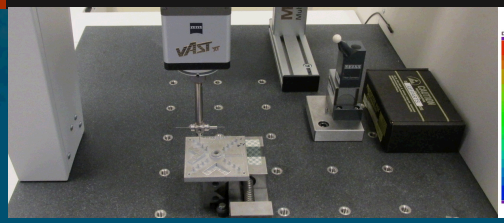
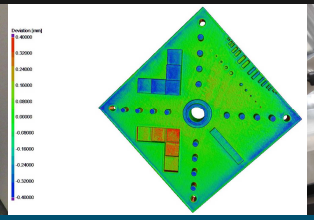
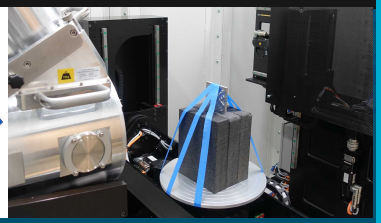
SAND2018-1977C

Metrology of Additive Manufacturing Using Computed Tomography







PRESENTED BY

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Metrology of Additive Manufacturing Using Computed Tomography

- Introduction
- CT as a validation tool
- Standards and Phantoms
- Experimental measurement results
- Future work
- Conclusion

Introduction

Additive manufacturing (AM) is driving the need for volumetric qualification and quantification for the development and build of precision high quality components

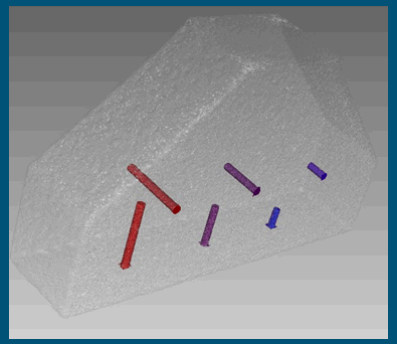
- There is a need to characterize dimensionality, porosity, missing material, poorly fused or poorly cured material, material shrinkage ….

Assembled part vs fused solid

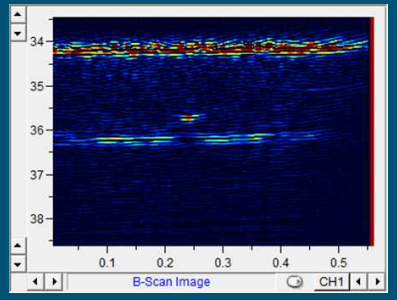
- AM allows for the building of internal features as the component is built
- Need for in-situ measurement or volumetric post process measurement for fused solids

Computed Tomography (CT) is an ideal tool for detecting defects and measuring physical features volumetrically (both internal and external)

- CT is one of very few volumetric tools in existence (CT, Ultrasound, Terahertz)
- CT is high resolution capable, versatile and available



CT

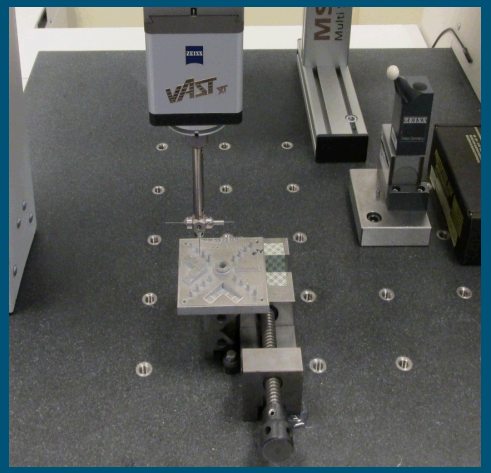


UT

Introduction

Support for CT metrology in AM

- Agreement that CT is an exceptionally valuable method
  - *Kruth, 2011*
  - *Thompson, 2016*
- Agreement that suitable standards need to be determined
  - *Kruth, 2011*
  - *Beraldin, 2007*



CMM

What is needed for metrology

- Measurable and calibratable known reference with uncertainty
- Traceable back to a primary reference standard
- Current standards are surface phenomena only -- (rods, gage blocks, surface textures)
- Need a volumetric standard that is traceable

