How To Achieve
The Resolution You Need

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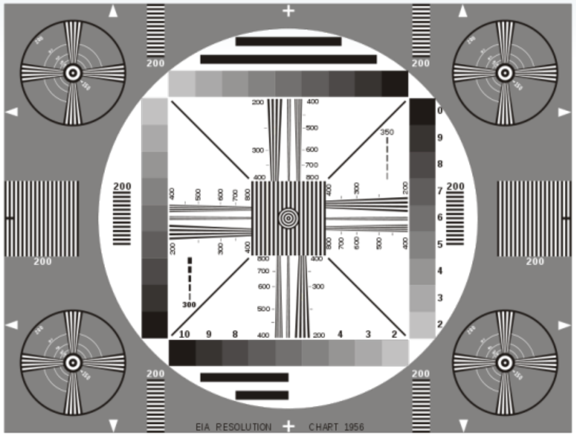
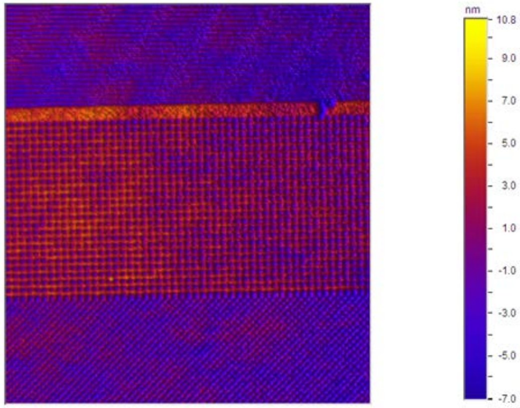
Presentation Overview

- Basics of Resolution
- What resolution do you need?
- Comparing results across systems
- Resolution in Stylus Profilometers
- Resolution in 3D optical microscopes
- Conclusions and Discussion

What is Resolution?

- The fineness of detail that can be distinguished in a result
- Resolution for surface measurements can vary in all three dimensions: X, Y, and Z
- Resolution does NOT equate to accuracy or uncertainty!
  - You can have high resolution and still get the wrong result.
  - You can have poor resolution and still get a good measurement with enough sampling

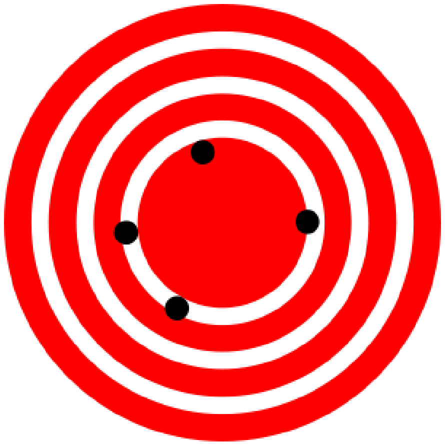




Accuracy, Precision, and Resolution Are All Necessary For Good Metrology

- Precision is the repeatability of a measurement result
- Accuracy is closeness of the average result to a true value
- Both are essential for proper metrology
- Precision relates to resolution, but is not the same

