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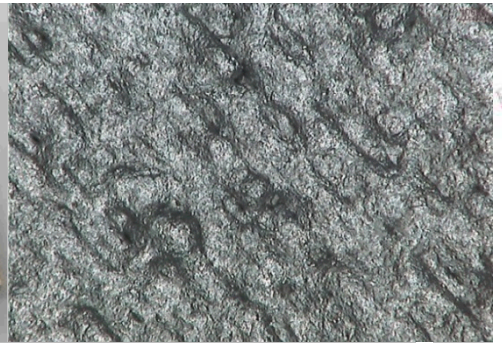
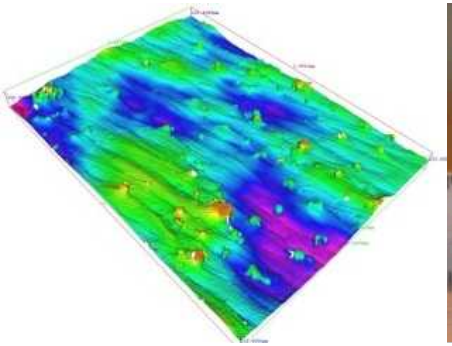
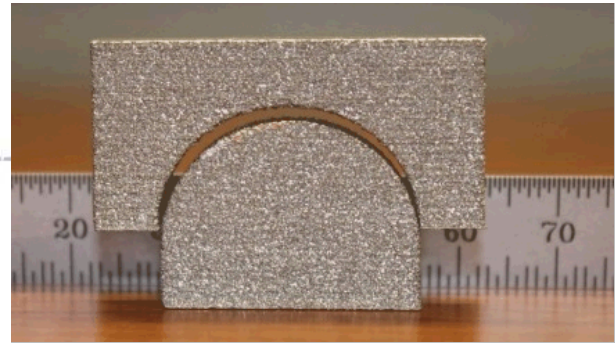

Metrology Artifacts for Additive Manufacturing Process Characterization

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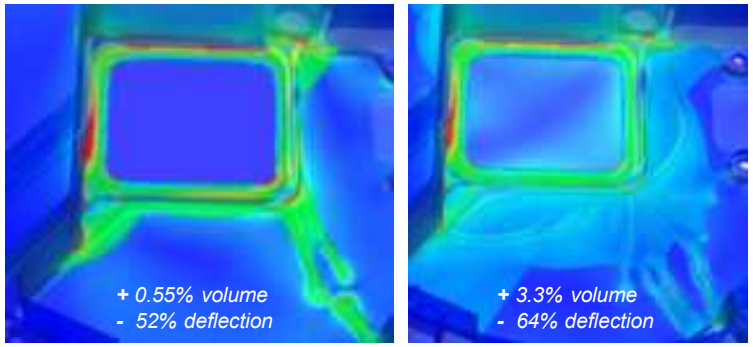
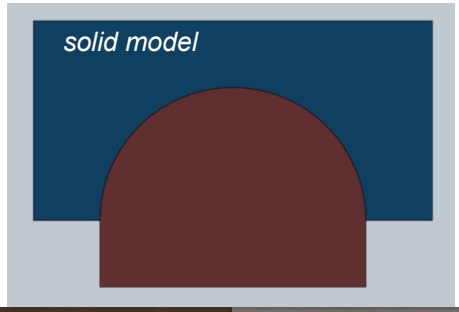
Balanced View of Additive

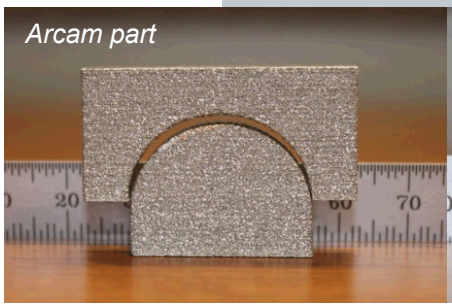
- Motivation
  - reduce risk (cost & schedule)
  - design freedom
    - non-traditional geometries
    - topological optimization
      - performance constrained
      - non-intuitive solutions via material synthesis
    - new engineered materials