CT as a Metrology Tool

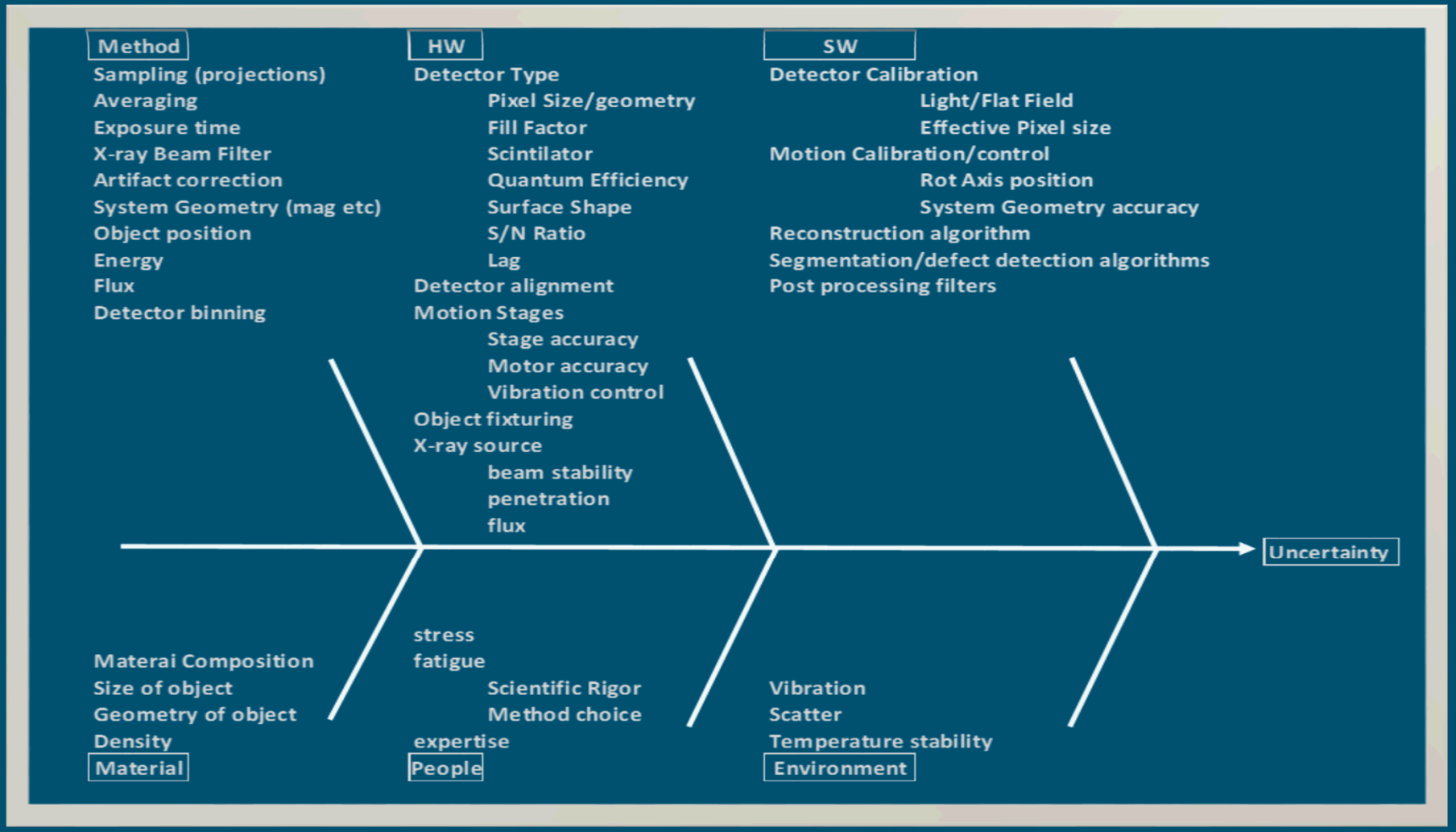
CT Advantages over Coordinate Measurement Machine (CMM) and Optical Area Scanners (OAS)