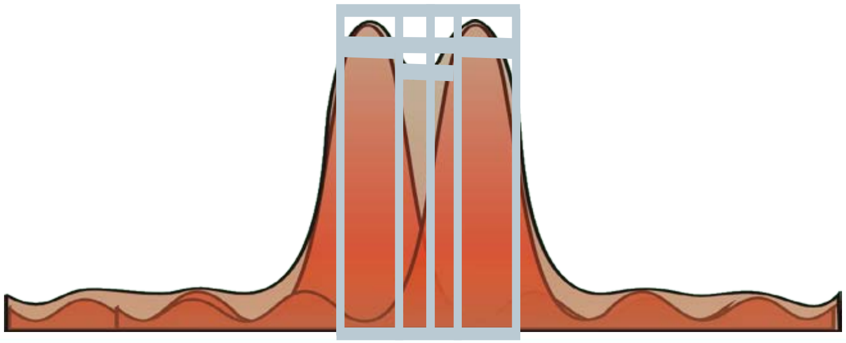
High precision, low accuracy

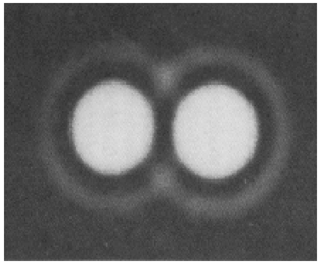


High accuracy, low precision

Resolution Specifications Are Often Confusing

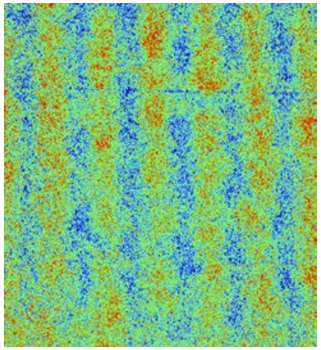
- Mathematical resolution is often used instead of something relating to a measurement
  - Some systems claim <1pm resolution. The helium (smallest) atom is 31pm in diameter!
  - 20 significant digits might not be meaningful, nor might 16 camera bits
- Lateral resolution often confused with pixel (or sample) spacing
  - For contact systems, the resolution is different along the scan direction as compared to between scan lines
  - For microscopes, optics often determine the resolvable feature size
  - Even when not optics limited you need at least 2 (preferably 3 or 4) pixels across a feature to resolve it





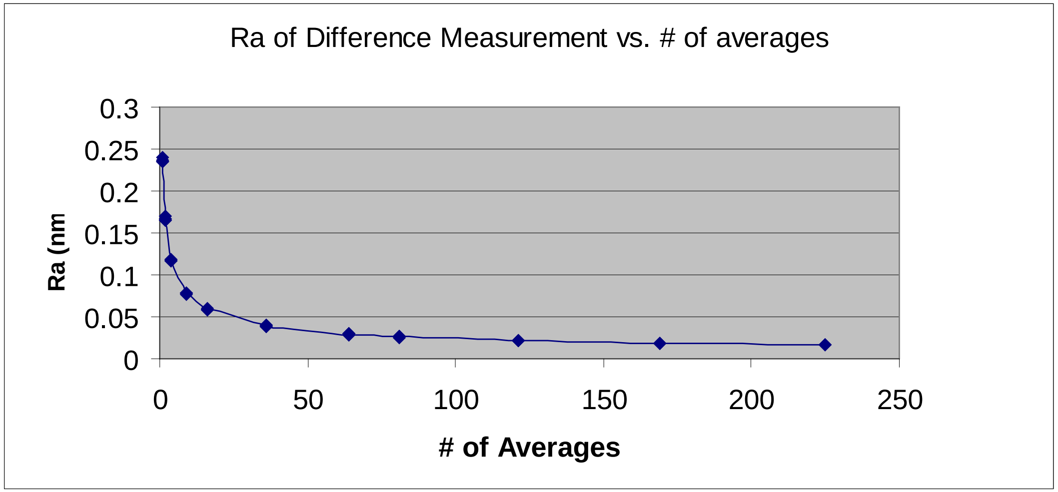
Many Factors Affect Resolution

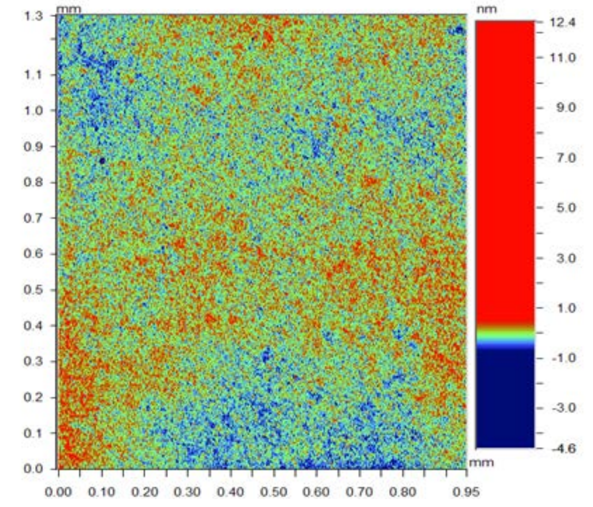
- Measurement Setup
  - Scan speed – trade resolution for throughput
  - Tip size (stylus)
  - Field of view (optical)
  - Processing algorithm – analyze differently based on the measurement needs
  - Systematic errors that can mask real features
- Sample properties
  - Amount of dynamic range of the instrument being used
  - Signal to noise varies based on roughness, slopes, feature spacing
- Environment
  - Temperature drift during a measurement
  - Acoustic Noise
    - Can move the part during measurement
    - Can affect the instrument itself
  - Floor vibration

