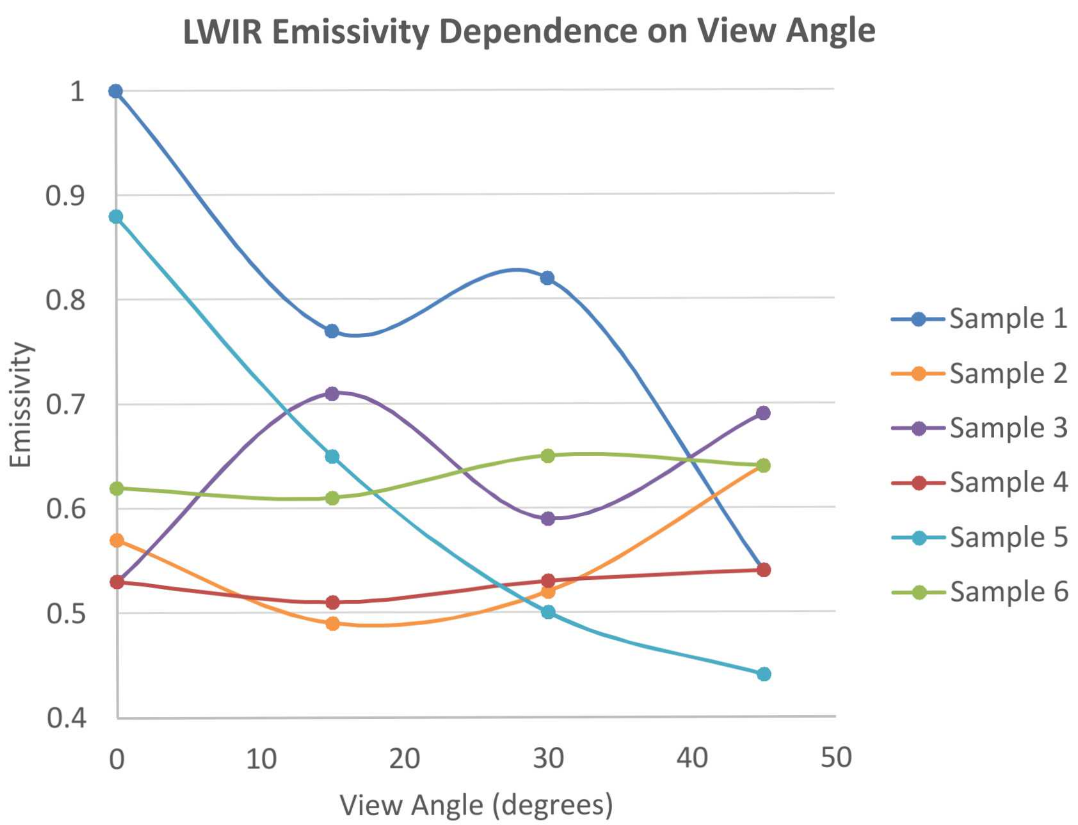
Experimental Set Up

- Sample and holders contained in an aluminum oxide crucible
- Bare type K TCs welded to back of samples using Micro TIG welder (Orion Pulse 250i)
- Angled sample holders were made of 316 stainless steel
- Aluminum foil shroud placed over crucible assembly to create aperture to reduce environmental radiation from reaching the camera

