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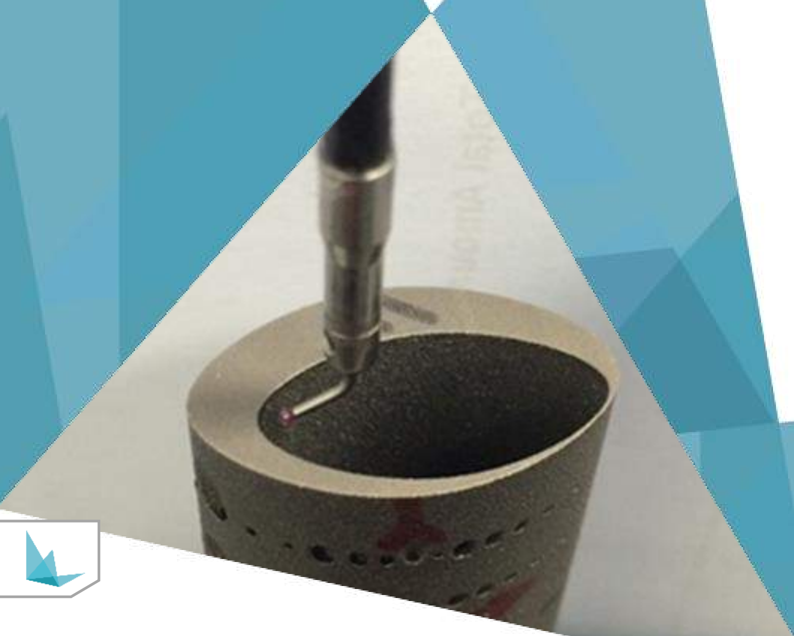

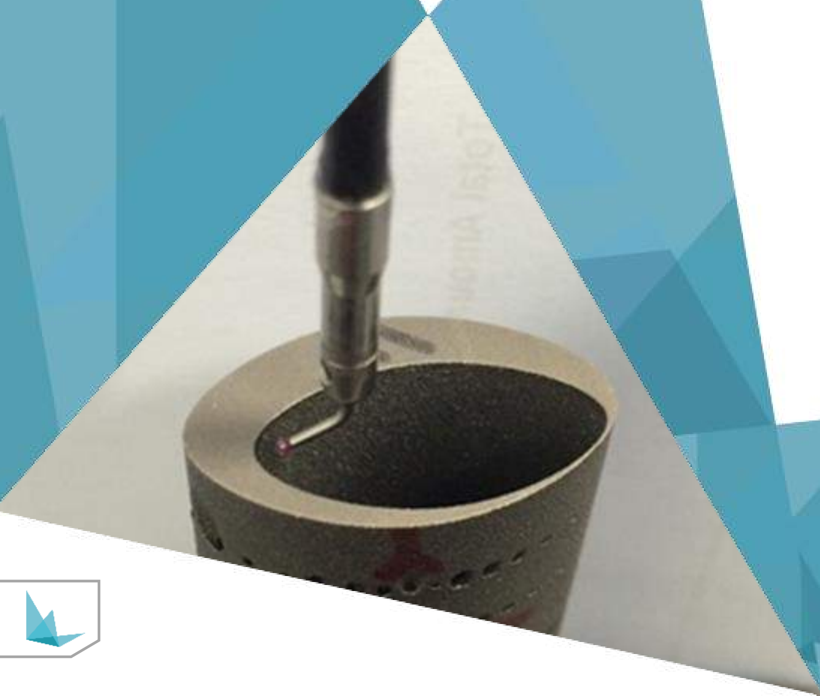

Dimensional Measurement Uncertainty of Computed Tomography Data

Jonathan J O'Hare, Program Manager CT Solutions

July 25-26, 2016

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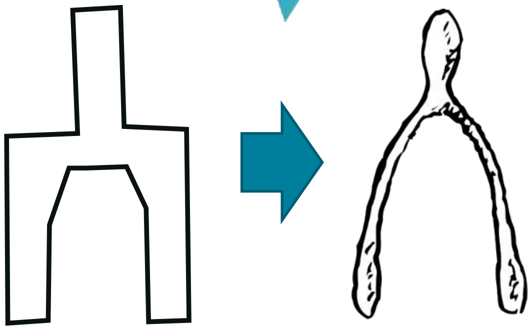
Contents

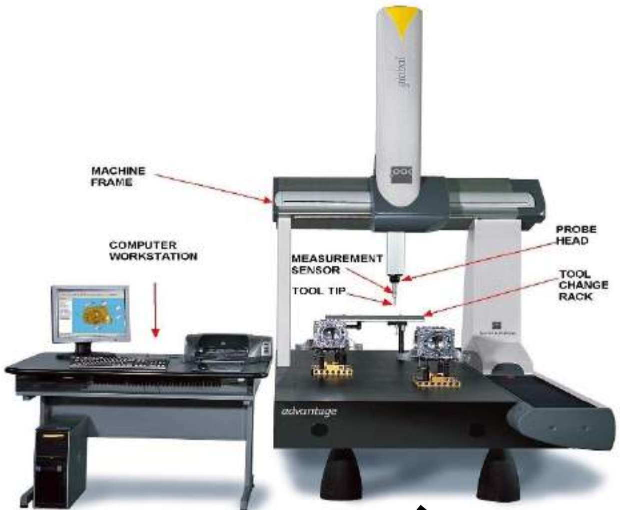
Design Paradigm Shift

- **Drivers**
  - Performance improvement
  - Cost reduction
- **Impact on Design**
  - Weight reduction
  - More Internal features/cavities
  - More complex surfaces
- **Impact on Manufacturing**
  - New materials: composites, high-strength alloys
  - New processes: Additive Manufacturing
- **Need for more sophisticated Inspection**
  - Design & Process Validation
  - Process Control



More bionic designs

Typical Solutions for Industrial Metrology



Tactile
Coordinate Measuring Machine (CMM)

Optical
Vision System

Multisensor
Vision/Tactile System

Not any one sensor can do it all!

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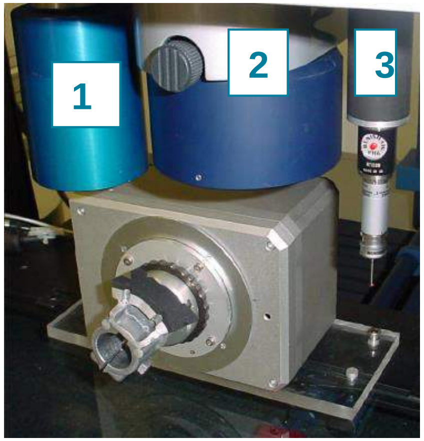
Limitations

- **Tactile CMM**
  - Part setup / low deflection fixtures
  - Probe setup and stylus design
- **Optical CMM – Vision System**
  - Part surface / reflectivity or translucency
  - Lighting
  - Only 2½ d, Difficult to see hidden edges
- **Multisensor CMM – Tactile + Vision System**
  - Cost of combined sensors
  - Added complexity for implementation

Typical CMM fixture setup



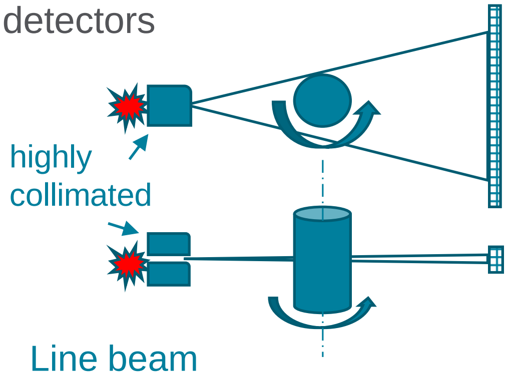
Multisensor system: (1) WLS, (2) CCD, (3) TTP

Computed Tomography as a Measurement Tool

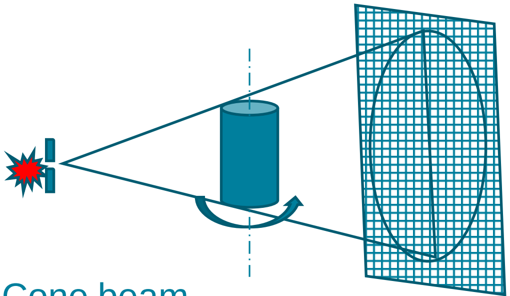
- **CT has improved drastically in recent years**
  - Micro-focus x-ray sources
  - Better thermal stability
  - Higher resolution detectors

- **Two main classes of technology for measurement:**
  - Cone beam / Flat panel detectors
  - Line beam / Linear detectors

Above: YXLON's FF20 CT (cone beam)



Line beam
Enables higher energies for dense objects



Cone beam
Typically <240Kv for light metals and plastics

CT Influences on Measurement Uncertainty

Workpiece Induced

- **Due to material properties and geometry:**

- **Thermal effects**
  - Expansion during measurement*
  - IR absorption of polymers esp. under high magnification

- **X-ray effects**
  - Too little attenuation
  - Beam hardening
  - Scattering

*workpiece at steady-state temp can be easily compensated.