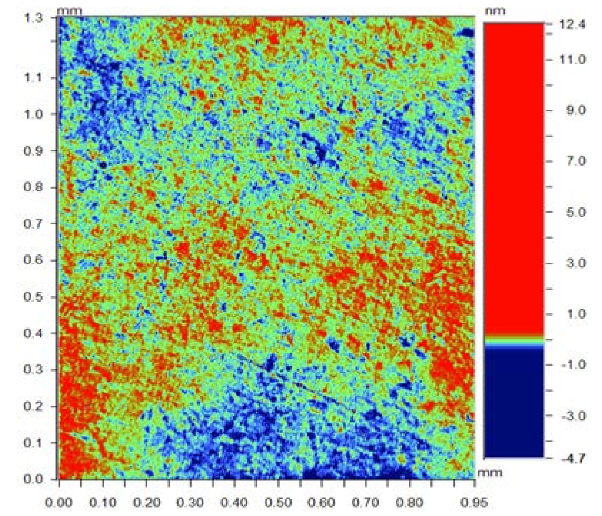


Averaging Can Reduce Noise and Improve Vertical Resolution

- Random (most) noise reduces by the square root of the number of averages.
- Averaging can help see finer detail than is otherwise possible.
- Examining Difference Measurements can tell you the noise floor you are achieving.
- Averaging may not help in loud or high vibration environments