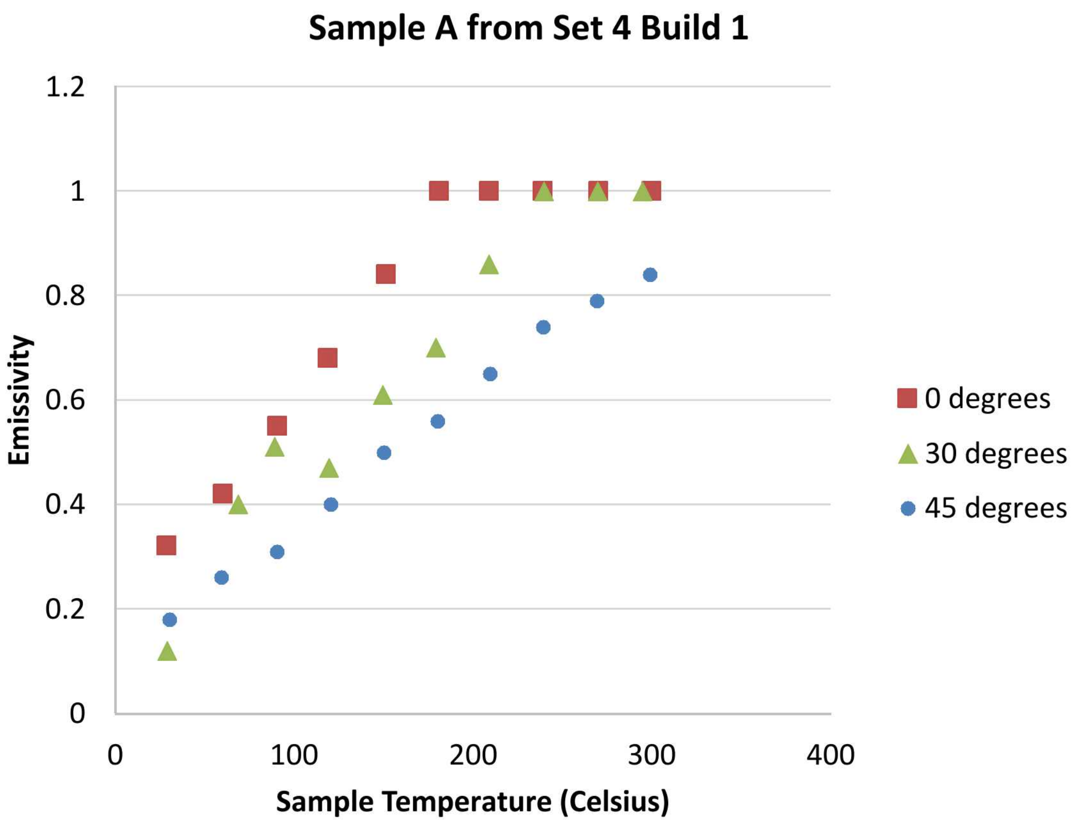


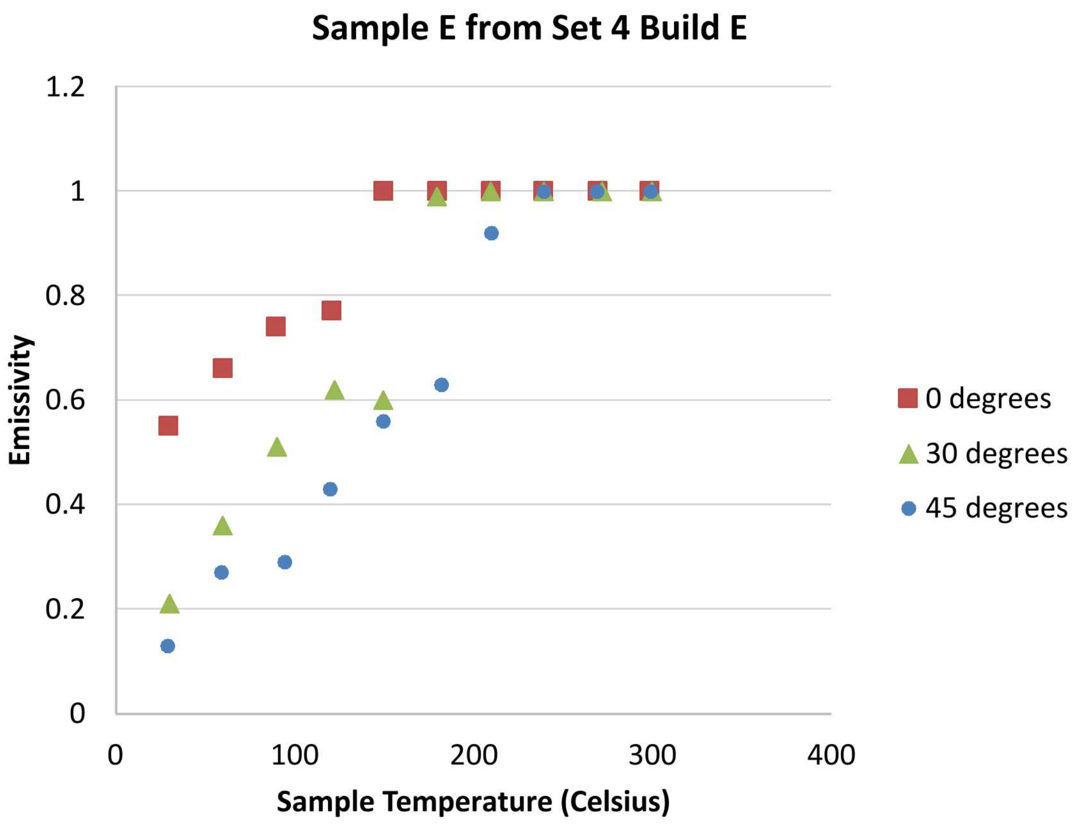
Room Temperature Results – No Window



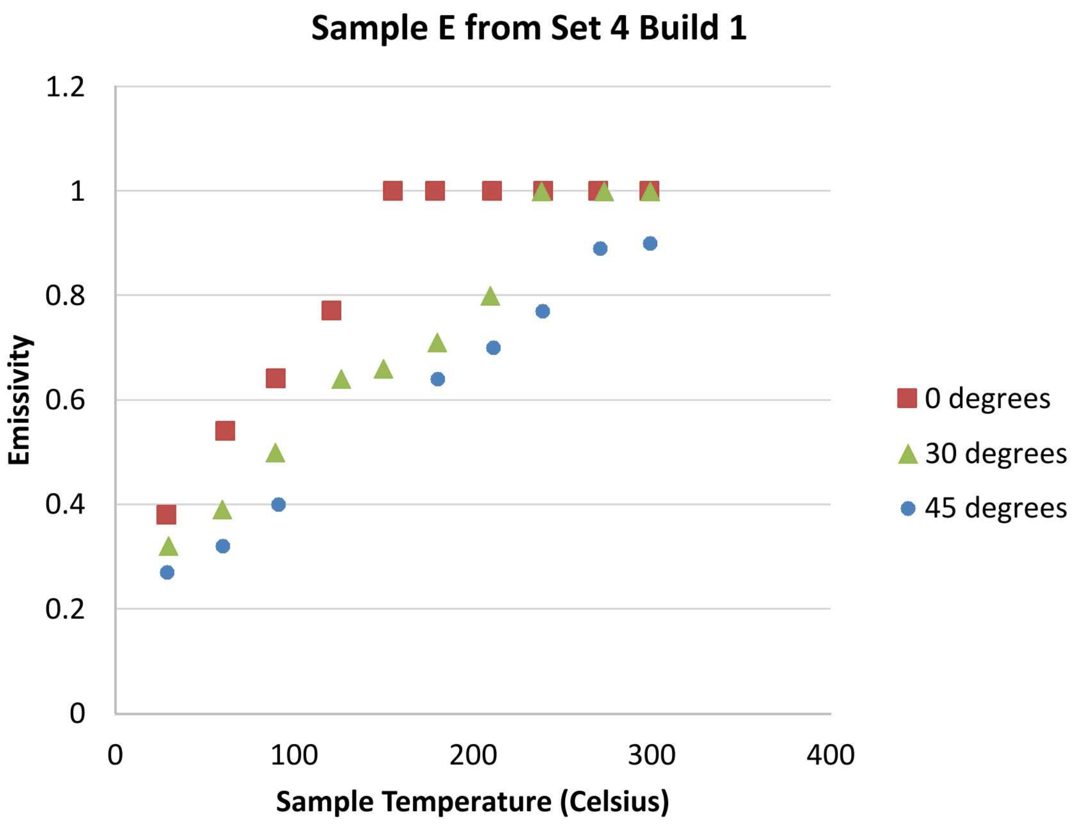


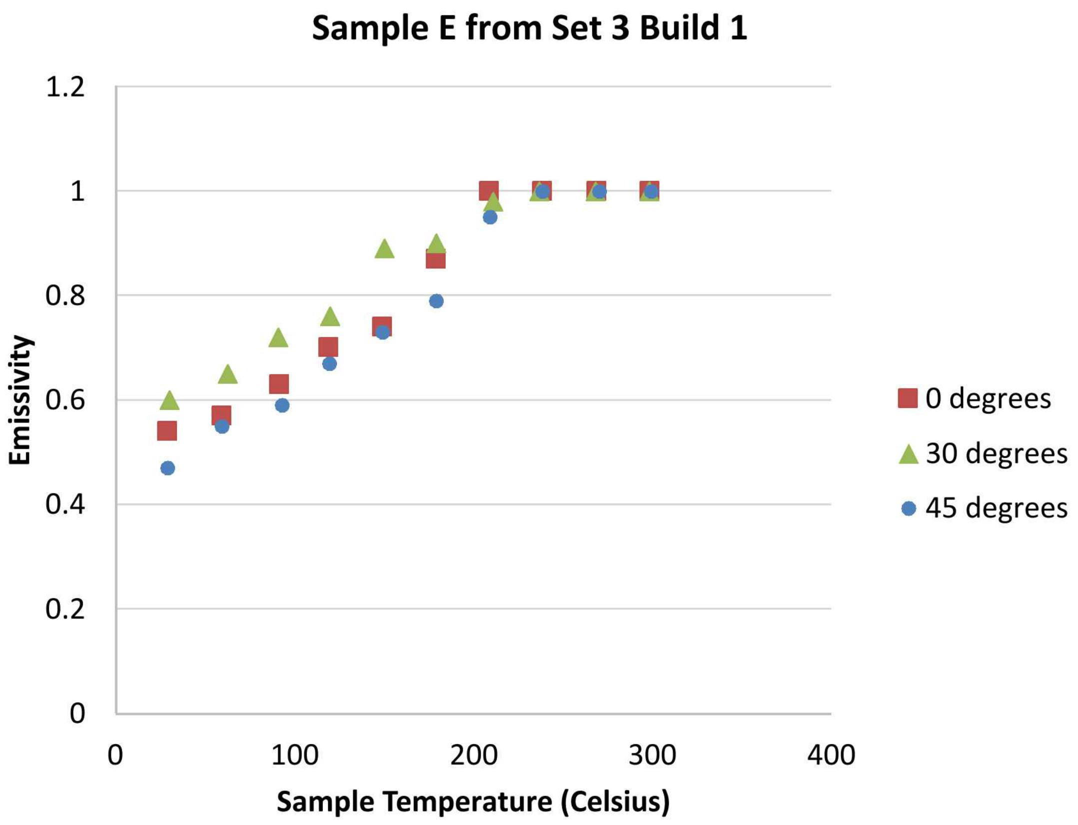
Elevated Temperature Results (MWIR only)





Elevated Temperature Results (MWIR only)





View Angle Conclusions

- As view angle increases, emissivity decreases
  - The rougher the surface, the less effect view angle has on emissivity (shadowing is not as effective)
- 45 degree angle minimizes emissivity differences
- After certain temperature threshold, differences in view angle are reduced – so not applicable at higher temperatures

Third Task: In-Situ Surface Roughness Measurements

- Purpose: to test capability of measuring surface roughness of as built AM surfaces in-situ
- Test viability of using in-situ measurements to adjust emissivity on a layer wise basis