** helical scanning can avoid this

Instrument Induced

- **Machine geometry**
  - Axis position
  - Focal spot drift (self heating)

- **Image Quality**
  - Spatial Resolution
  - Contrast
  - Cone beam angle**

Software Induced

- **Finding the Surface**
  - Surface mesh approximation
  - Global threshold calculation

- **Method of Dimensioning**
  - Feature type calculation
  - Analysis procedure

Influences on Measurement Uncertainty

Workpiece Induced

- **Due to material properties and geometry:**
- **Thermal effects**
  - Expansion during measurement
  - IR absorption of polymers esp. under high magnification
- **X-ray effects**
  - Lack of attenuation
  - Beam hardening
  - Scattering

Can be the most significant part of the error budget

Instrument Induced

- **Machine geometry**
  - Axis position
  - Focal spot drift (self heating)
- **Image Quality**
  - Spatial Resolution
  - Contrast
  - Cone beam angle

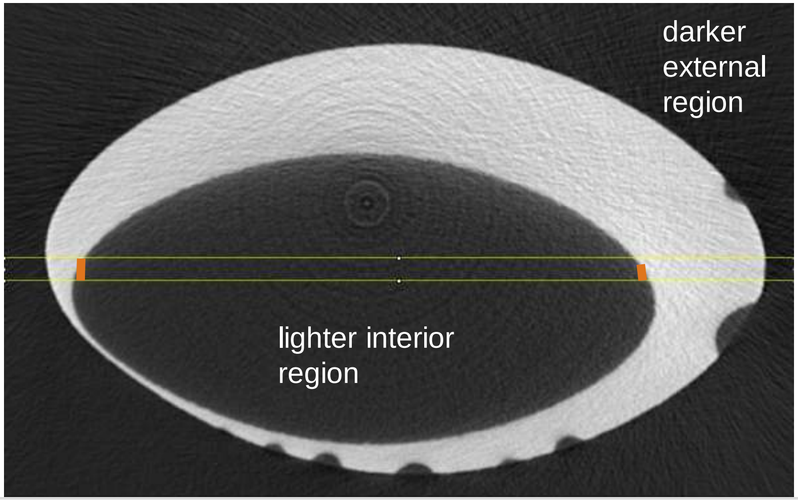
Software Induced

- **Finding the Surface**
  - Surface mesh approximation
  - Global threshold calculation
- **Method of Dimensioning**
  - Feature calculation
  - Measurement procedure

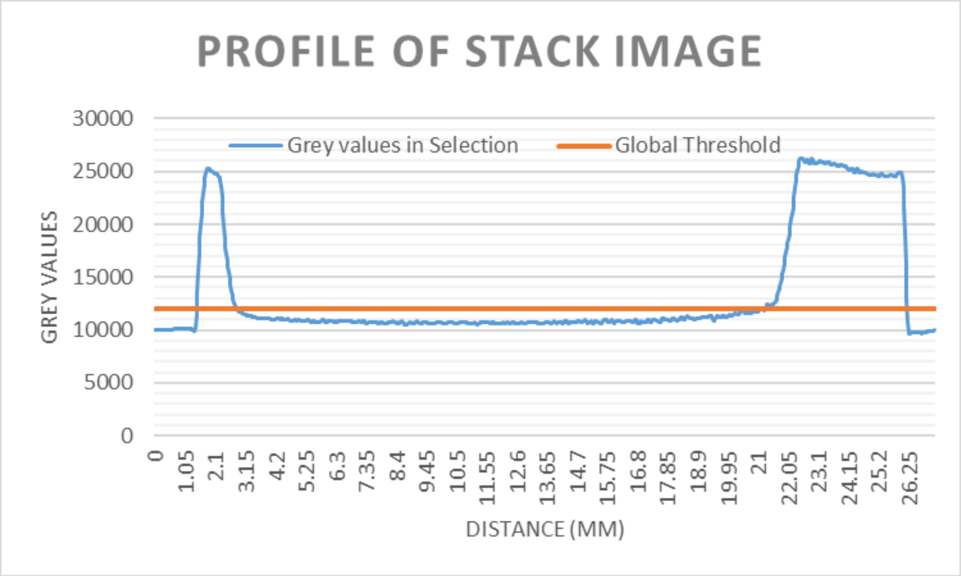
Challenges in Finding the True Surface

Conceptual example:

- Single reconstructed image (1 voxel thick)
- Cross-section with varying wall thickness
- Beam hardening reduction applied



- Yellow box selected for gray value profile



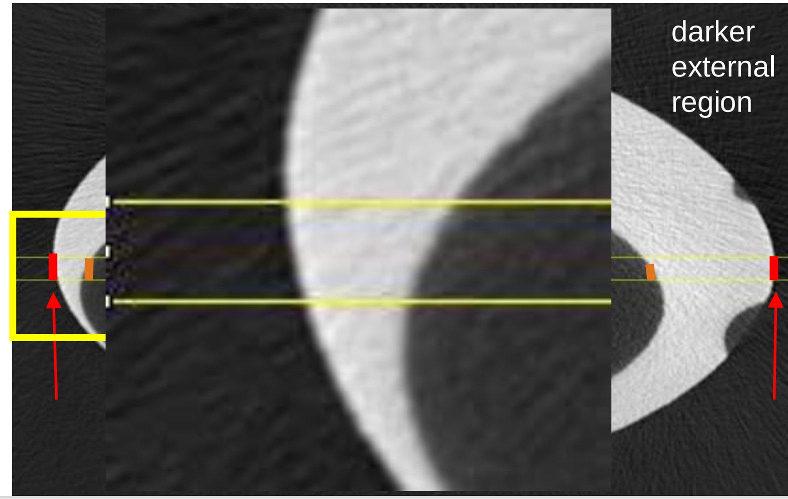
Global Threshold Selection

Orange: favors inside surface boundary

Challenges in Finding the True Surface

Conceptual example:

- Single reconstructed image (1 voxel thick)
- Cross-section with varying wall thickness
- Beam hardening reduction applied

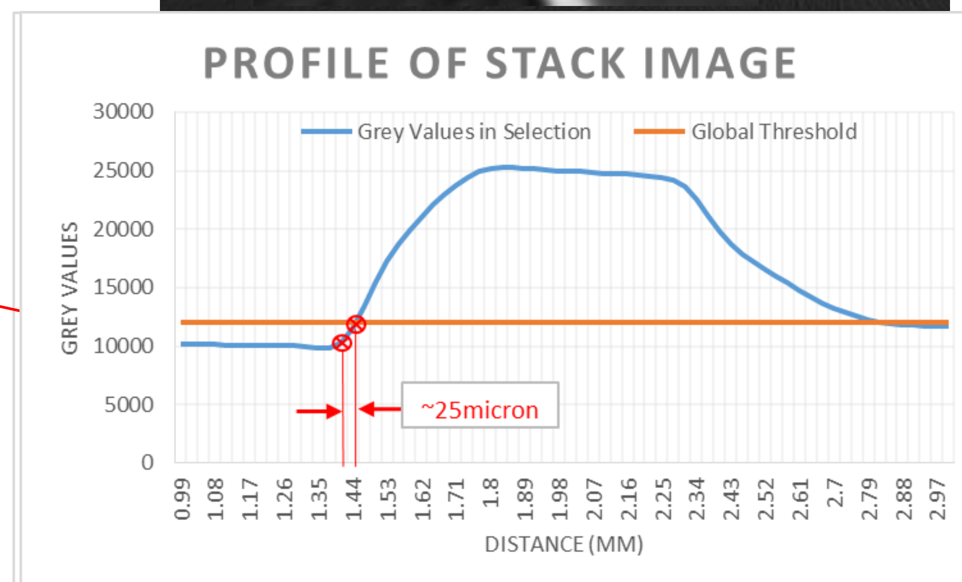


- Yellow box selected for gray value profile

Global Threshold Selection

Orange: favors inside surface boundary

Red: favors outside surface boundary



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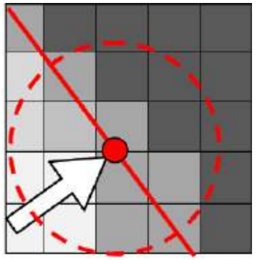
Methodologies: Finding the true surface

Local Threshold Calculation vs. Global Threshold Calculation

Local Threshold Calculation

- Surface boundary locally determined
- Uses greyscale data only around target point

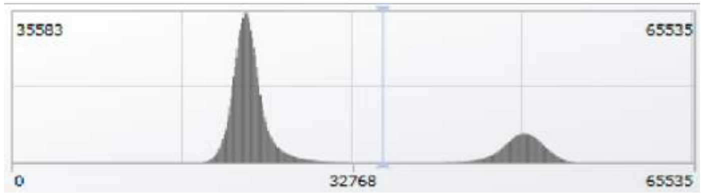


- Requirements:
  - Target point (nominal X,Y,Z)
  - Target vector (I,J,K direction for threshold evaluation)
  - Target threshold (initial condition & error handling)
  - Spatial search limits before and after target point
- Options:
  - Filtering radius :

    Uses greyscale data within # voxels around calculated point to filter noise

Global Threshold Calculation

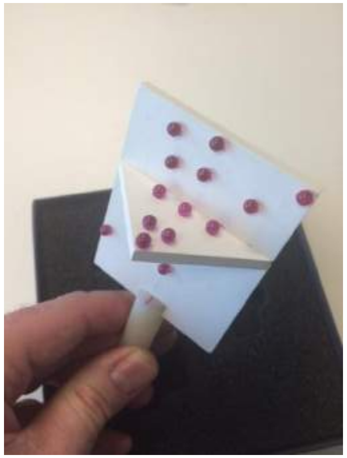
- Surface boundary globally determined
- Uses greyscale data for whole volume (histogram)



- May use half way between peaks
- May optimize threshold by minimizing noise
- Global threshold commonly used for mesh extraction due to computation time