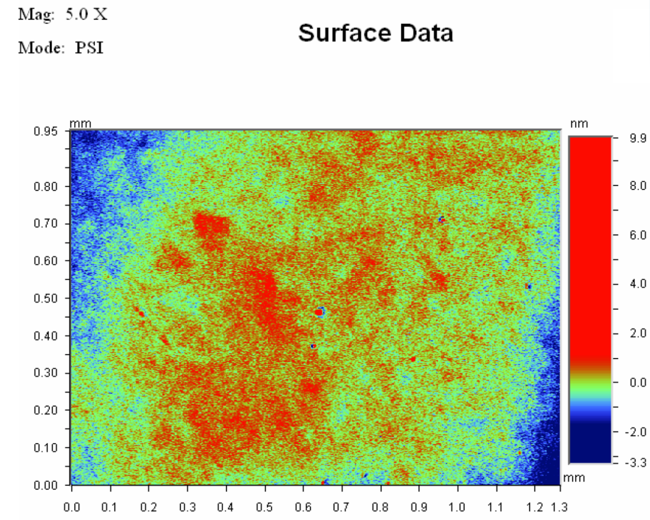


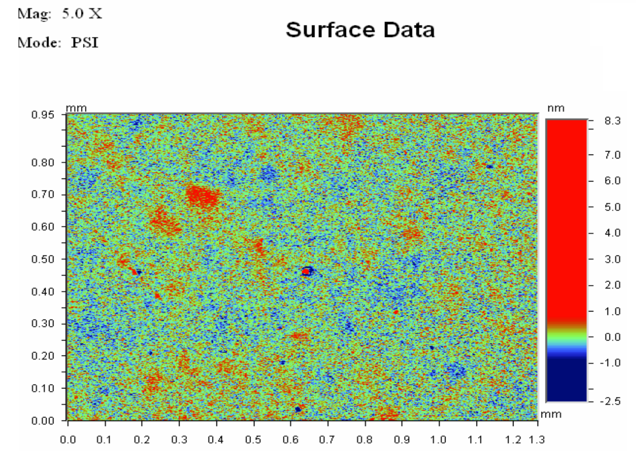




Subtraction of Systematic Errors Exist on All Systems

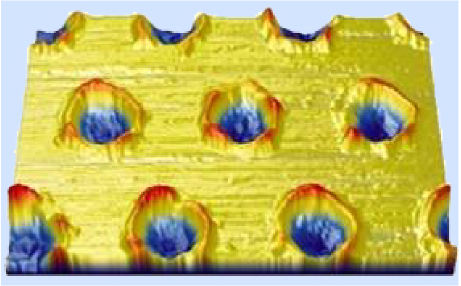
- Scan stage flatness affects stylus results
- Optical aberrations affect microscopes
- Errors are near-constant and can be subtracted to improve resolution
- Details may then be observed which were previously impossible





Knowing Your Resolution Target Can Be Difficult

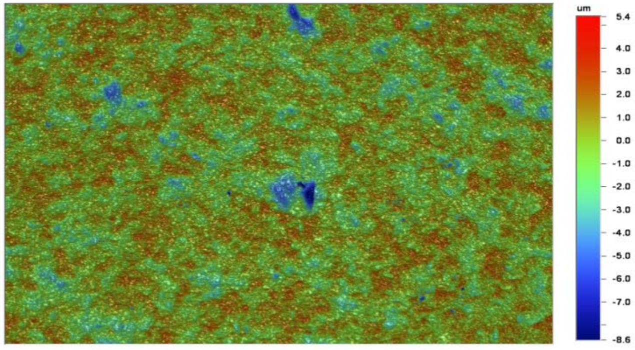
- What size defects or deviations matter?
- What parameters are important?
  - Roughness
    - Does Ra mean the same thing to you and your customer (or vendor)?
  - Heights
  - Curvature
  - Width
  - Defect Count
  - Structure size

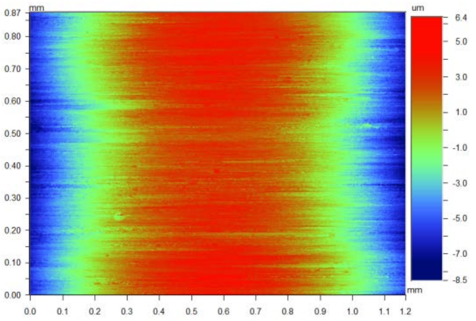


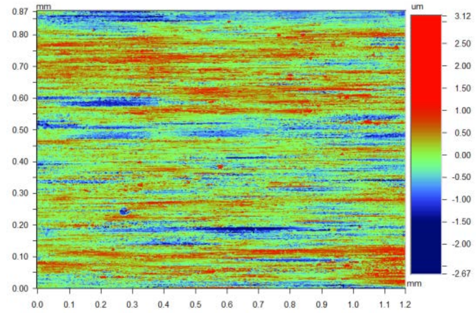
- What tolerance is acceptable on those parameters
  - Each parameter will be resolved differently even with the same measurements!
- What areal coverage is needed for statistical significance?

Resolution Guidelines

- Roughness
  - For polished surfaces, use the highest lateral resolution that meets your throughput needs
  - For rougher surfaces, make sure you capture the dominant frequencies
  - Use the highest vertical resolution that meets your throughput needs
  - Make sure you filter the data appropriately so you are measuring roughness!
- Defects
  - Use modeling or failure analysis where possible to determine critical defect sizes
  - Covering more area may be more important than seeing fine features