Possible In-Situ SR Measurement Techniques

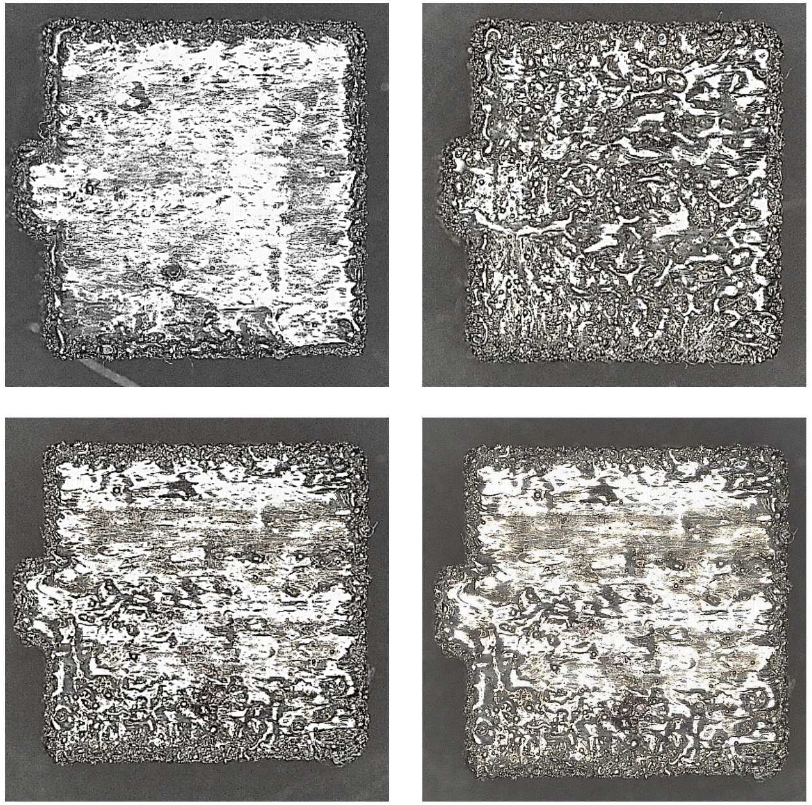
- Laser profilometry
- Raman Spectroscopy
- Moiré Profilometry
- Optical Coherence Tomography

Optical Coherence Tomography (OCT)

- Time of flight differences creates interference pattern
- Ease of implementation
- LD-600 (Laser Depth Dynamics)
- Implemented on an Aconity Lab L-PBF research machine
- Experimental axial resolution: 25 microns

Experimental Design

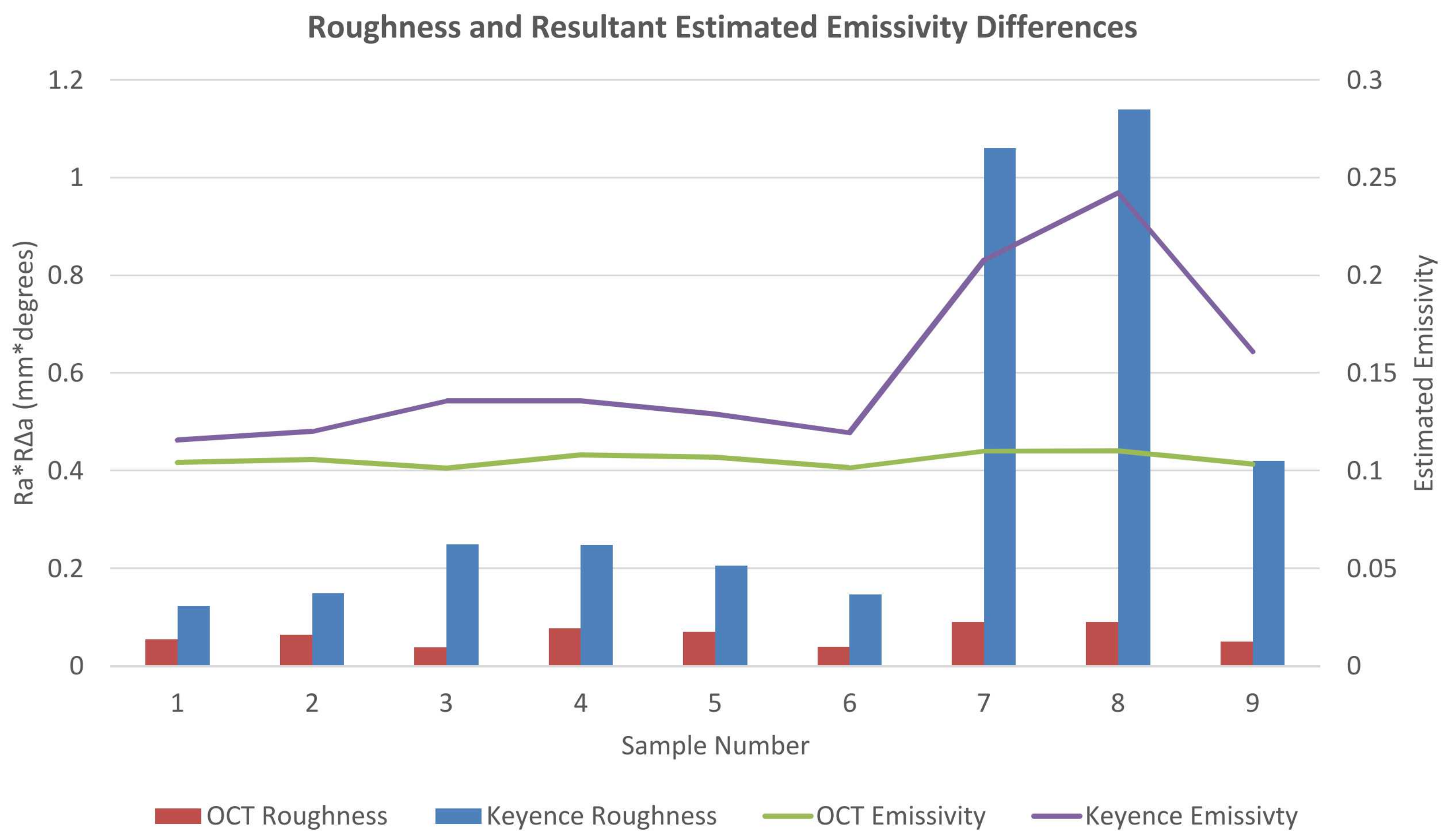
- 1cm cubes were built with a range of process parameters
- OCT measurements taken on top surface of parts during build
- Keyence VR3100 measurements taken after the build
- Measurements compared for resolution capabilities and emissivity estimations