- High resolution interior measurement
- Mapping complete porosity morphology
- Lack of fusion Measurement
- More sampling points than CMM and OAS

CT		CMM		OAS	
Pros	Cons	Pros	Cons	Pros	Cons
Full Volume	Very technique dependent	Established (well understood)	Surface only	Area scan	Surface only
More sampling points	Slow*	High resolution	Limited sampling points	Fast	Surface reflection dependent
	Material dependent	Simple standards	Stylus dependent	Simple standards	Small inset features not well resolved
	Standards not well defined	Large area	Small inset features hard to measure	Medium area	
	Small FOV				

Factors Affecting Uncertainty

- Correct CT method is very complex
- Not all factors have as much impact on measurement



Experimental Direction

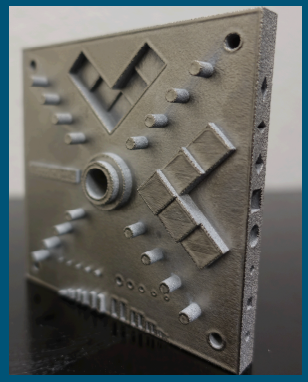
Choose variables to be studied:

- Standard/phantom/artifact choice
- Operator technique choice
  - Analyze variability of operator skill
    - Evolve to include choices on reconstruction of raw data*
- Acquisition Machine capability
  - Energy
  - Expand factors*
    - Sampling frequency, scatter reduction (LDA, filtering…), detector capability
  - Quantify best technique vs what is commonly available (is it good enough)*
- Reconstruction Techniques*
  - Iterative artifact reduction, beam hardening correction, contrast enhancement, filters, scatter reduction algorithms

Generic Holistic Phantom

Generic CT for Metrology

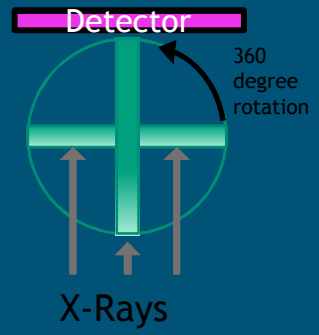
- Must have multiple relevant geometric and spatially located features
- Features must test the more difficult aspects of a wide range of geometries
- No consensus (one size does not fit all)
- Must be available in different material densities

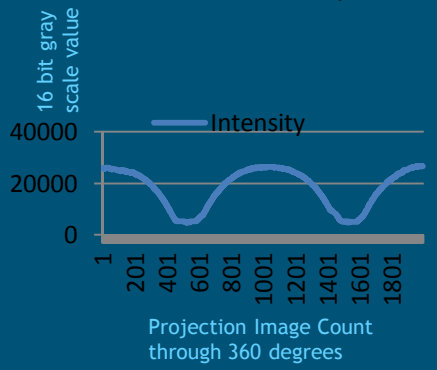


NIST AM standard was chosen both for AM and CT qualification – Moylan, 2012

- Public domain
- Printable with all the common AM materials
- Dual purpose (printer and measurement system validation)
- Form and shape tests worst case conditions for AM geometries
  - Inset, raised, large flat features
  - High Aspect Ratio
    - Angular thickness variation
    - Energy range needed at min thickness vs. max thickness