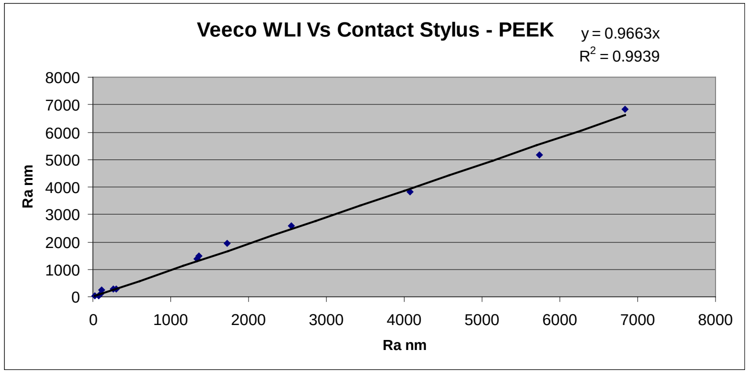


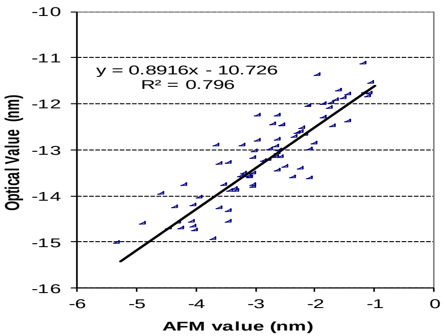


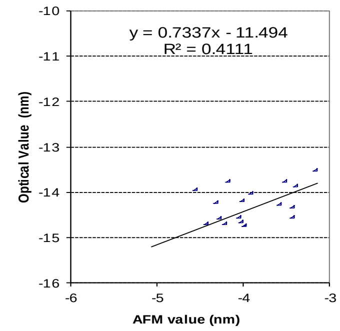


Comparing Results Between Systems Has Many Pitfalls

- "New System X measures a part 10nm differently than our old system. How do we offset System X"
- "I measured some parts across the two systems and the correlation is terrible!"
  - How was each system calibrated?
  - How do results vary within and across systems of each type?
  - Can the two systems detect the same features?
  - Are you examining the same areas on each system?
  - Do the analysis algorithms on the two systems match?
  - Is there sufficient range in the values for correlation to be meaningful?







Standard Error is Used to Evaluate Agreement Between Two Systems

- Good for parts with small range in values compared to the average
- Assumes measurement of the same features
- Two methods are considered agreeable to twice the calculated standard error
- Avoids having to know the true sample standard deviation required by the correlation coefficient

Correlation coefficient

$$R = \frac{\sigma_T{}^2}{\sqrt{\left(\sigma_{sys1}{}^2 + \sigma_T{}^2\right)\left(\sigma_{sys2}{}^2 + \sigma_T{}^2\right)}}$$

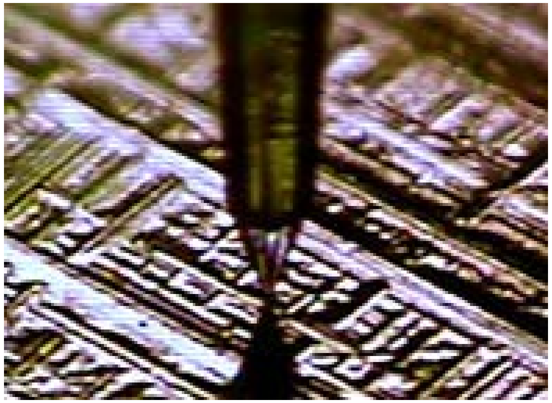
Standard error: standard deviation of the difference

$$\sigma_{SE}{}^2 = \sigma_{sys1}{}^2 + \sigma_{sys2}{}^2$$

Resolution in Stylus Profilometry

The Evolution of Stylus Profiler Resolution

- The World's First Stylus Profiler…
- The "Finger-Nail" Test
- Used by machinists through the 1940's to inspect the surface texture, **But…**
  - No data was gathered
  - No mathematical analysis conducted
  - No quantifying a surface
- **Stylus Profiler Resolution Evolution**
  - Improved sensor sensitivity
  - Smaller, sharper stylus tips
  - Increased number of data points
  - Increase number of profiles for 3D
  - Reduce instrument noise floor