Experimental Procedure

- OCT system at Lawrence Livermore used
- Parts shipped from Lawrence Livermore to Sandia for post-build measurements
- Top surface measured with OCT
- Measurements were compared with measurements gathered from Keyence VR3100 high resolution images

OCT vs Keyence Measurements



OCT Conclusions

- Filtering causes aliasing of surface features, which reduces the accuracy of the measurements
- However, even for the roughest surfaces, the emissivity differences did not exceed .12
- Average deviation did not exceed .04
- The extremely rough surfaces would most likely not be produced during normal manufacturing

Overall Conclusions

- Geometric Optical Region
- $R_a R\Delta a$
- View angle increase = emissivity decrease
- 45 degree best view angle tested
- OCT measurement technique suitable for in-situ surface roughness measurements

Future Work

- Improve predictive ability for wider range of surface conditions and materials
- New materials
  - Aluminum, Titanium
- Look at effects of SR on other IR cameras
- Improve OCT Accuracy

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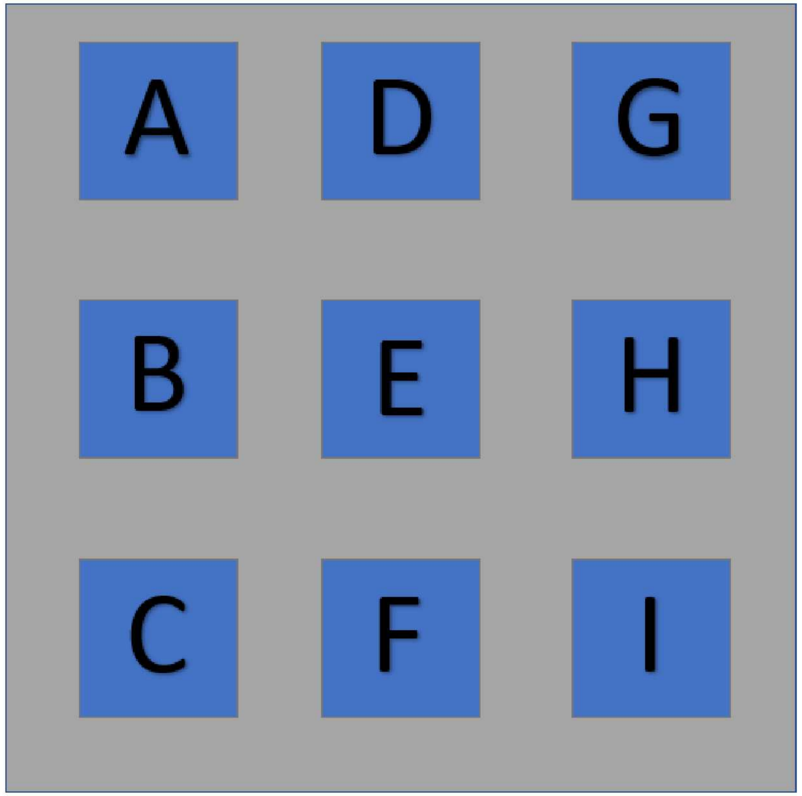
Questions?

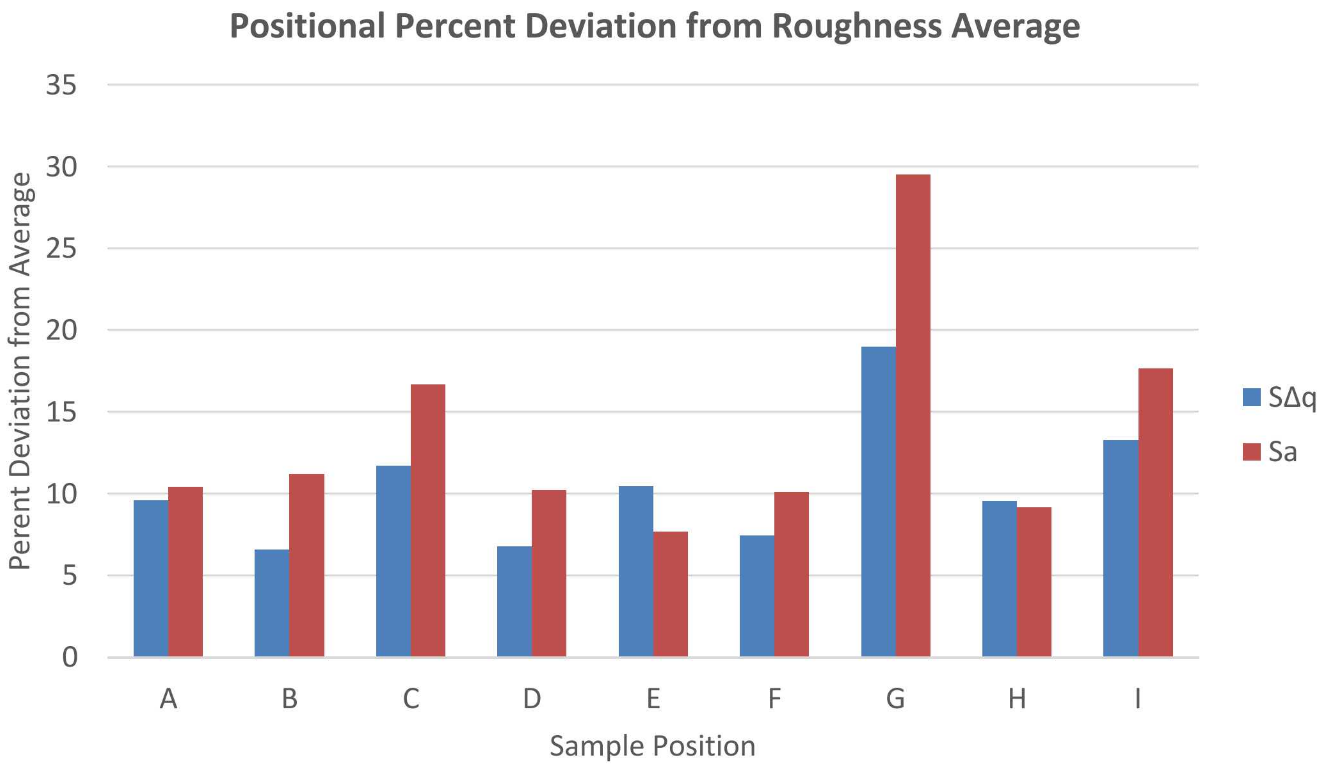
Surface Roughness Measurement Technique Comparison