NIST does not cover porosity or other internal features

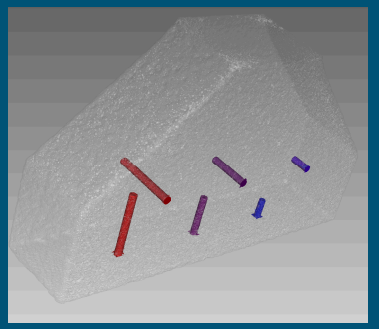


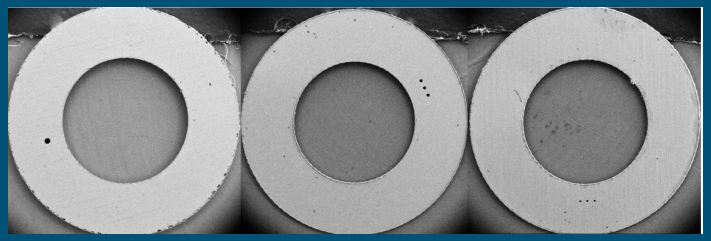


Feature Specific Phantom

Porosity Phantoms

- Internal features
  - Measureable with conventional tools for traceability
  - Should be completely embedded
- Previous designs at Sandia National Labs (SNL) and elsewhere
  - Drilled from outside
    - not representative of internal feature
    - Hard to measure
  - Welded hollow spheres in place
    - Not post process measurable
    - Hard to control weld process
  - Stacked disks with drilled holes
    - Interface gap artifacts
- SNL New Design
  - Modular, can be measured and calibrated
  - Addresses the interface gap

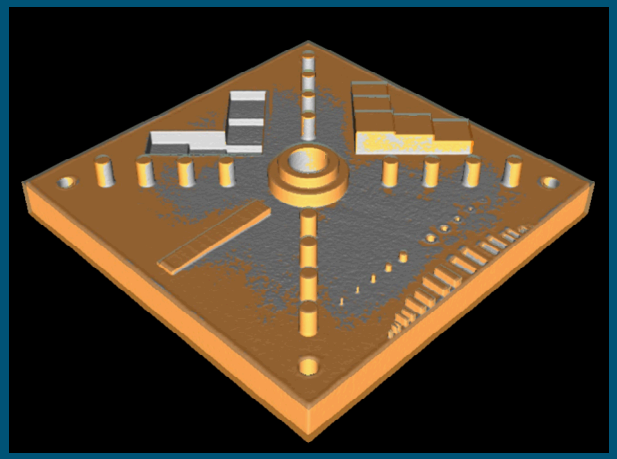


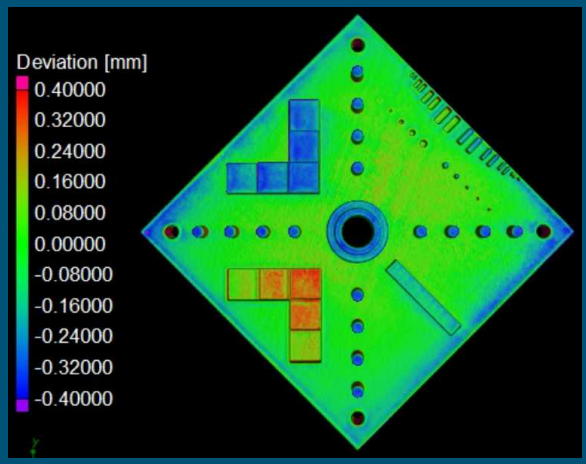


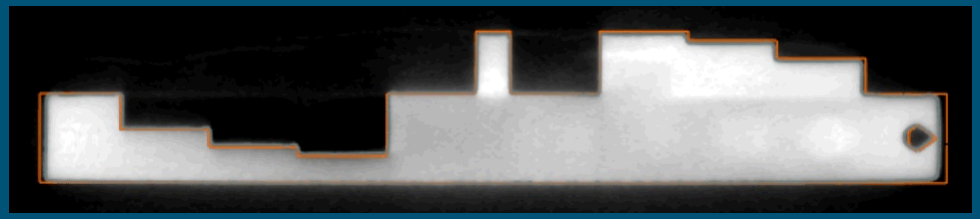
Holistic Uncharacterized Results

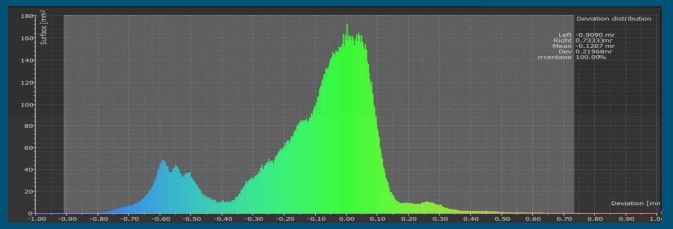
Volume Analysis		
Mesh Volume mm^3	Printed Volume mm^3	Shrinkage %
101,112	97,314	3.75

Deviation Analysis		
Min Deviation um	Max Deviation um	STD Deviation um
-909.5	733.0	219.7