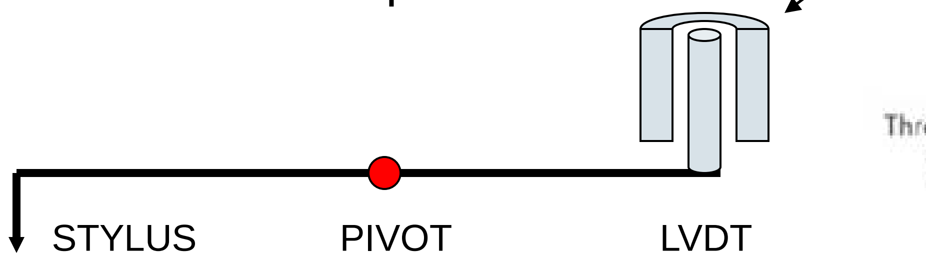


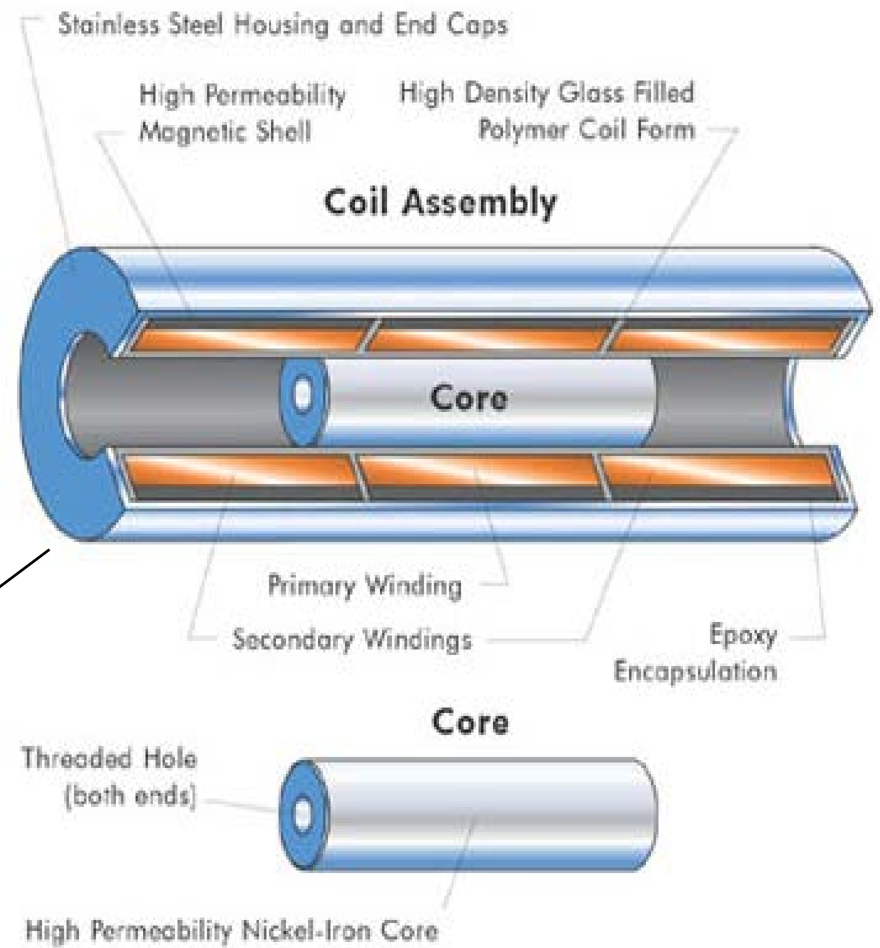
Stylus Sensor = Vertical Resolution

LVDT Sensor Technology

(Linear Variable Differential Transducer)

- Infinite Resolution
- Unlimited Mechanical Life
- Environmentally Robust
- Repeatable, even over wide temperature range.
- Friction-Free Operation
- Fast Dynamic Response
- Absolute Output