- Keyence consistently reads rougher, showing possible aliasing of Dektak

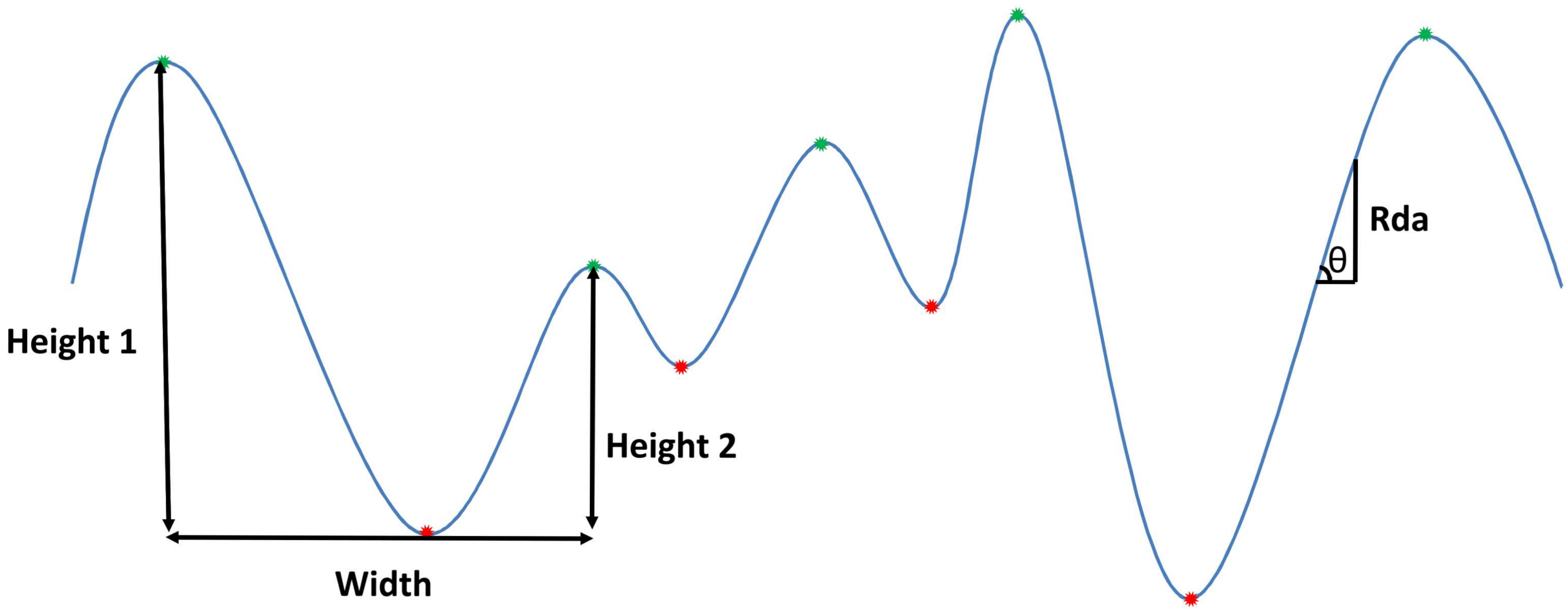
	LENS milled			LENS glazed			DMLS A			DMLS B			DMLS Milled A			DMLS Milled B		
	Keyence	Dektak	Difference	Keyence	Dektak	Difference	Keyence	Dektak	Difference	Keyence	Dektak	Difference	Keyence	Dektak	Difference	Keyence	Dektak	Difference
Ra (µm)	3.390	0.642	2.748	2.020	0.567	1.453	6.970	7.402	-0.432	9.790	6.429	3.361	1.570	1.813	-0.243	1.380	1.705	-0.325
Rq (µm)	4.130	0.744	3.386	2.530	0.677	1.853	8.720	9.029	-0.309	12.500	8.646	3.854	1.970	2.262	-0.292	1.750	1.992	-0.242
			3.067			1.653			0.371			3.607			0.268			0.284
															Average Difference:			1.542