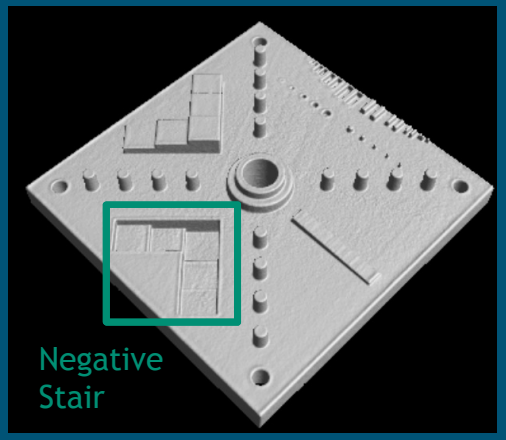


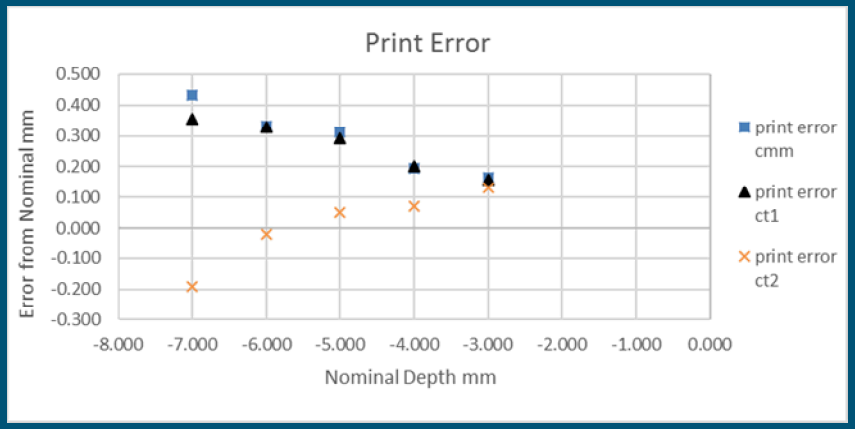


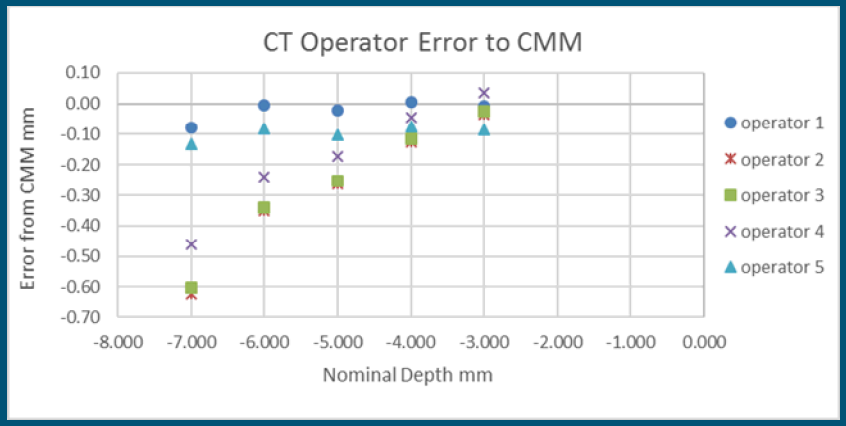
Experiments –Operator to Operator Variation

Operator Error on Ti NIST

- Same reconstruction data set
- Single ISO segmentation only
- Worst errors found on Negative Stair
- Best data set is 6MeV LINAC
  - Lowest spatial resolution
  - Highest penetration
- Compare to CMM (industry standard)
- Expert operator correlates very well with CMM
- Worst operator predicts false positive correlation to nominal
- Printer has a systemic additive error