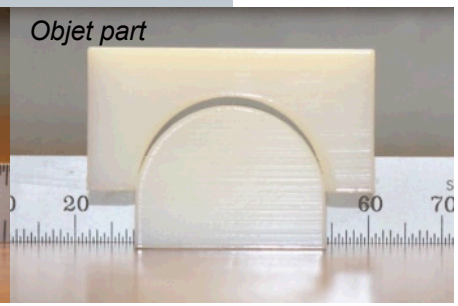


elasto-static stiffness optimization

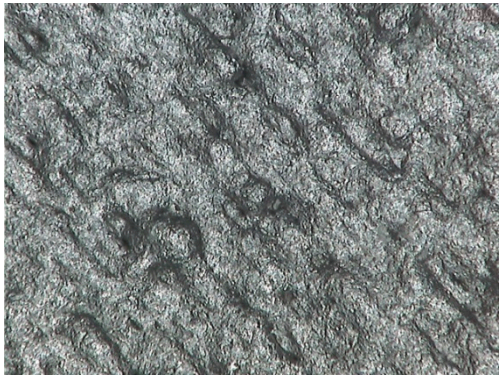
- But, "complexity is not free"
  - process limits
    - accuracy, finish, size, material, open loop, throughput, residual stress, post-processing
  - material assurance / qualification
    - geometry & material formed concurrently
  - metrology & inspection
    - complex geometries, internal structures
    - cost, throughput
    - designers need to know process capabilities
    - can we accurately predict part geometry?







Metrology Challenges

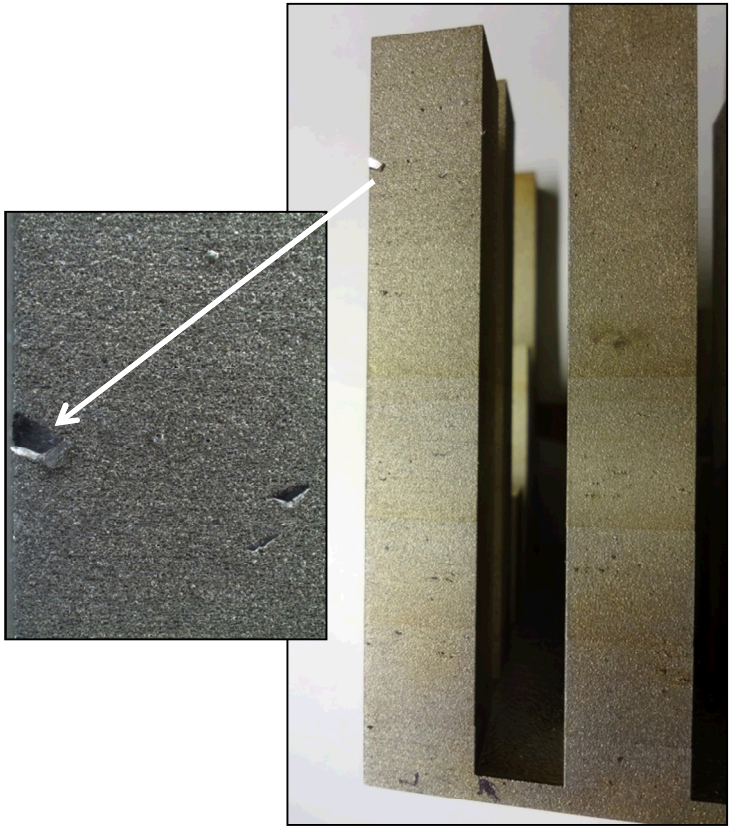


surface finish ~ 5μm Ra

- New & unique requirements for process & equipment characterization

- Final geometry
  - depends on material, build orientation, support structures, post-processing…
    - equipment generally exceeds process
  - relatively arbitrary geometries are possible, but features incur cost

- Measurement challenges
  - inferior surface quality to machining
    - uncertainty analysis must include form deviations
    - coordinate measuring machines (CMM) likely underestimate flatness due to flaws
    - optical methods can capture flaws, but may be more difficult to setup
  - many analyses possible, which is most useful?
    - large data sets, slow throughput

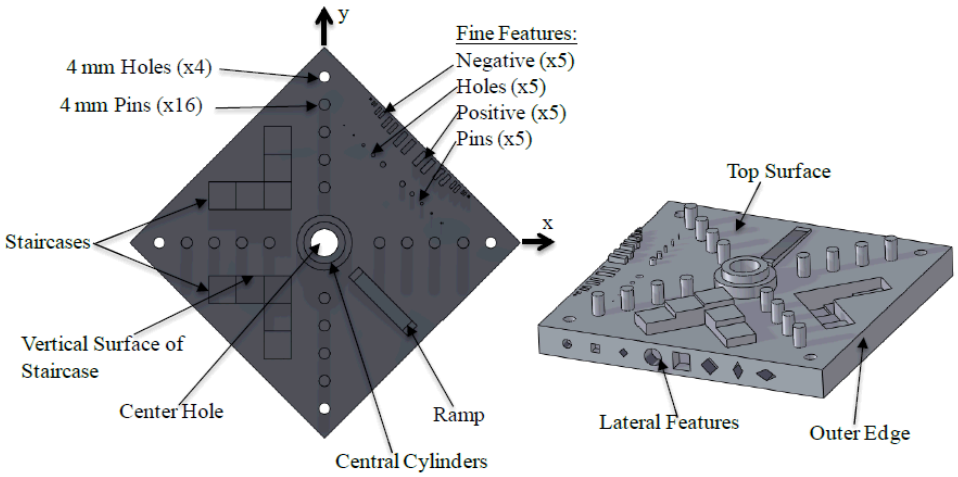


PH17-4 EOS "Manhattan" structure

Prior Work

- Machine tools
  - deterministic error modeling & budgets for machine axes
    - machine geometry ~ part geometry
  - standards (ex. ASME)
    - B5 for machine tools, B89.4 for CMMs, B46.1 for texture…