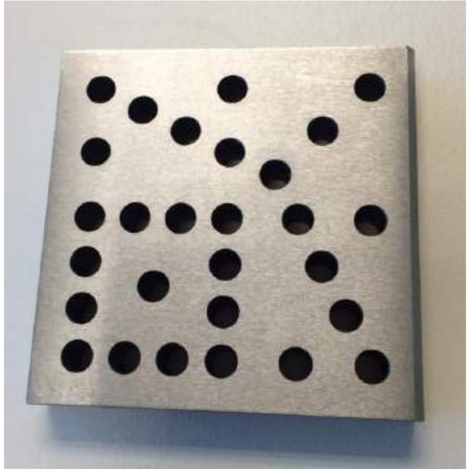
Experiments

- Single points using precision reference objects
  - Precision ruby spheres (diameter and roundness <= 0.0001mm)



#1 precision sphere gauge

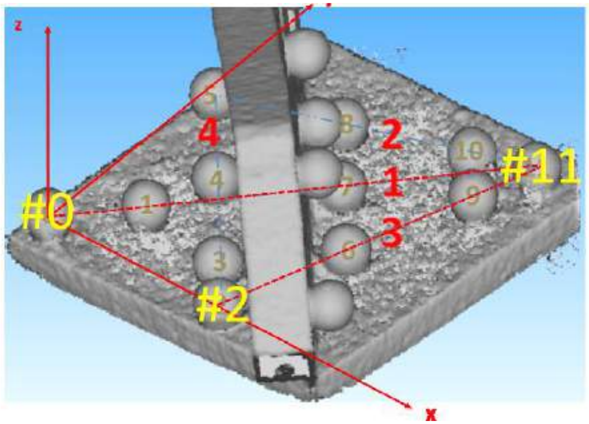
- Feature measurements using representative manufactured parts
  - CMM correlation using same point sampling strategies

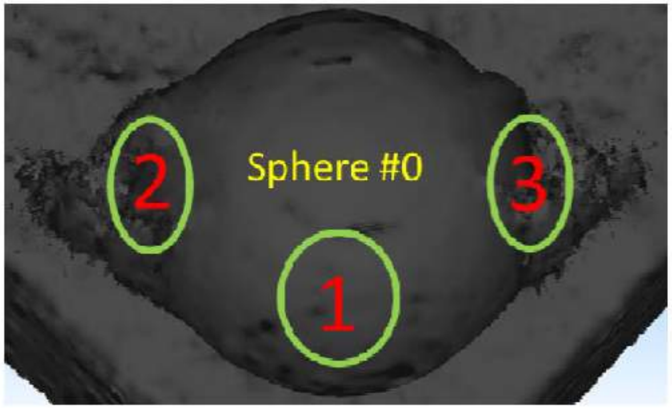


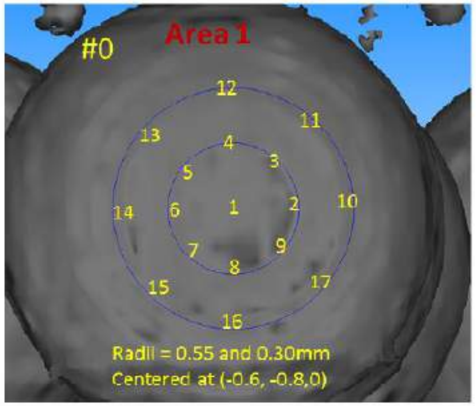
#2 aluminum hole plate

#3 titanium additive part with varying wall thickness

Experiment #1: Point Sampling Study



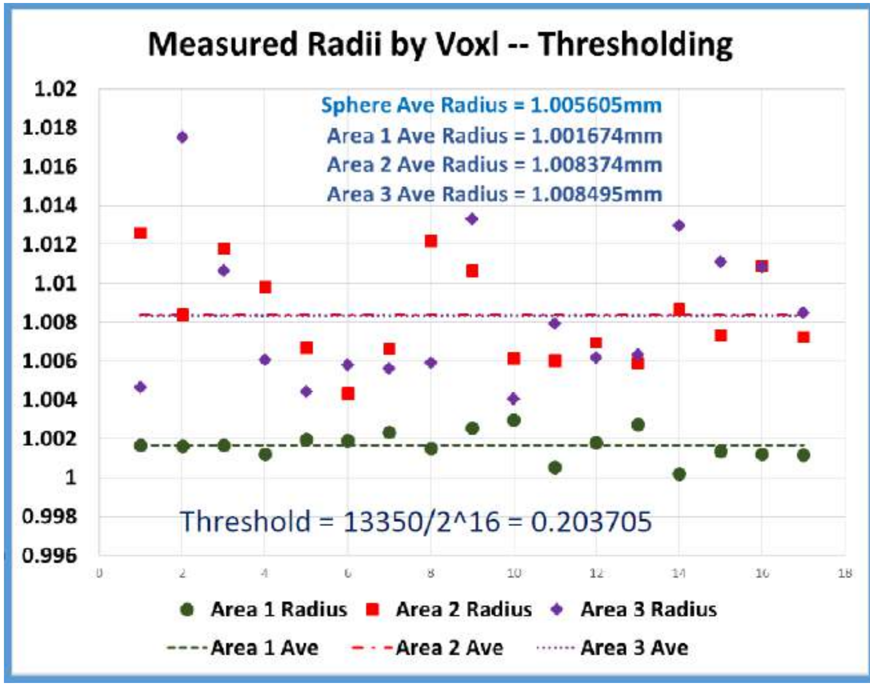


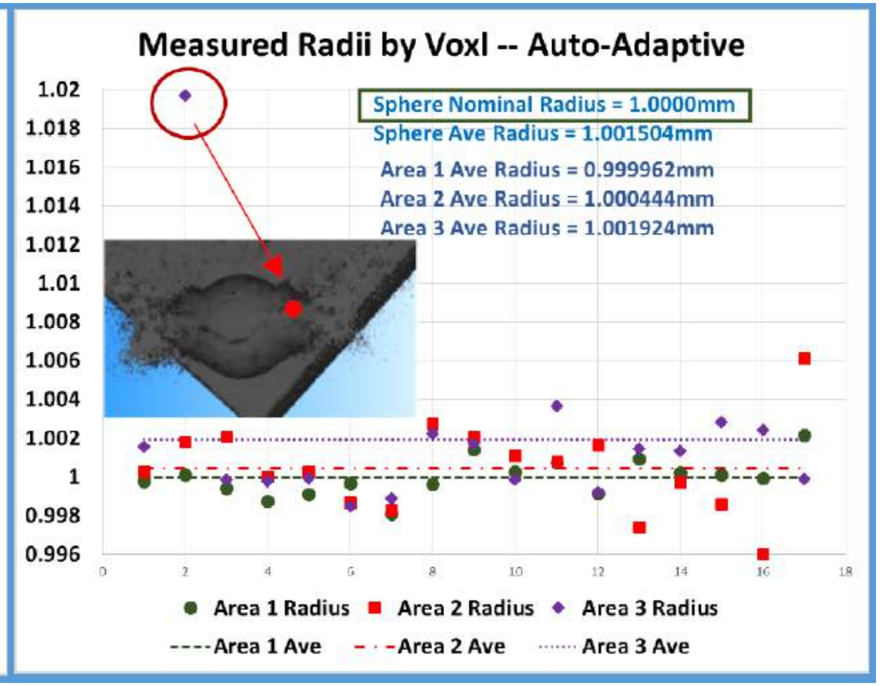


Comparative study using precise points on a gauge sphere

- **Setup**
  - Target centers positioned on a sphere in three directions
  - (17) points evenly distributed around each target position
  - Coordinate system at sphere center
- **Procedure**
  - Measure sphere with VOXL software using “Auto-Adaptive”, local thresholding and “Threshold”, global thresholding at halfway between peaks.

Threshold Methodology: Comparative Point Sampling Study





Results

- **Radial measurement variation**
  - **Global Thresholding : 6.8 microns** **Local Thresholding : 1.9 microns**
- **Average error from nominal**
  - **Global Thresholding : 5.6 microns** **Local Thresholding : 1.5 microns**

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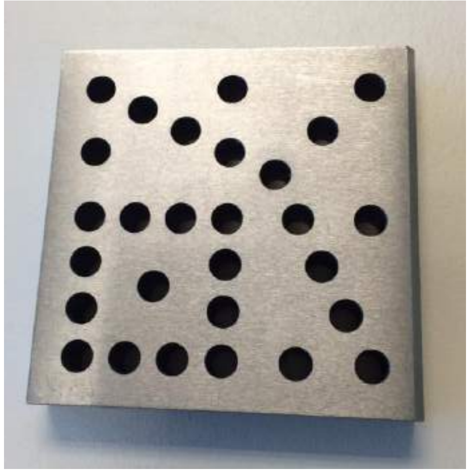
Experiment #2: Aluminum hole plate

- CMM correlation for real manufactured parts.
- Comparing attributes of geometric features on an aluminum hole plate