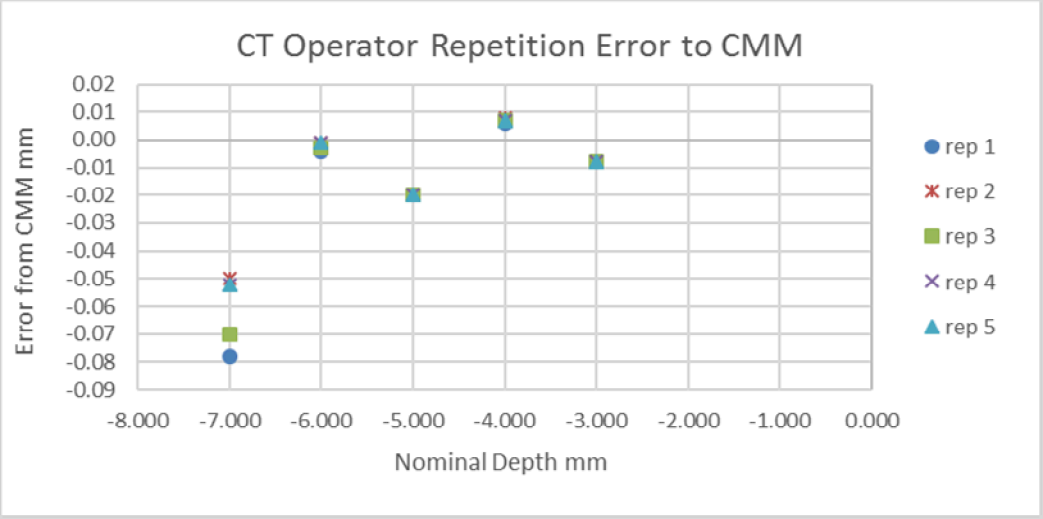


Experiments – Operator Repetition

Operator Repetition Error on Ti NIST

- Vary only the initial setting of the surface determination
- Most operator dependent variable
- Subpixel measurement variation for most
- Worst case was ~1 pixel

Operator Repetition	
Rep	ISO Value
1	34619
2	33331
3	34297
4	33492
5	33492
STD Dev	513



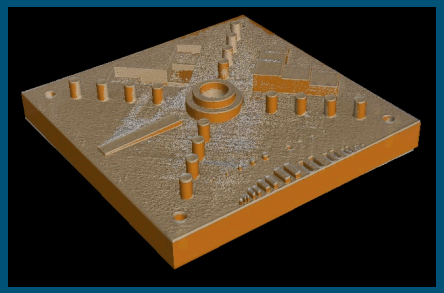
Experiments – Material Variation

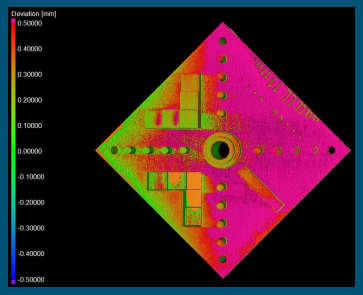
Material Stainless Steel

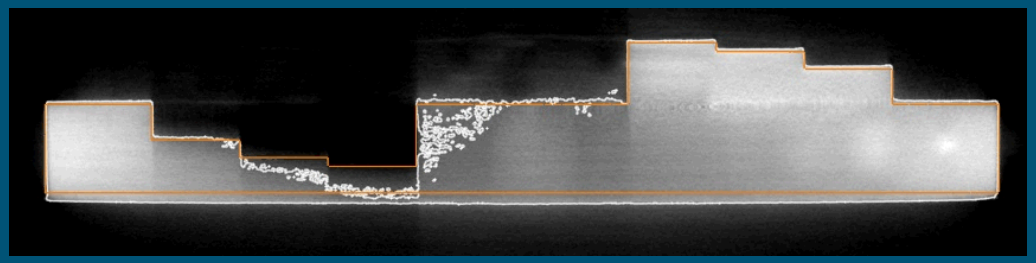
- Single ISO segmentation insufficient
- Extreme beam hardening artifacts
- Technique was 1/3 frame averaging of Ti due to time constraints and utilized smaller pixels affecting the Signal to Noise Ratio