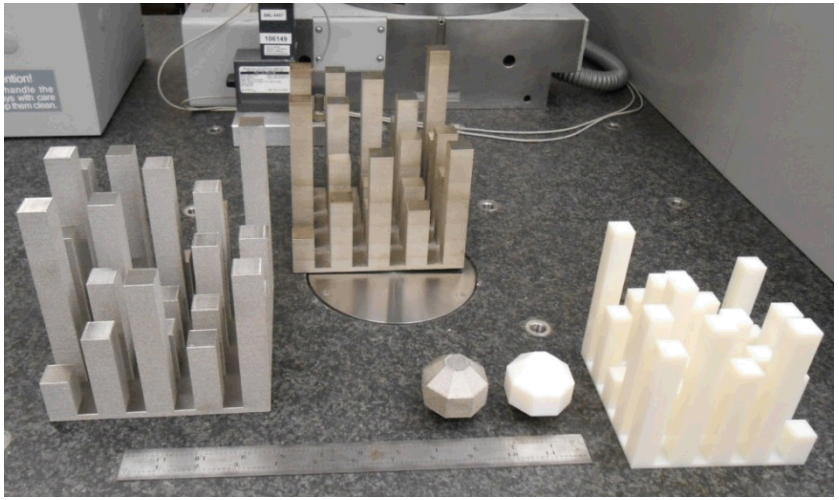
- Additive
  - numerous rapid prototyping artifacts
  - NIST reference sample (Moylan)
    - designed for metal laser sintering
    - easy for CMM measurement
    - unaddressed issues
      - "digital" quantifications
      - anisotropy
      - overhangs
      - minimum feature size



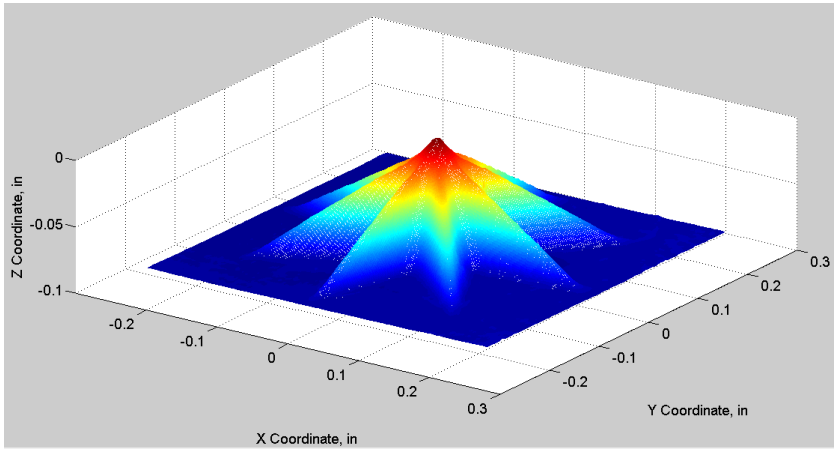
NIST proposed standard, Moylan, SFF 2012

Our Work

- Scope = dimensional metrology
  - address size, location, form, orientation & texture
  - specifies product geometry per ANSI Y14.5
- Artifact based characterization
  - artifact family of parts originally designed & tested
    - seek simple parts w/simple measurements (not necessarily CMM)
  - artifacts fabricated across range of equipment & processes
    - consumer grade Makerbot Replicator 2
    - professional grade Objet 30
    - EOS M280
    - Arcam A2X
  - incomplete data compiled to date
  - fabrication has been easier than metrology