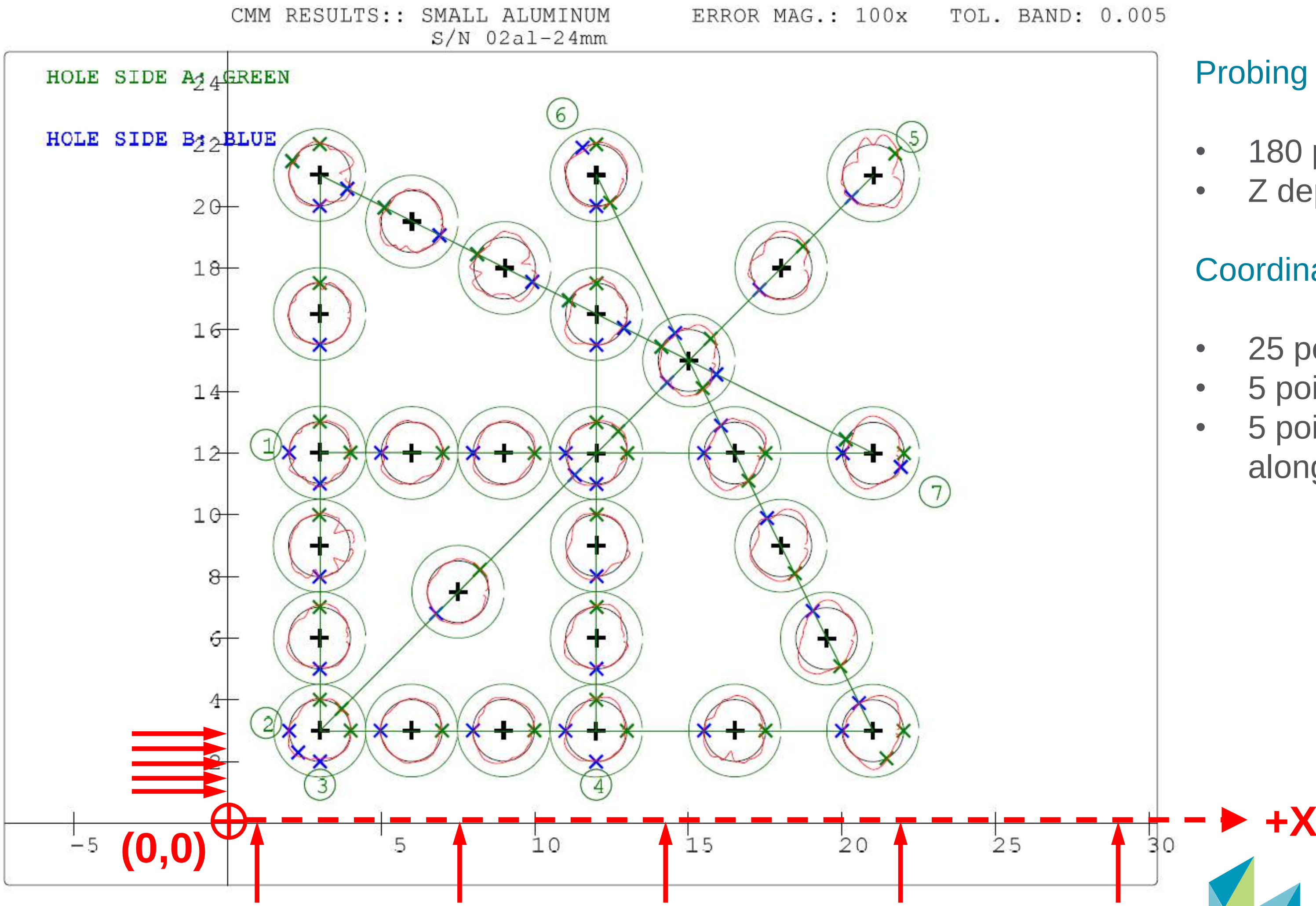


Overall Dimensions:
24mm x 24mm x 4mm

2mm holes

CMM Correlation Study: Feature Geometry Test

Hole Plate



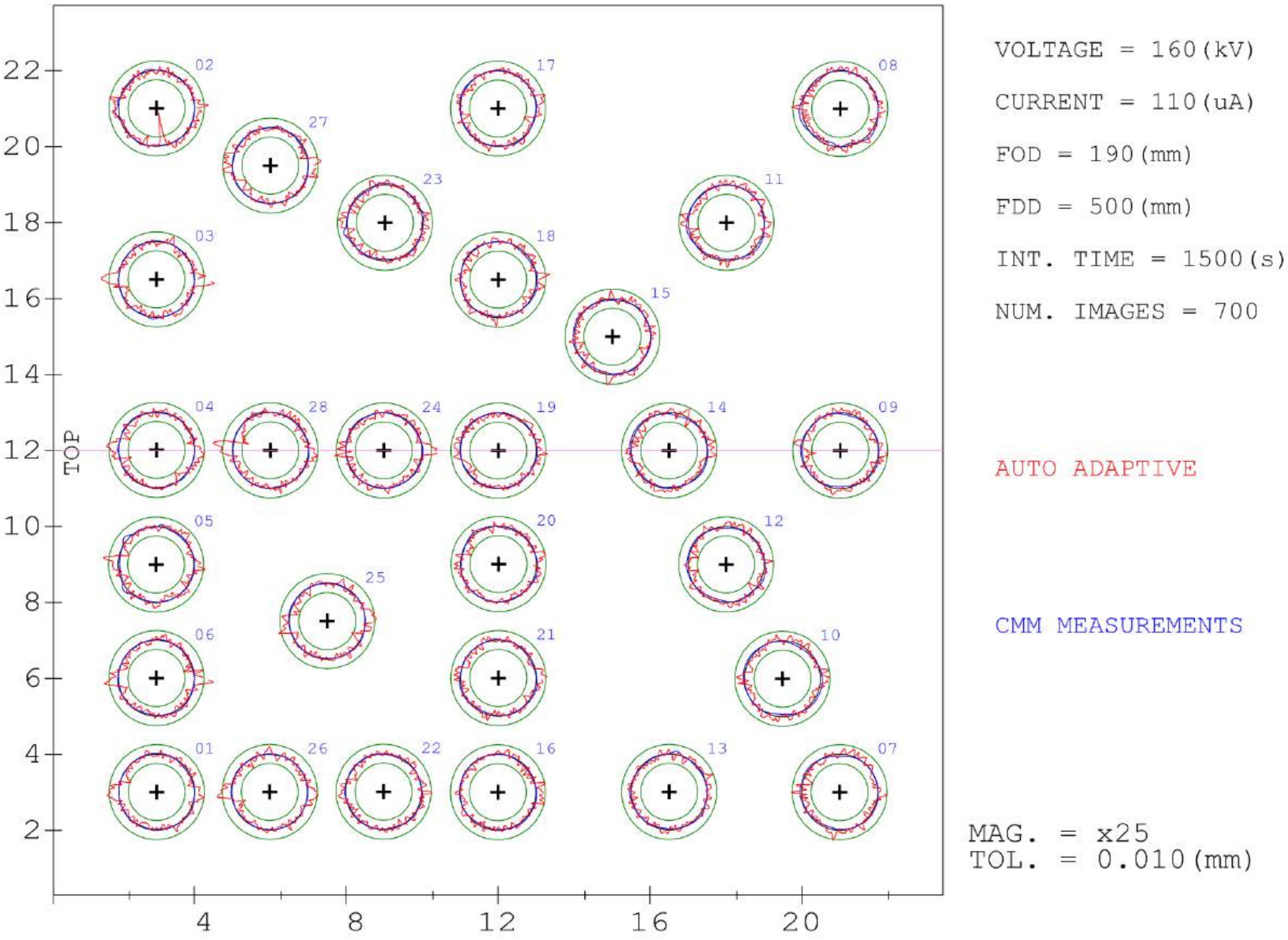
Probing strategy

- 180 points/hole
- Z depth at -1mm

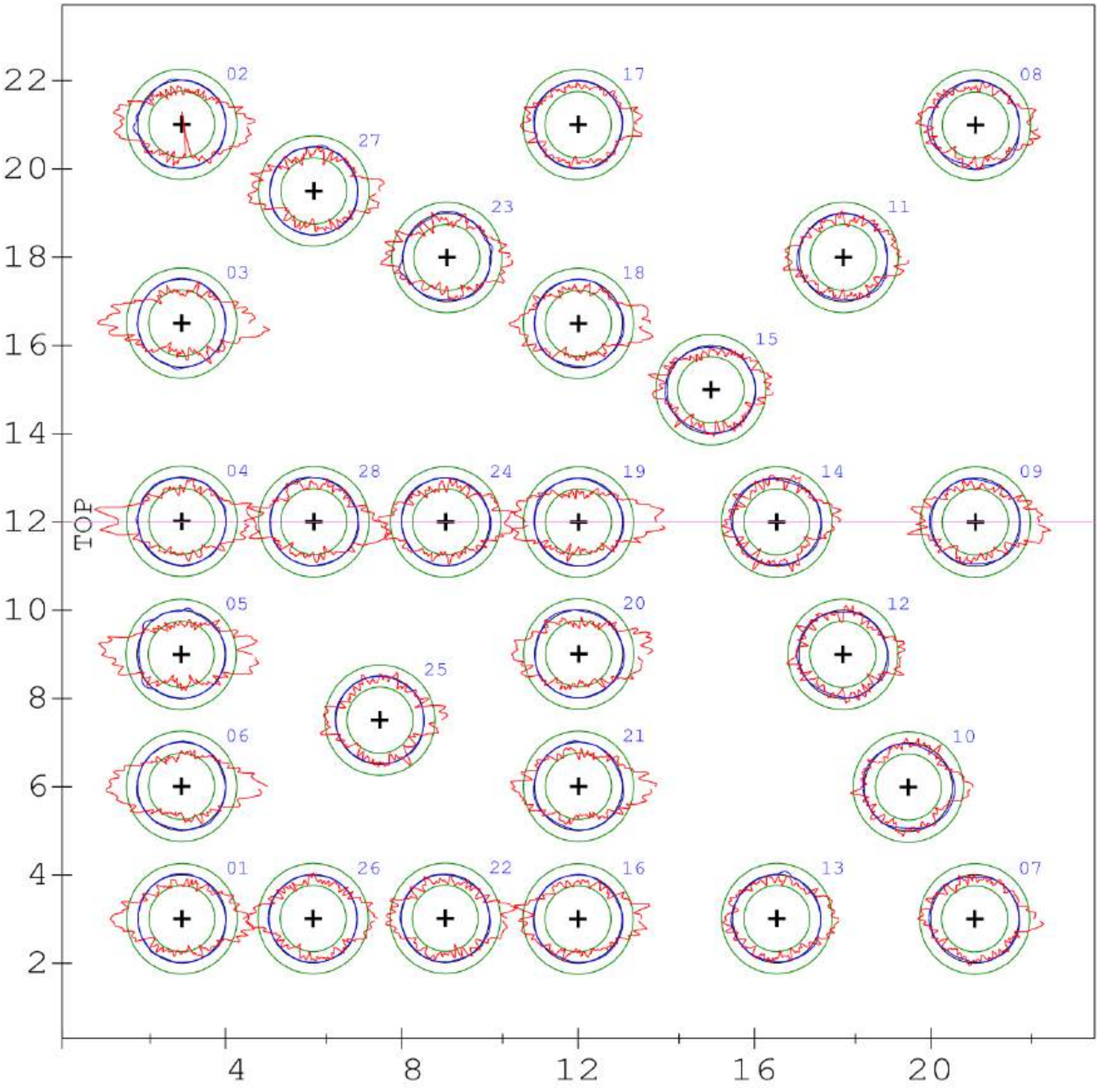
Coordinate System

- 25 points on plane
- 5 points on corner Y
- 5 point distributed along X

Local Threshold Method



Global Threshold Method (ISO-50)