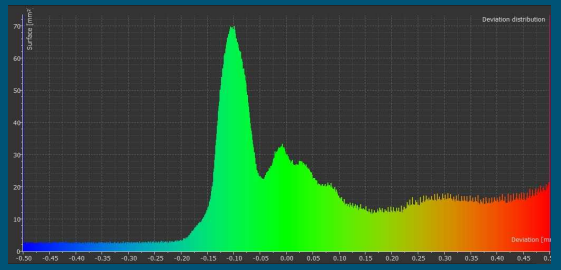
Volume Analysis		
Mesh Volume mm^3	Printed Volume mm^3	Inflation %
101,112	113,889	12.6

Deviation Analysis		
Min Deviation um	Max Deviation um	STD Deviation um
-4980	2100	835





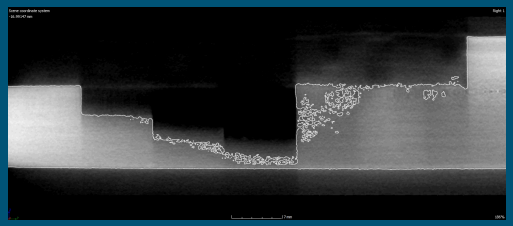




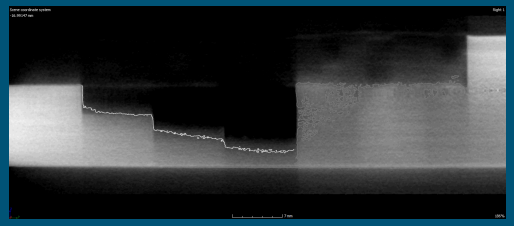
Material Variation Segmentation

ROI

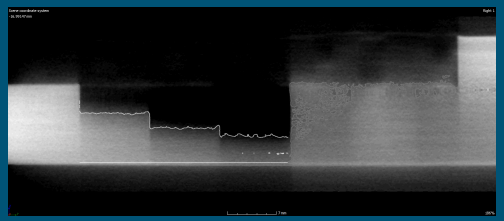
- Define a region for smaller range of grey scale
- Add CAD model for starting contour with advanced mode



Standard



ROI only

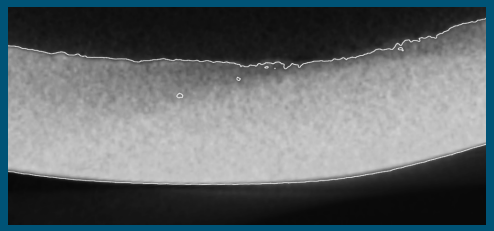


ROI/CAD for
Starting Contour

Advanced/Expert Mode No ROI

- Adds a search distance parameter
- Considers contour when calculating gradient
- Extends the search distance depending on local grey value gradient