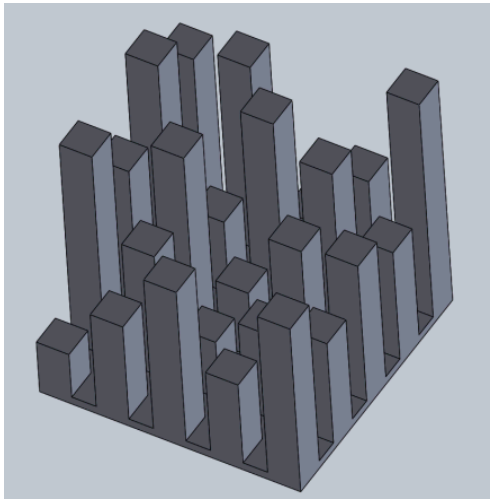
artifacts ready for measurement



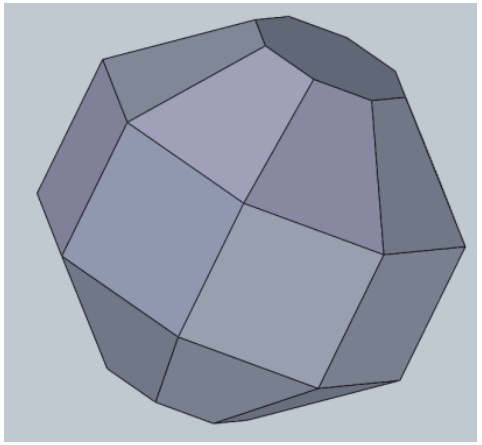
Siemens star profile data

Process Accuracy

- "Manhattan"
  - investigate size, location, form & orientation
  - 5x5 randomized posts
  - centered & scaled to ~60% of work volume
  - measured 3x3 array
- Polyhedron
  - 26-sides, 45° increments
  - size, location, form, orientation