VOLTAGE = 160 (kV)

CURRENT = 110 (uA)

FOD = 190 (mm)

FDD = 500 (mm)

INT. TIME = 1500 (s)

NUM. IMAGES = 700

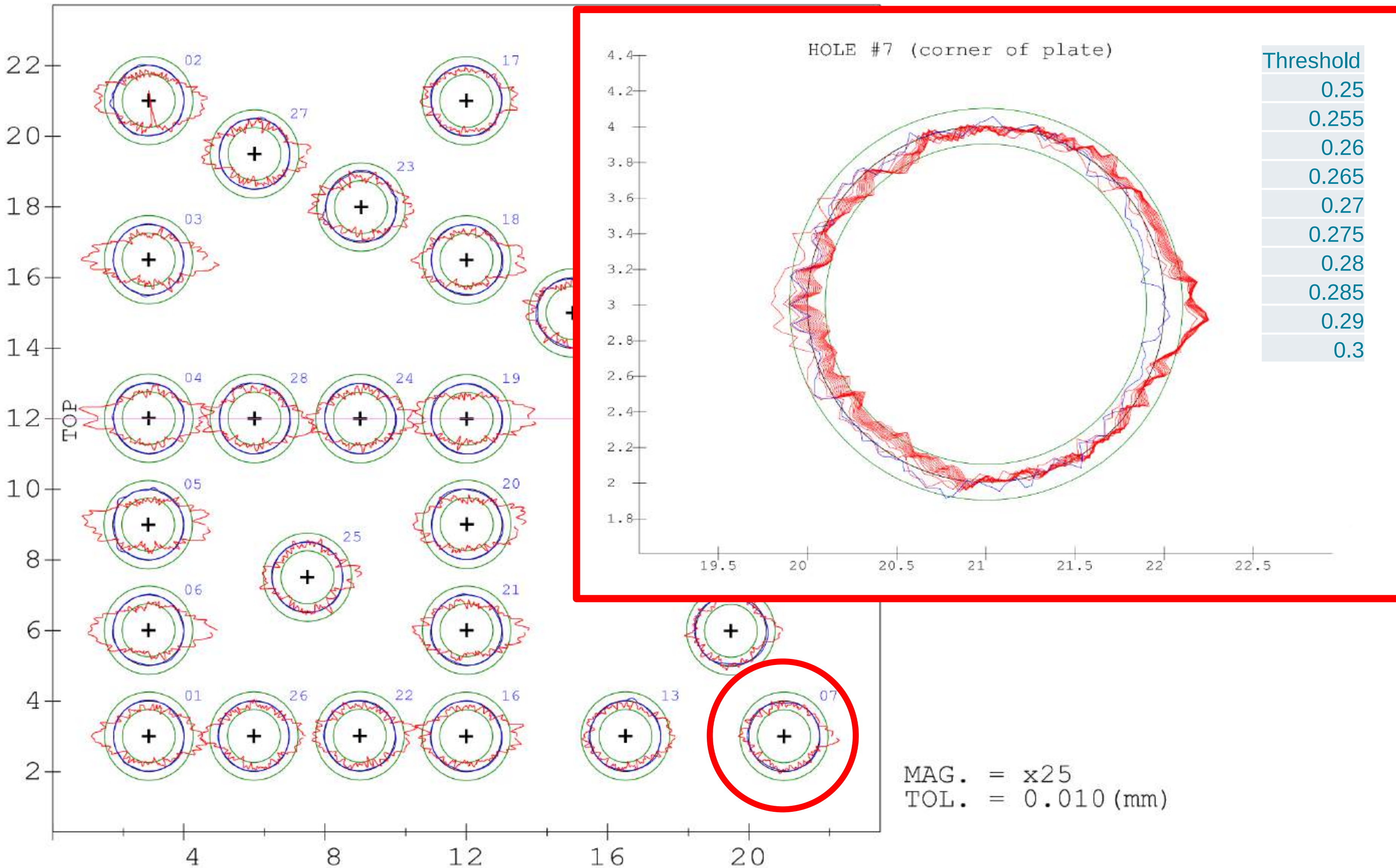
CONSTANT THRESHOLD:

ISO-50 = 0.268

CMM MEASUREMENTS

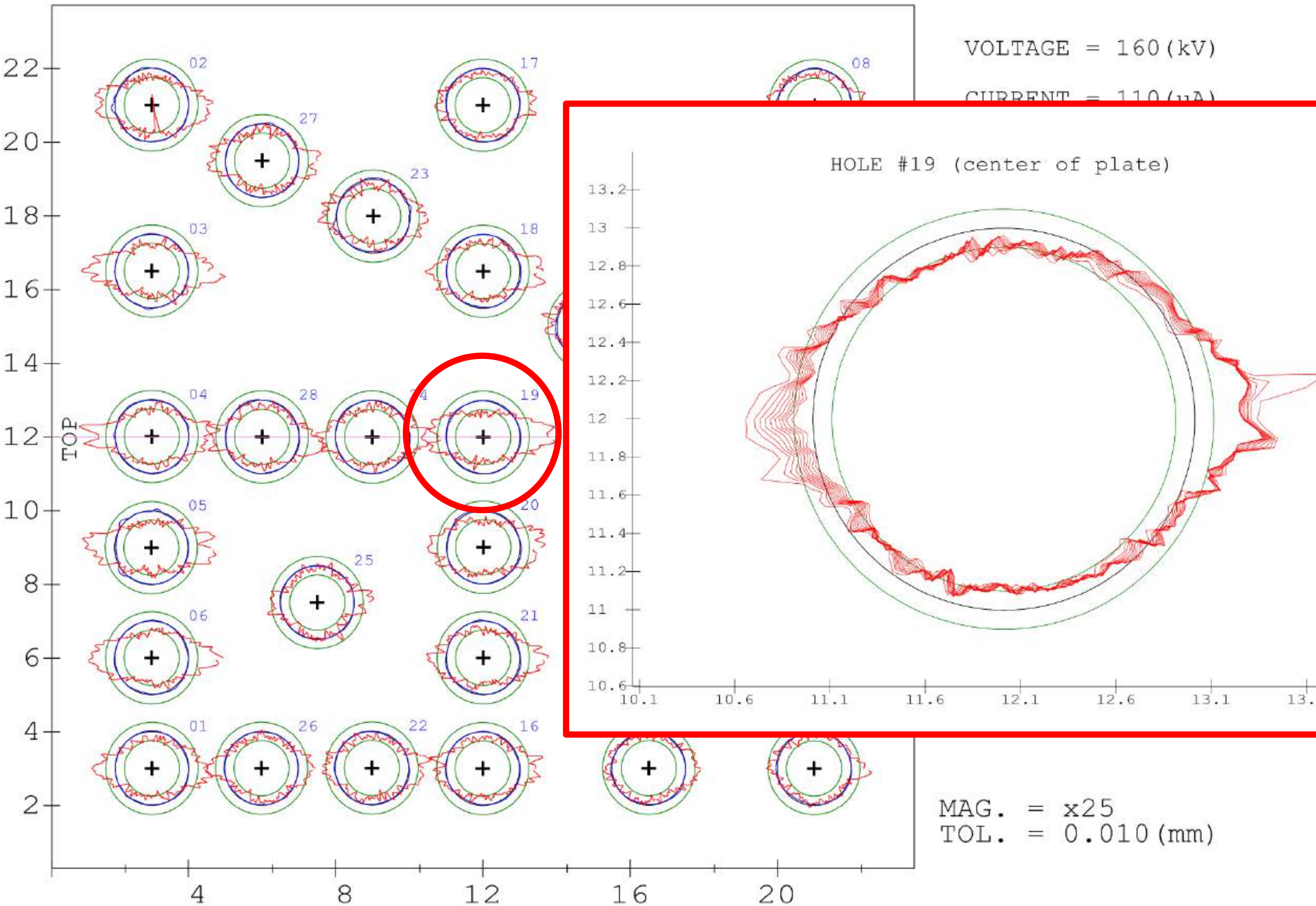
MAG. = x25
TOL. = 0.010 (mm)