Standard

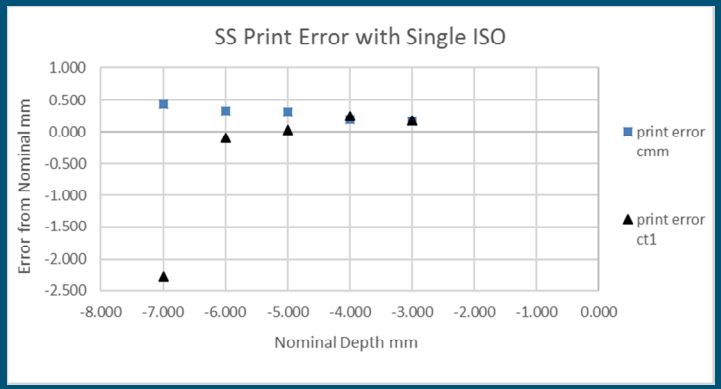


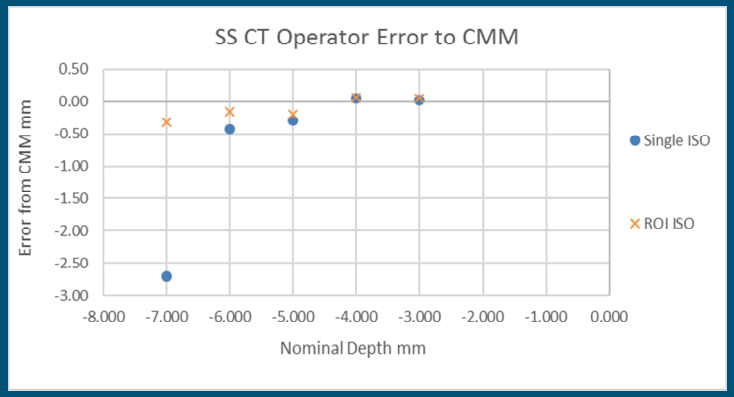
Adv/Expert
Iterative/starting contour

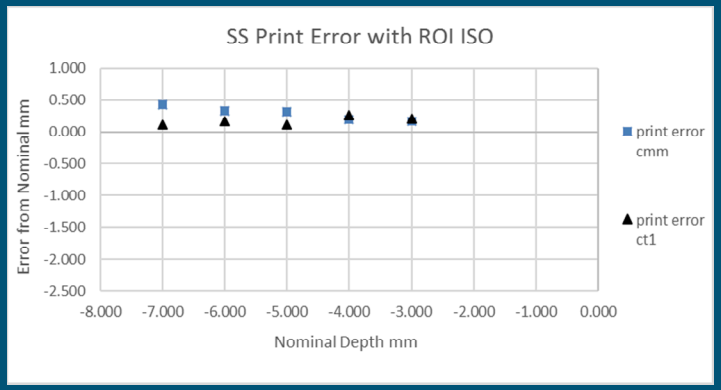
Experiments – Material Variation

Material SS Negative Stair Comparison

- CT error ~2.5mm without regionalized ISO surfaces
- With Region Of Interest ISO surfaces the data agrees within 250um
- Rescan with exact same parameters to confirm technique variation*
  - Determine cause of variation
    - Frame averaging
    - Detector binning (SNR reduction)
    - Steel Density







Future Work

Inter-lab comparison of CT techniques and equipment

- A larger matrixed sample study to review capability, repeatability and reproducibility at various locations (machine to machine correlation)

Produce documentation for lab wide CT acceptance testing of a component created with additive manufacturing

- Fully characterize the uncertainty of measurements
- Define requirements for control of CT factors (technique, hardware, software etc.)

Correlate mechanical testing with CT characterization of lattice structures and topography optimized designs

FP detector configuration

- Does fill factor geometry affect surface boundary segmentation
- Partial volume affect biasing by material type/attenuation – Kruth 2011
  - Is 50% isosurface sufficient for segmentation

Conclusions

- Well controlled CT capable of high precision and accurate measurements.
  - Information becomes unreliable when uncontrolled and can lead to false positives.
- Correlates well with CMM and provides internal information not available from other measurement sources.
- An acceptance process can be created for specific items with factor control and validation tools.
- It still remains to be seen if a generic process can be agreed upon or what the final standards from the governing bodies will be.

Questions?

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Appendix A

Technique Information

Sample	***NIST Ti Sample***		
Energy	***6 MeV***	**Projections**	***1800***
R/Min @1 meter	***249***	**Effective Pixel Size**	***166um***
Magnification	***1.2x***	**Detector Type**	***Perkin Elmer 1621 –no bin***
Filter	***2mm Cu, 0.8mm Sn***	**X-ray Head Type**	***LINAC***
Exposure Time	***2.33 seconds***	**Frame Average**	***14***

Sample	***NIST SS Sample***		
Energy	***6 MeV***	**Projections**	***3300***
R/Min @1 meter	***249***	**Effective Pixel Size**	***83um***
Magnification	***1.2x***	**Detector Type**	***Perkin Elmer 1611 – no bin***
Filter	***?***	**X-ray Head Type**	***LINAC***
Exposure Time	***2.5 seconds***	**Frame Average**	***5***

Appendix B

Acknowledgements

I would like to thank the following individuals for their participation in the gathering of this data: Erin M. Dughie (SNL); Carl L. Jacques (SNL); Eric Jamieson (NSC); Henry T. Lorenzo (SNL); David G. Moore (SNL); Kyle R. Thompson (SNL); Dr. Hy Tran (SNL); Enrico Quintana (SNL).

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