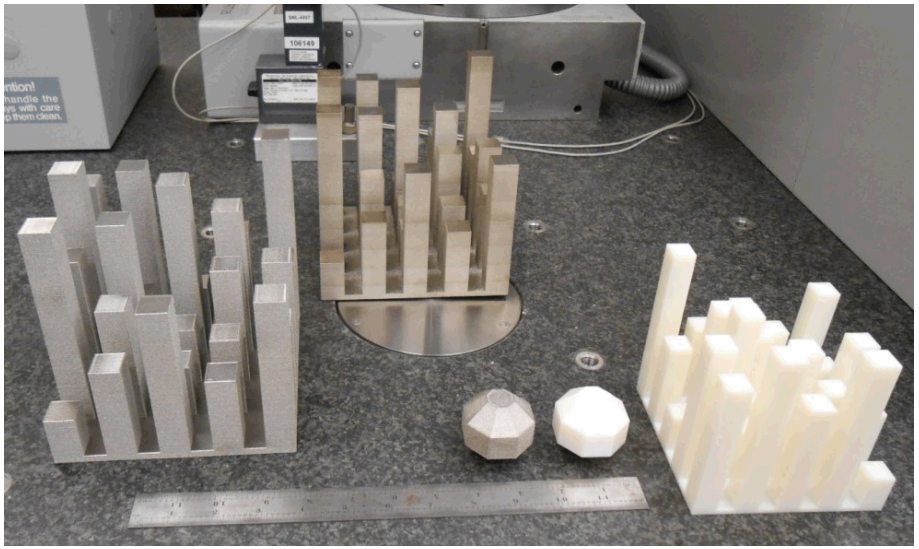


Manhattan



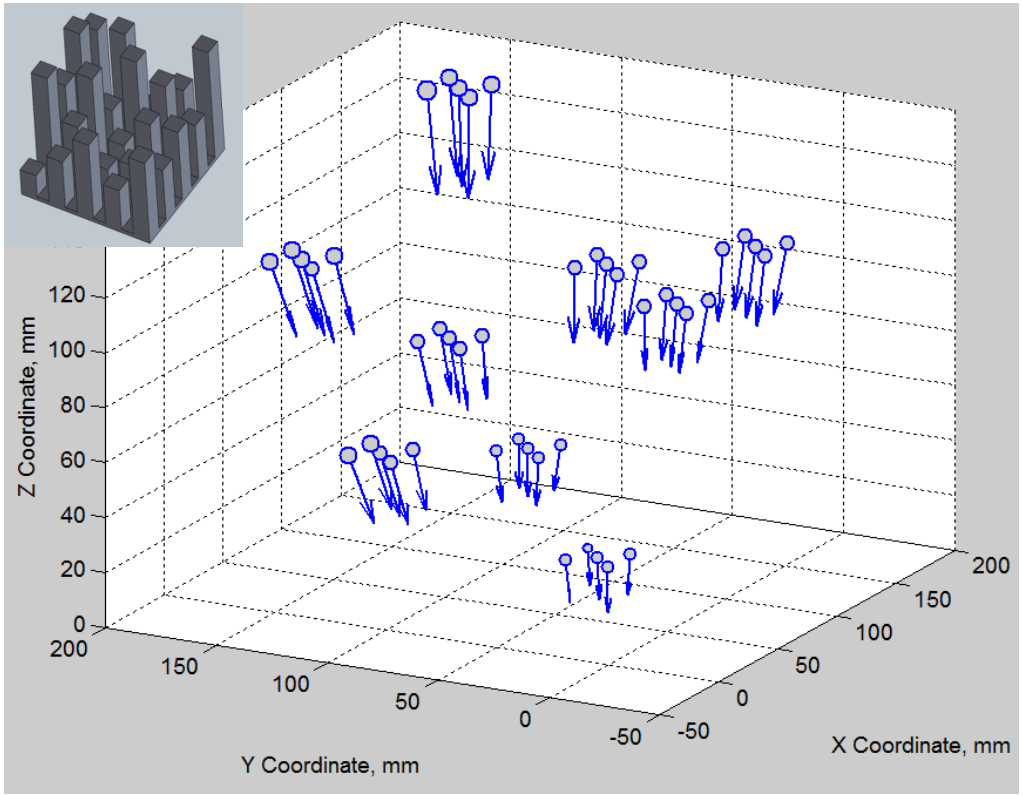
26-side polyhedron

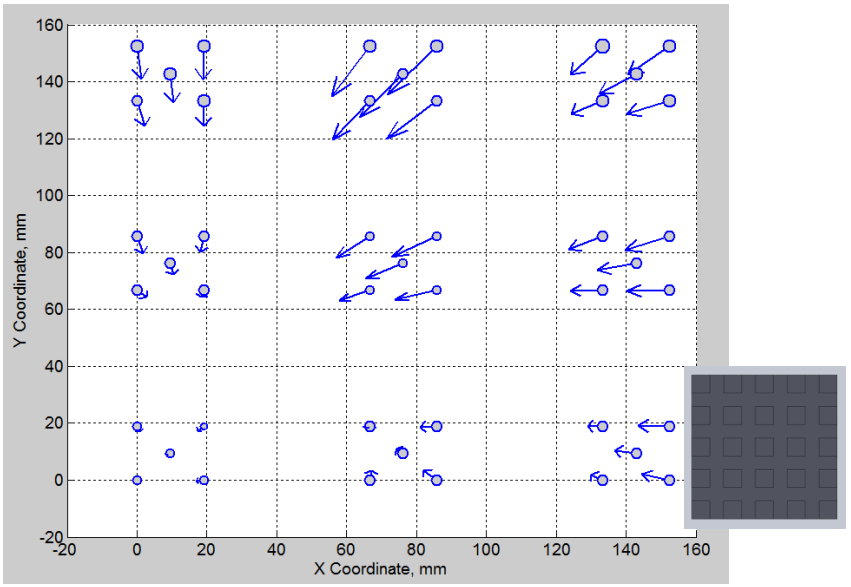
- Plane intersections provide lines & points in Cartesian space
  - polyhedron introduces orientation vectors
  - deviation plots provide trends
- Does machine, process, material or geometry dominate?
  - scale part & features
  - vary orientation & location

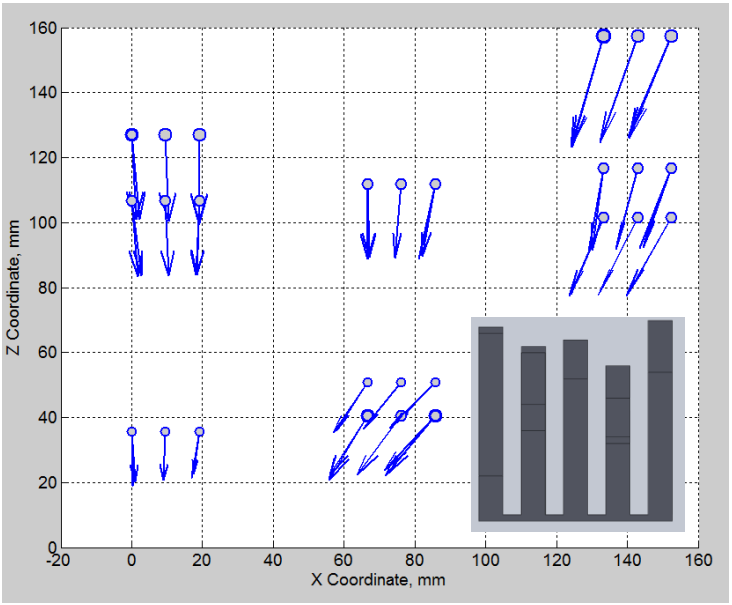


artifacts for measurement on a Zeiss UPMC 550 CMM

Arcam Ti6Al4V Manhattan Deviation Map





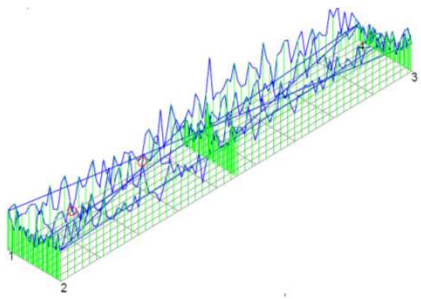


- points @ design intersections
  - vector is autoscaled
  - circle diameter = vector amplitude*100
- shows ~2% shrinkage in Z, ~1% in X,Y