Global Threshold Method



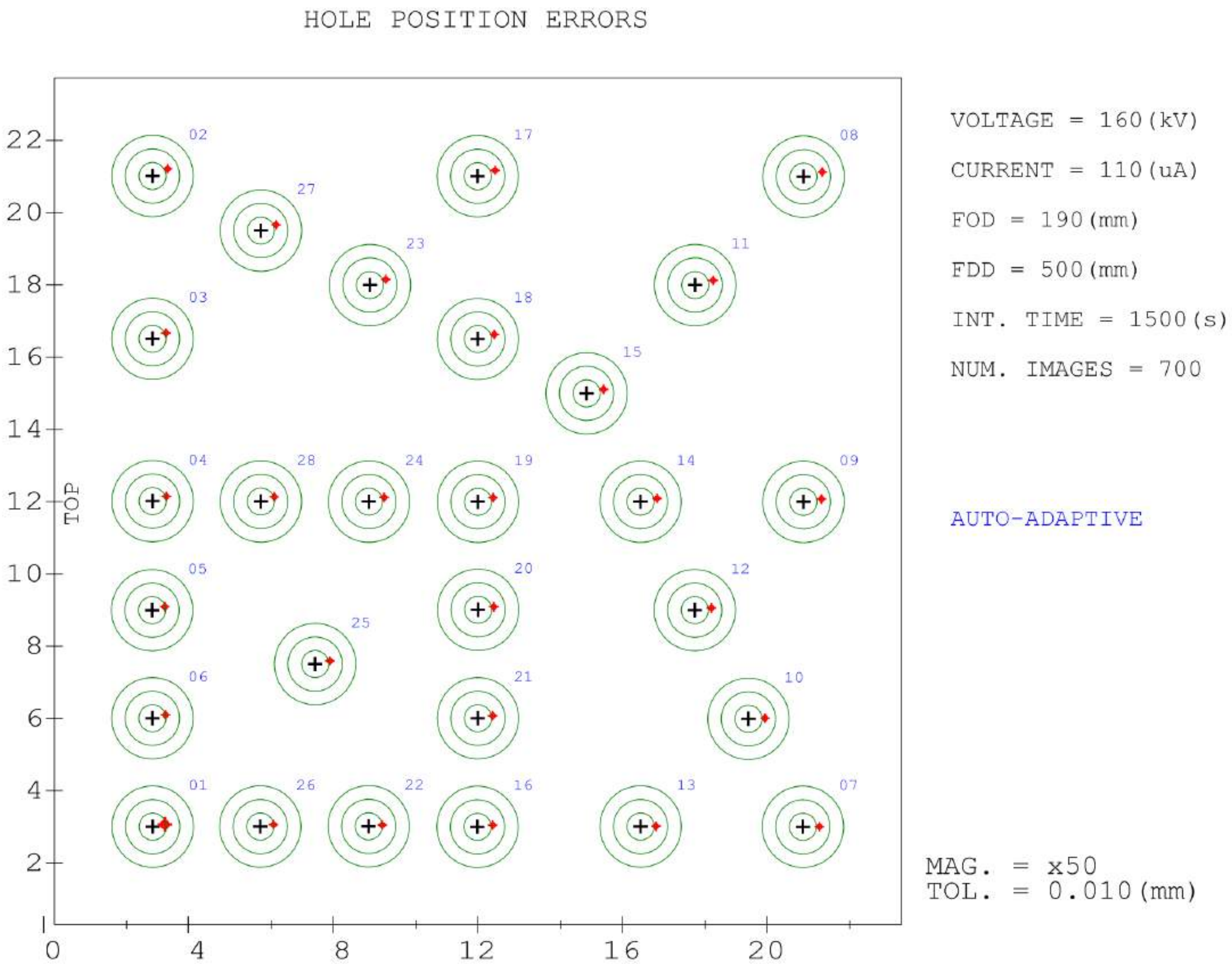
Threshold
0.25
0.255
0.26
0.265
0.27
0.275
0.28
0.285
0.29
0.3

Global Threshold Method

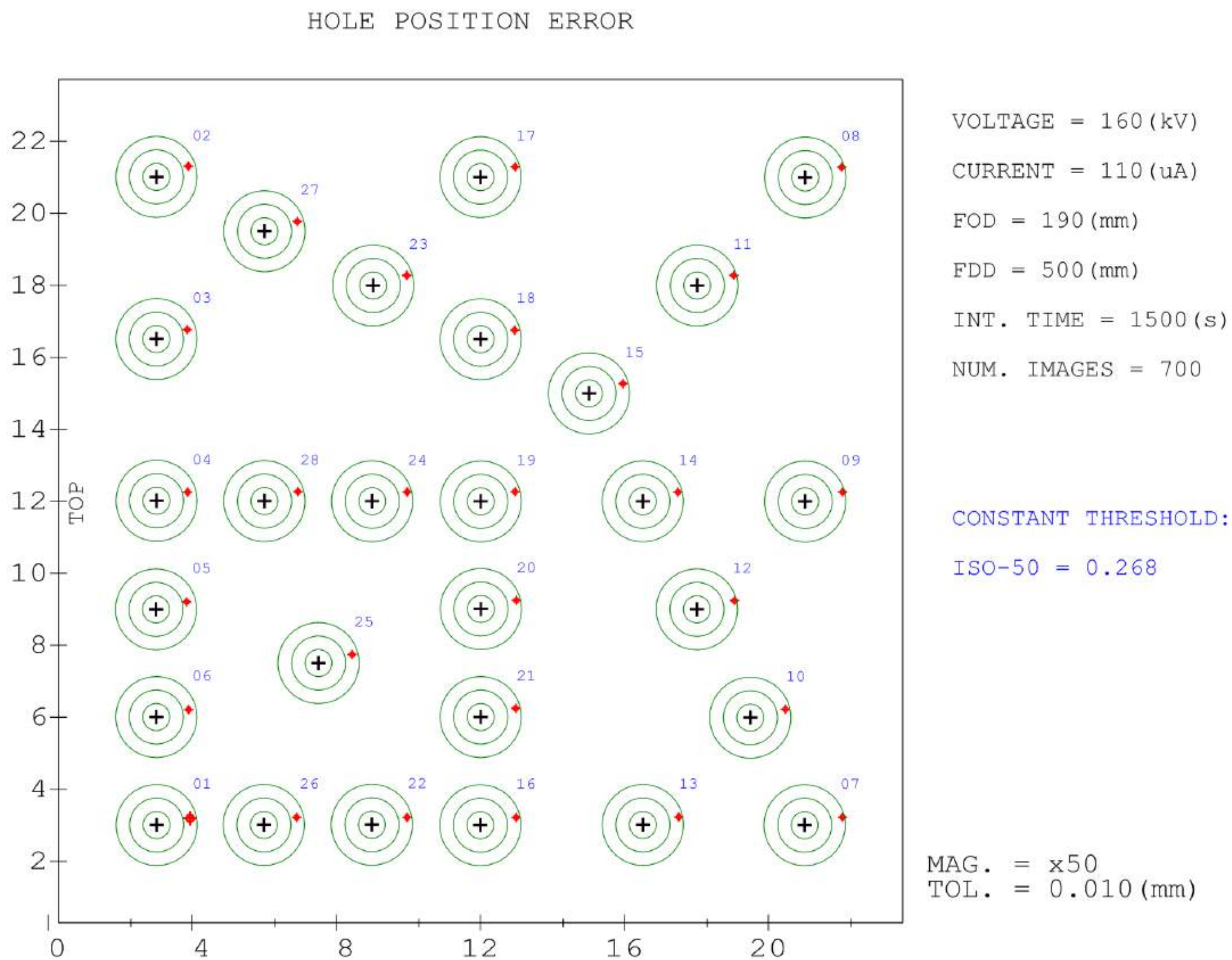


Threshold
0.25
0.255
0.26
0.265
0.27
0.275
0.28
0.285
0.29
0.3

Hole Position Using Local Threshold Method

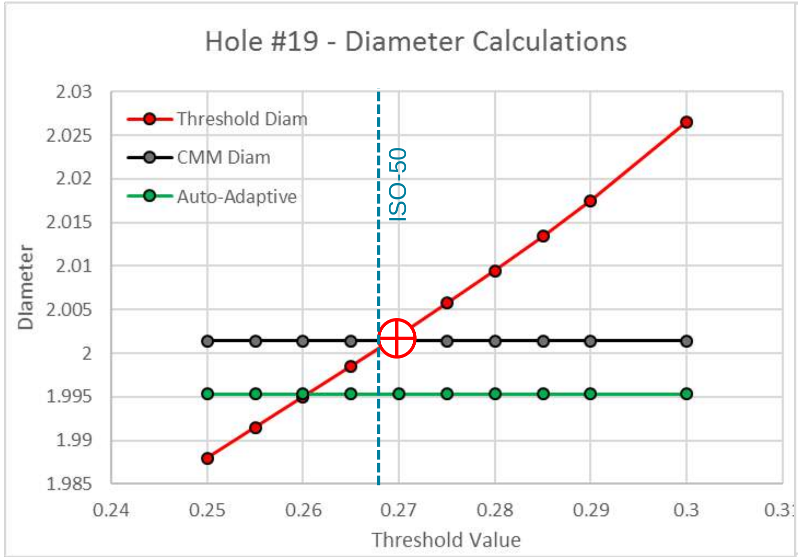


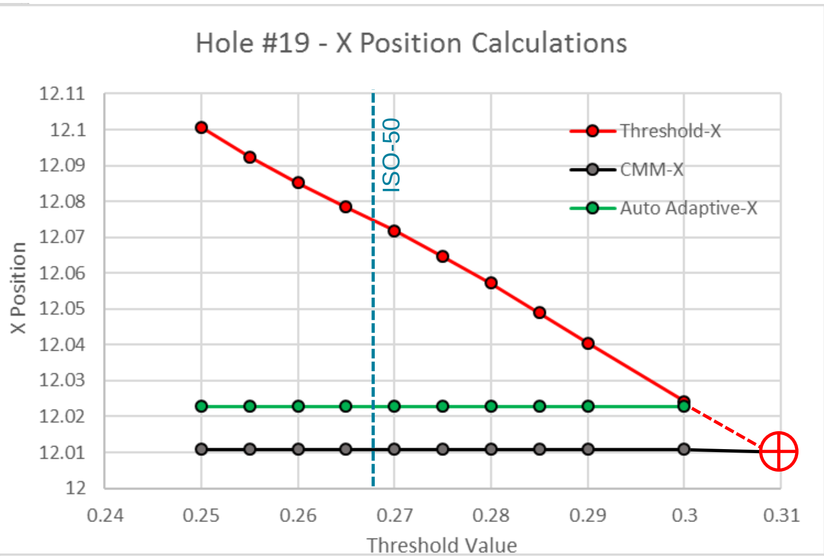
Hole Position Using Global Threshold Method (ISO-50)