Positional Dependence of SR

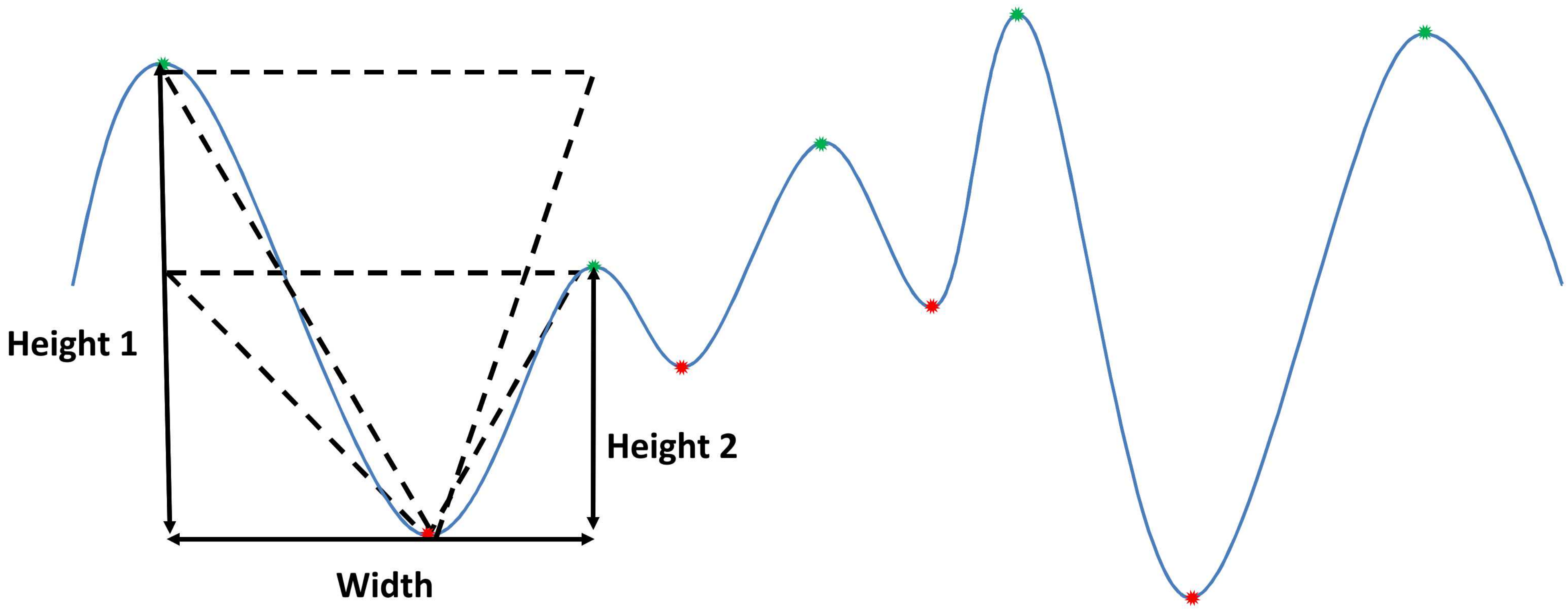




Valley Measurements



Valley Angle Calculation



Unusual Surface Feature Effects

- Vertical walls – just insert into calculation as really tall slope
- Partially or completely un-sintered particles that create overhangs
  - Does increase, but difficult way to measure in-situ
  - Outside of scope – future studies w/ XCT
- Effects of oxidation/method of storing samples before vacuum furnace – all samples were stored under same conditions

Publication Plan

- At least 2 Journal Articles
  - Emissivity vs SR (Simulations and then Experimental validation)
  - OCT in-situ SR measurements
- 2 conference papers
  - SFF 2019
  - Angular effect on observed emissivity

Repeatability/Uncertainty

HDR – Emissivity Measurements

- 10 measurements on AL6061 sample

  $\bar{x} = .237 \quad \sigma = .0027$ (~1%)

- Standard uncertainty = $\bar{x}/\sqrt{n} = 8.5$e-4

Keyence Surface Measurements

- R_a – std dev is .17% of measurement
- R_{rms} – std dev is .25% of measurement
- RΔa – std dev is .16% of measurement
- RΔq – std dev is .79% of measurement