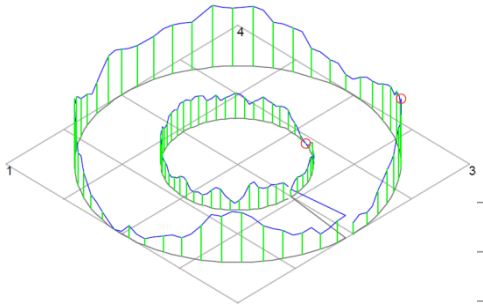
data from Zeiss UPMC 550

Form

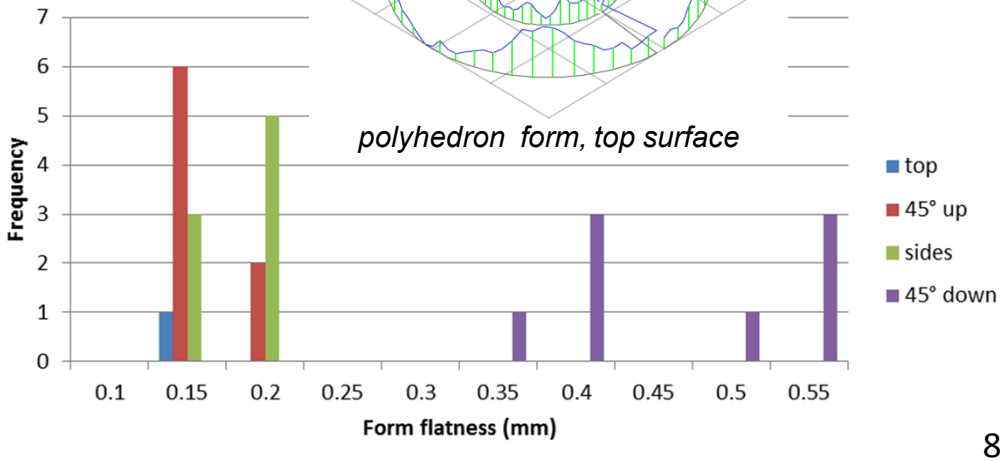
- Arcam Ti6Al4V
- Manhattan
  - top & 4 sides of 9 posts measured as planes
  - form deviations tabulated & plotted
  - top is better than sides
- Polyhedron
  - form degrades w/downward angle
- Compensation is non-trivial