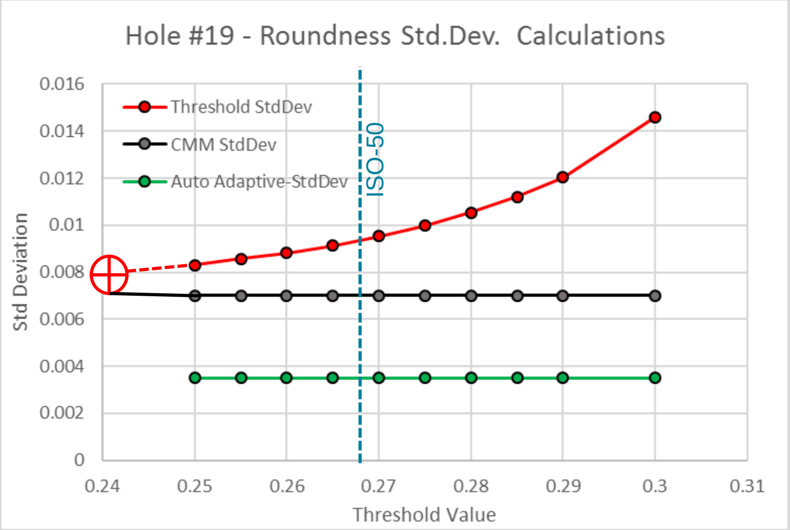


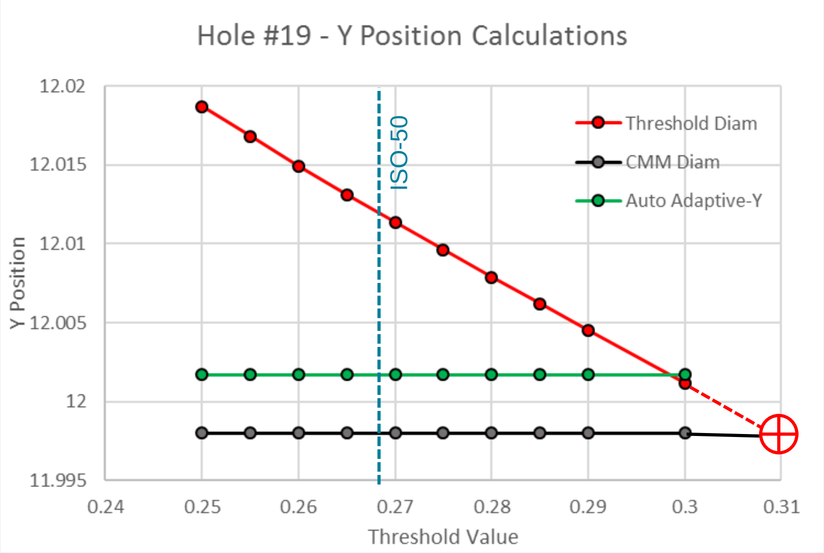
Which Threshold Provides the Best Overall Results?

HOLE # 19









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Experiment #3: Additive manufactured titanium part

- CMM Correlation for real manufactured parts.
- AM titanium generic blade. Varying wall thickness in different directions

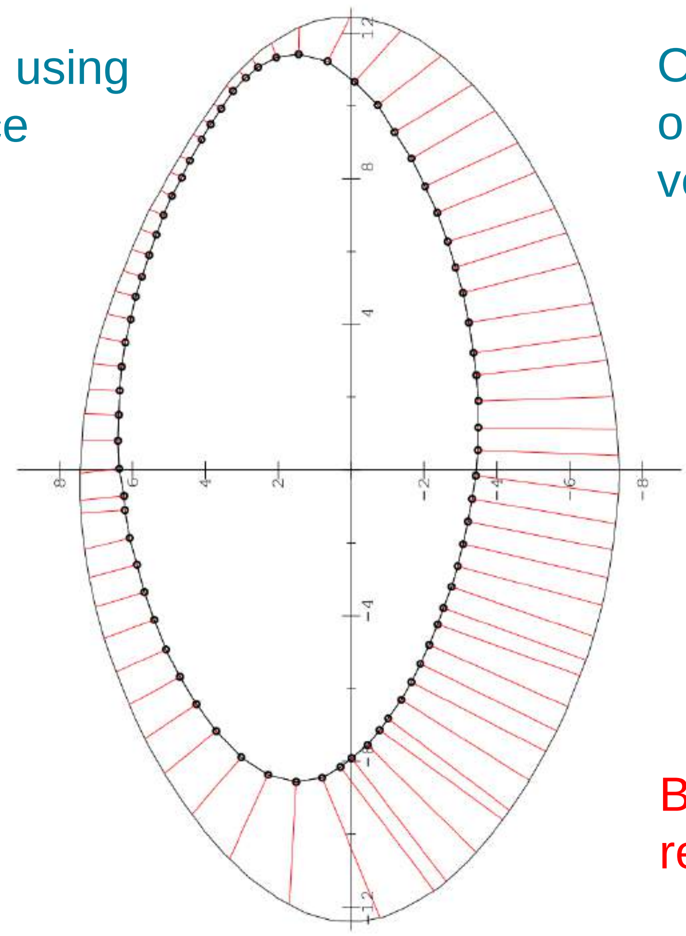
Overall Dimensions:
25mm x 15mm x 60mm

Wall Thickness:
0.381mm to 4mm

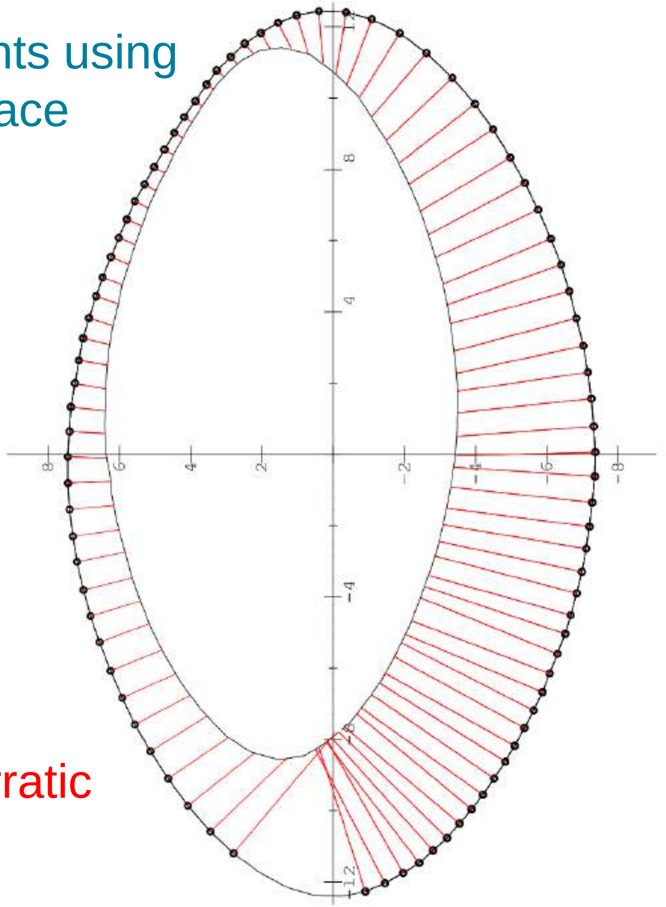
Analysis methods can make a big difference.

Wall thickness calculation using CMM target points and normal vector information:

Inside points using inside surface vectors



Outside points using outside surface vectors

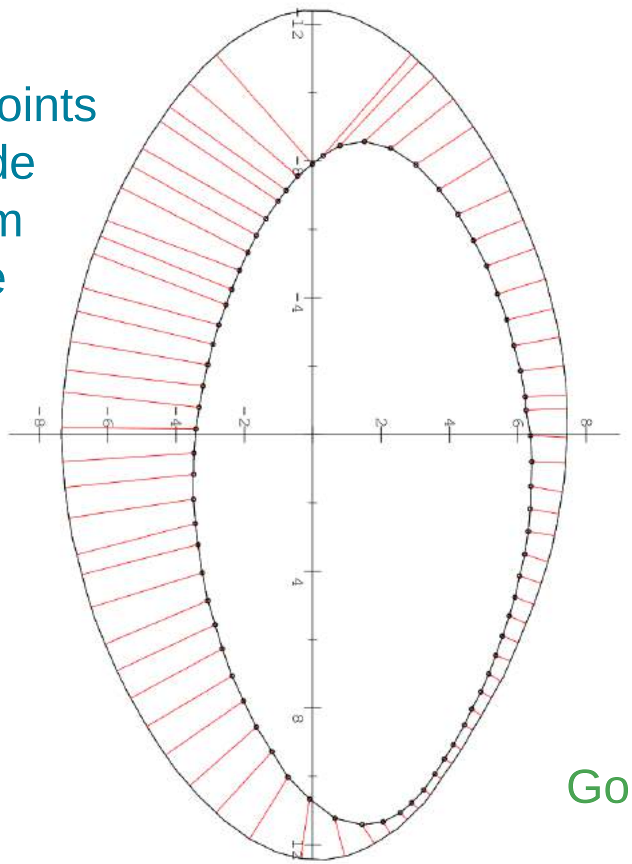


Both give erratic results!