- u_B= 3.04 microns

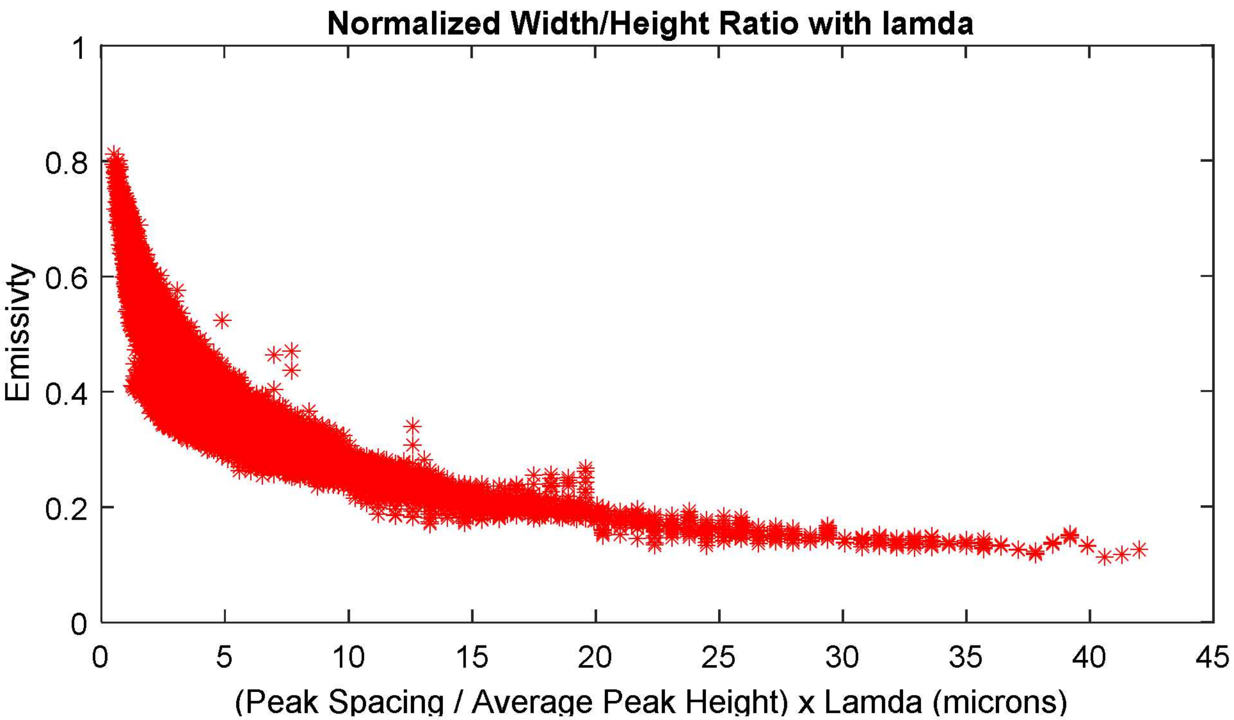
Simulations

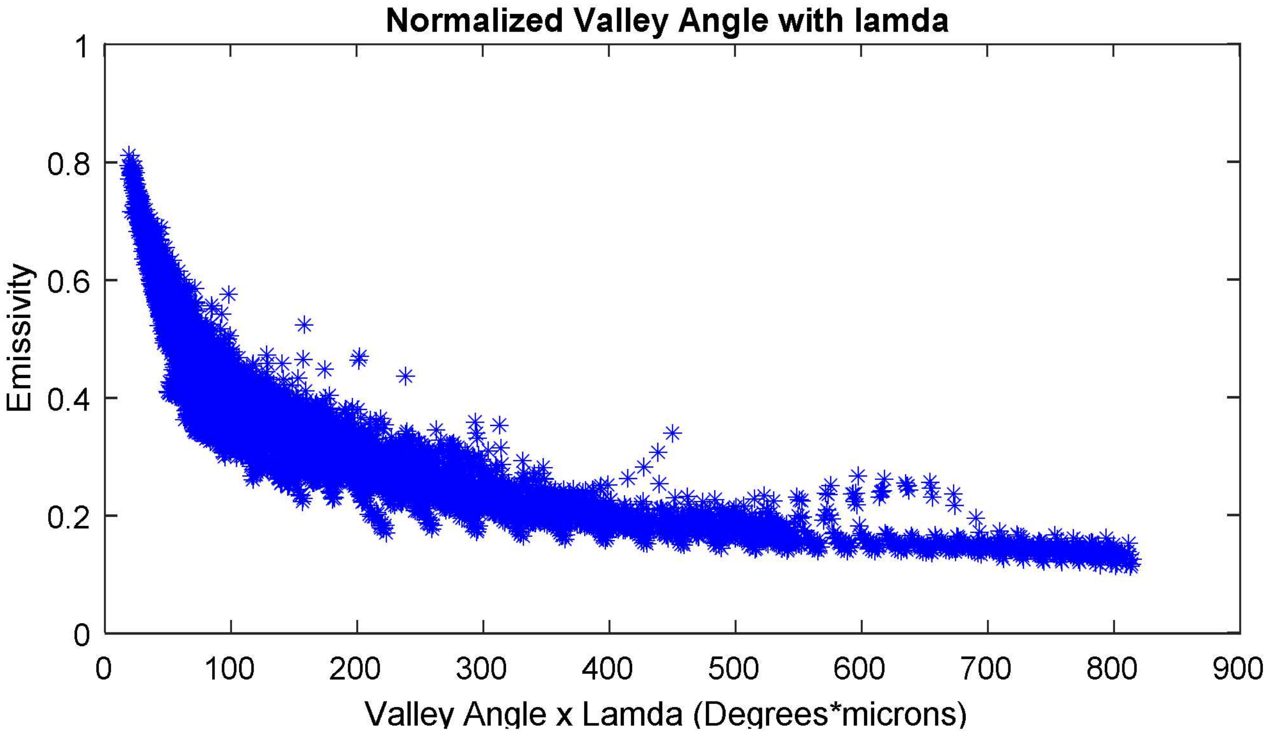
- Used for searching trends and relative nature
- Didn’t use absolute values from simulations for any purpose

Vacuum Furnace Measurements

- Atmospheric control of the lab
  - 23 +/- 1˚ Celsius
  - 40 +/- 5% Relative Humidity
- MWIR camera – unable to estimate due to inability to propagate input uncertainties to emissivity since conversion equation is unknown
- Thermocouples +/-2.2˚C uncertainty
  - Translates to standard deviation of .02 emissivity value

Skewed Triangles Results





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