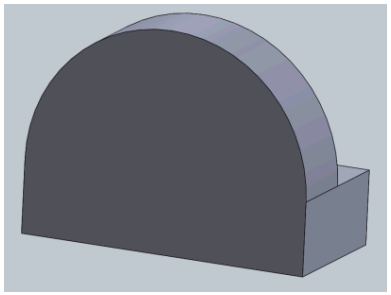
Manhattan form, post #2 front surface

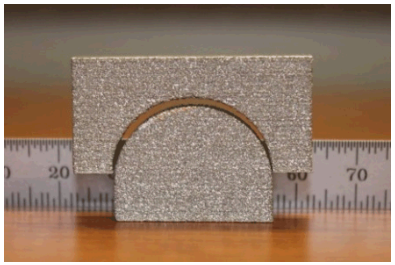


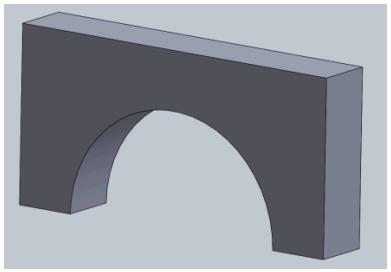
polyhedron form, top surface

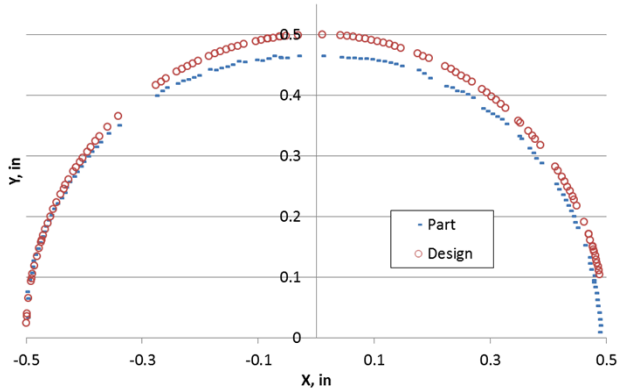


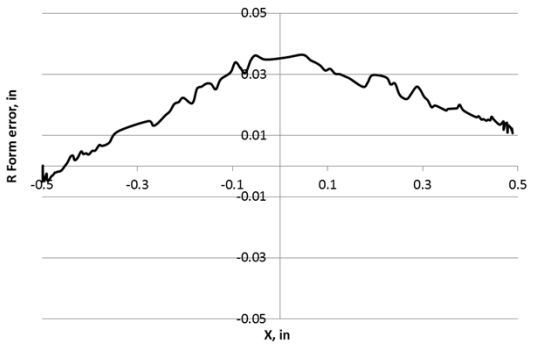
Overhang Geometries



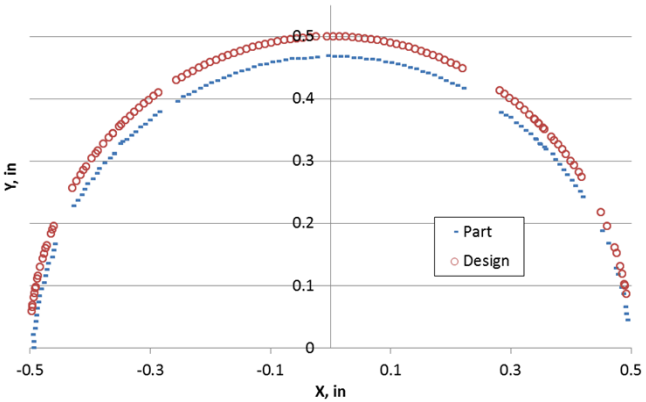


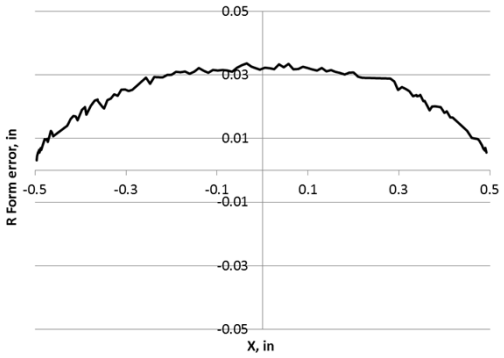






planar arch profile



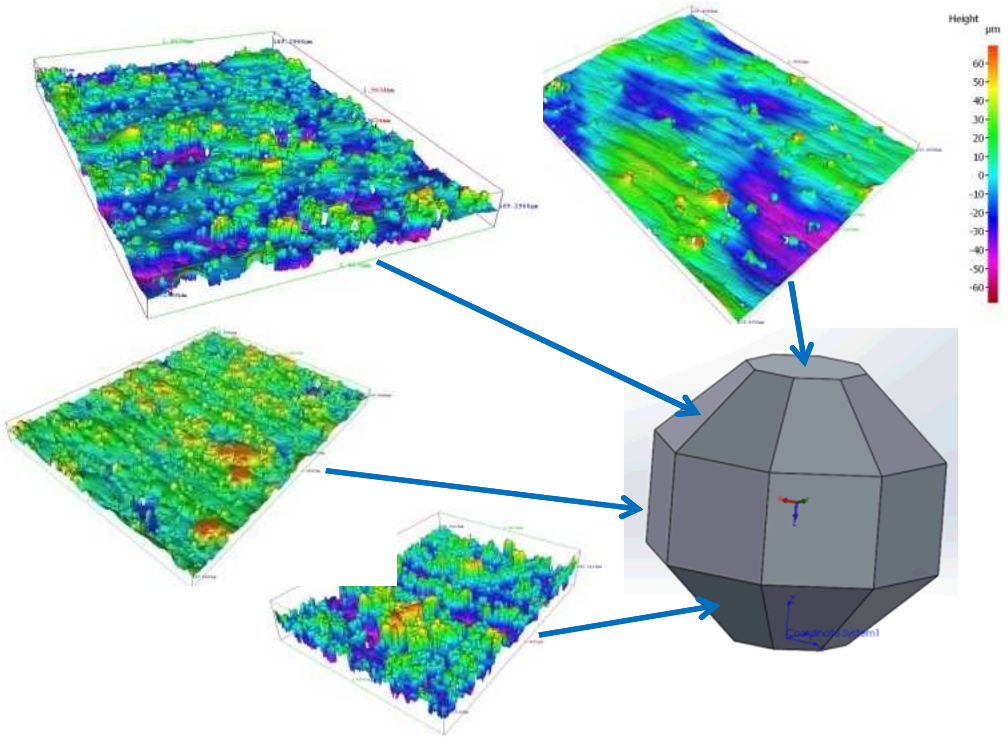


planar half circle profile

- Planar parts
  - arch, half circle
  - size, form, orientation
  - nominal 0.5” radius
- Arcam Ti6Al4V
  - optical profile measurements
  - errors dominated by scaling
    - based on material, process, geometry, …?