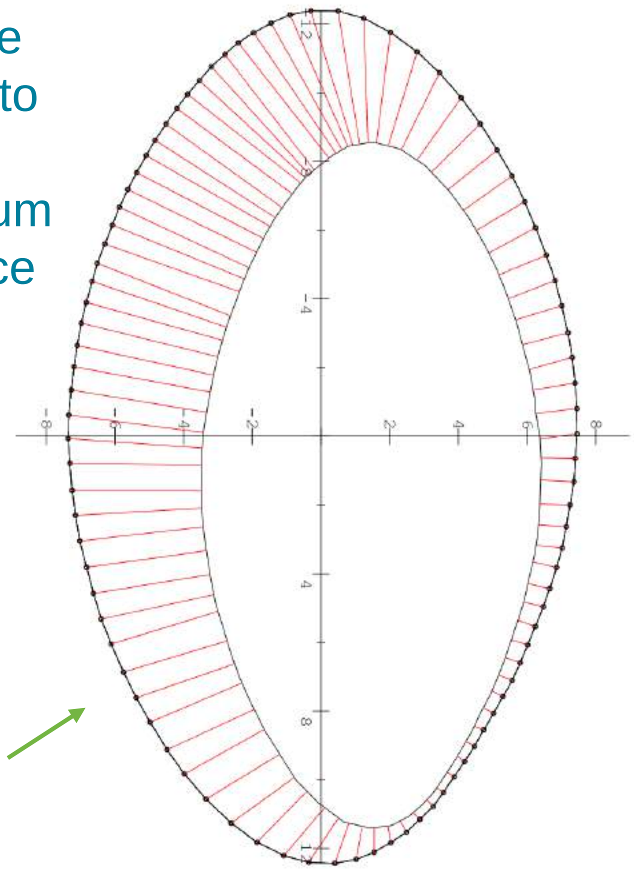
Analysis methods can make a big difference.

Wall thickness calculation using CMM target points' minimum distances:

Inside points to outside minimum distance



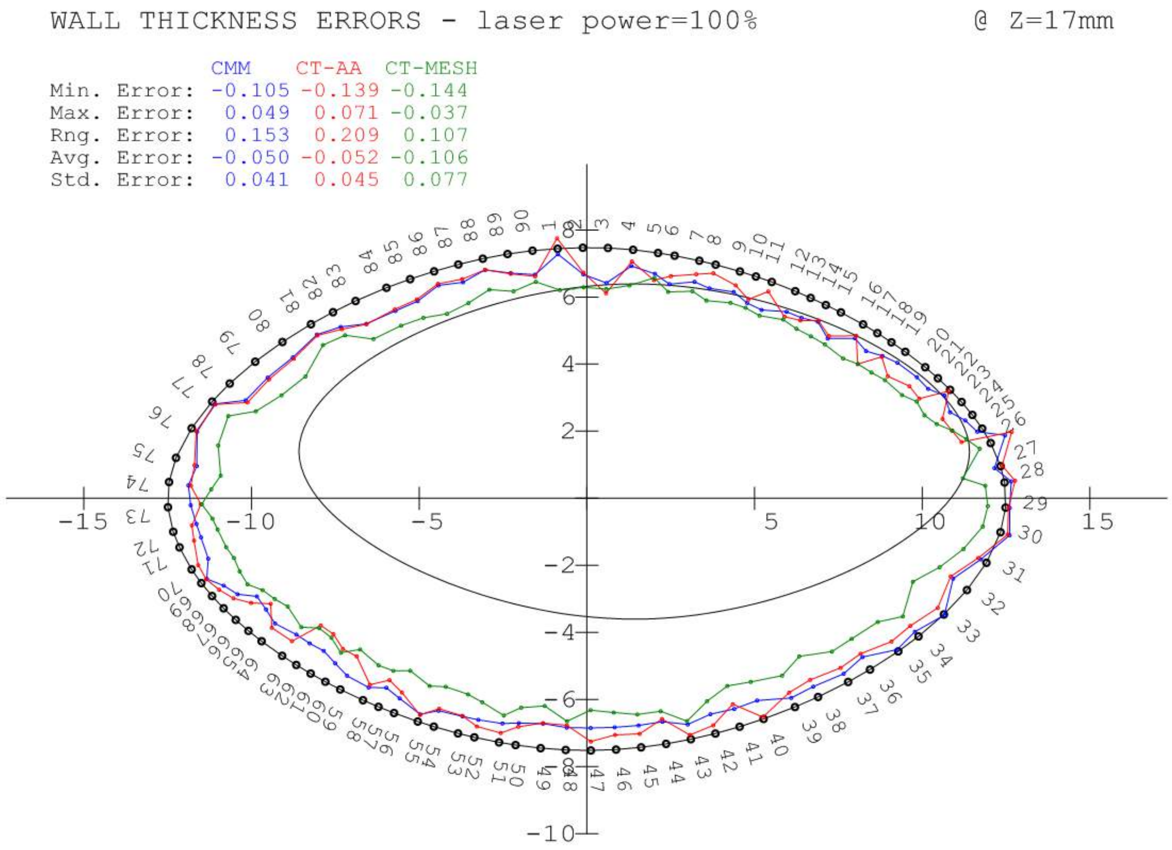
Outside points to inside minimum distance



Good results

Point-to-Point Correlation with CMM Target Points

(3) Different sampling methods using same points



Above: CMM probe setup

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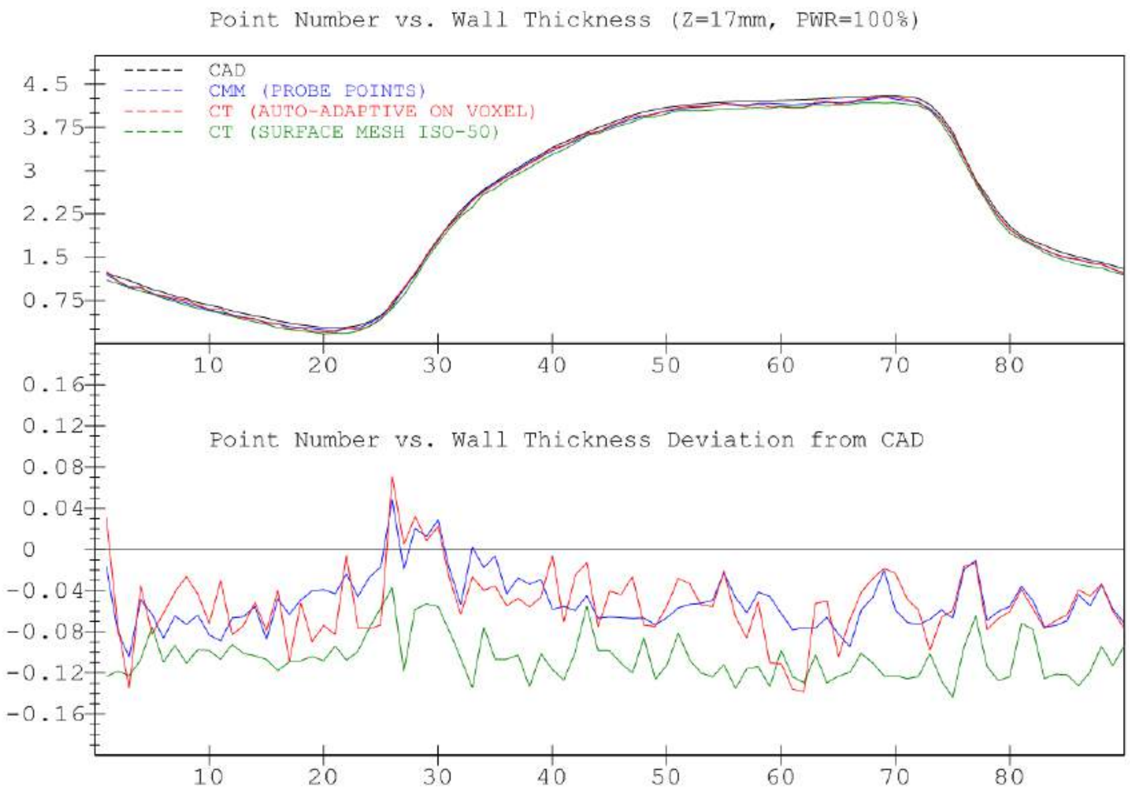
Point-to-Point Correlation with CMM Target Points



Standard deviation for VOXL's ***Auto-Adaptive*** method to the CMM is

4 microns

Compare to 36 microns difference in standard deviation between ISO surface mesh and CMM

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Conclusions:

- **Global thresholding techniques are insufficient for dimensional measurements**
  - Single threshold value cannot be optimized for all geometric features at once
  - Single threshold value cannot be optimized for different characteristics of the same geometric feature.
  - Typical method used for mesh extraction from voxel data.. Beware!.

- **Local thresholding techniques show significant improvement for dimensional measurements**
  - Must consider target information, algorithm constraints, for consistent results.
  - VOXL's *Auto-Adaptive* measurement mode is an extension of a localized thresholding technique, with a range of advanced user parameters including filtering radius option.

- **Measurement methodology can have a large impact on results**
  - Point sampling strategy critical for reproducible measurements
  - Analysis methods will determine the usefulness of the results

- **Common point sampling strategies ideal for demonstrating CMM correlation**
  - The best way to validate CT inspection process for dimensional measurement

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Questions?

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