Texture

- EOS PH 17-4
- 26-side polyhedron
- Texture trends
  - poorest for down-facing
  - side is better than up-facing
  - surface metrics are insightful for AM
    - $S_a \sim R_a$
    - S_{sk} = if positive, more peaks than valleys
    - S_{tr} < 0.5 indicates strong anisotropy (i.e. lay or structure)
      - S_{tr} ~ 0.25 measured for an FDM part



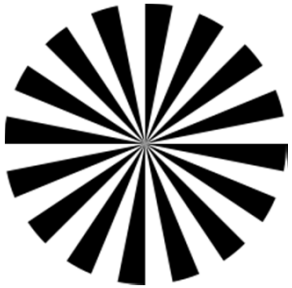
polyhedron texture anisotropy map

	Sa (um) roughness	Ssk skewness	Str isotropic
top	5.191	2.043	0.627
45° up	21.603	0.122	0.686
sides	12.727	0.368	0.820
45° down	31.617	-0.094	0.904

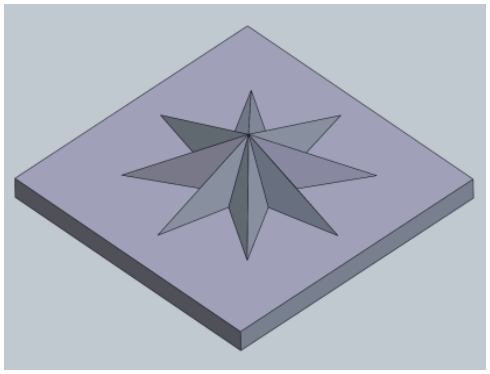
data from Alicona InfiniteFocus G4, 20x lens

Minimum Feature Size

- Siemens star
  - based on 2D analog for optical systems, printers & displays
  - triangles provides exact representation in STL
  - measurement has proven challenging
- "Death star"
  - 26-side polyhedron w/Siemens star
  - introduces orientation

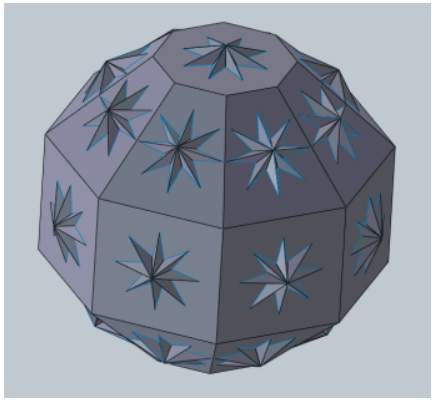


2D Siemens star, Wikipedia



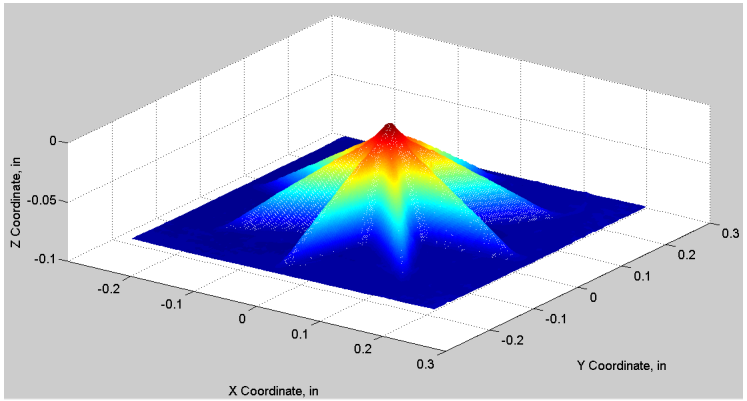
Siemens star model

EOS PH17-4 Siemens star



Death star

EOS PH17-4 Death star



Objet Death star data

data from Keyence VR-3000 measuring macroscope

Conclusion

- Family of metrology artifacts have been designed & demonstrated for characterizing AM processes & equipment
- Additional work is desired for further utilization & improvement
  - working to utilize artifacts for process correction

- Acknowledgement
  - SNL – David Saiz (Makerbot), Brad Salzbrenner (Objet), Tyrell Lorenzo (Zeiss UPMC)
  - KCP – Chris Boucher (EOS), Joe Dinardo (Arcam)
  - measurements – Brad Etter (Alicona), Kevin Dugan (Keyence)

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QUESTIONS?

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