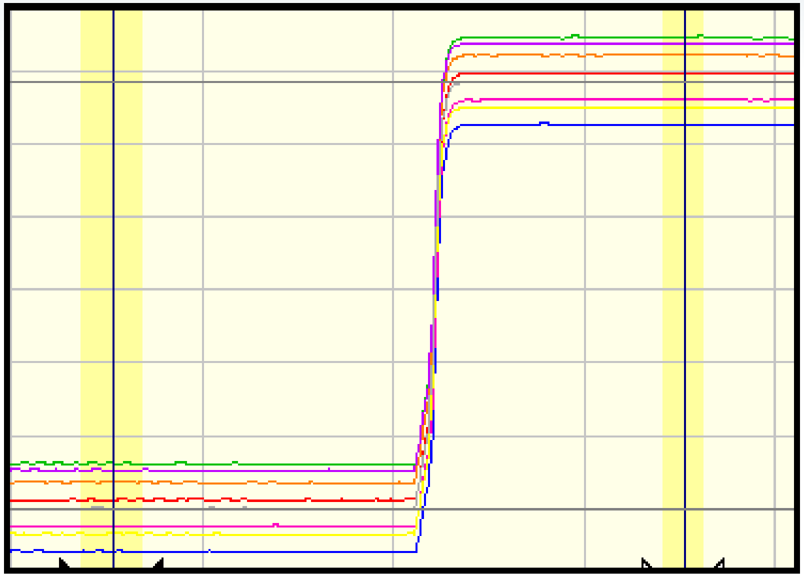




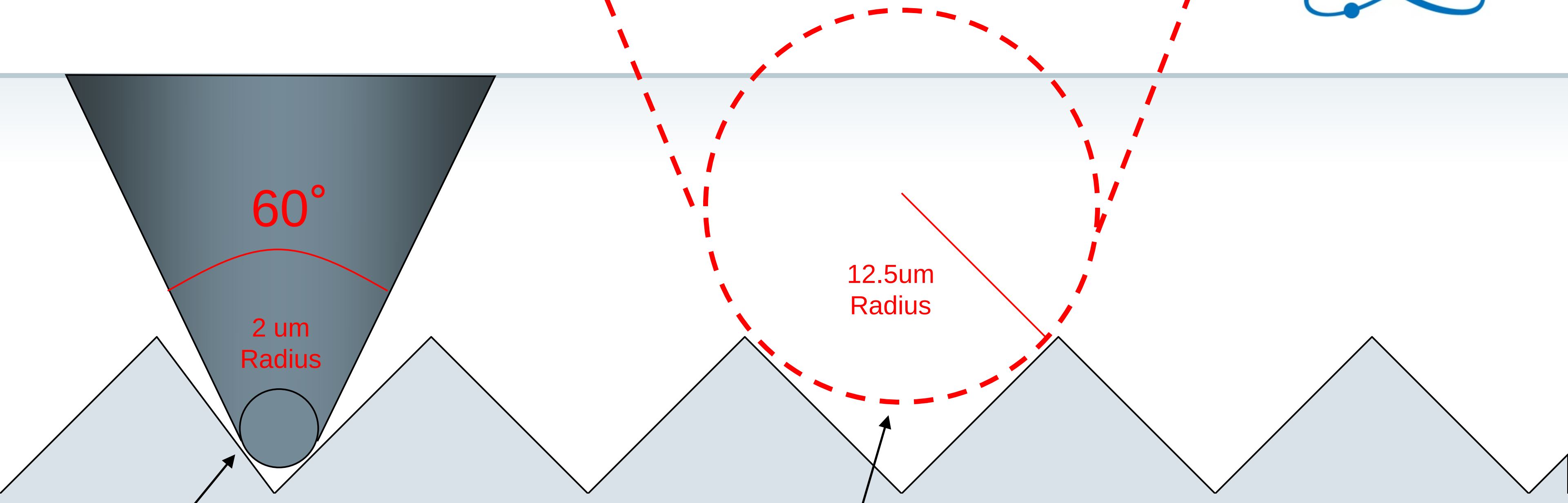
Resolution vs. Repeatability

Repeatability Worth Repeating

- Some stylus profiler companies claim 0.01 Angstrom resolution!
- Repeatability is a more realistic spec that can be proven
- Repeatability is determined by performing 30 scans on a 100nm NIST traceable calibration standard
- Repeatability looks at the standard deviation of the profiler by scanning in the same location on the calibration standard
- For example, the DektakXT can achieve a step height repeatability of better than 5 Angstroms, 6 sigma



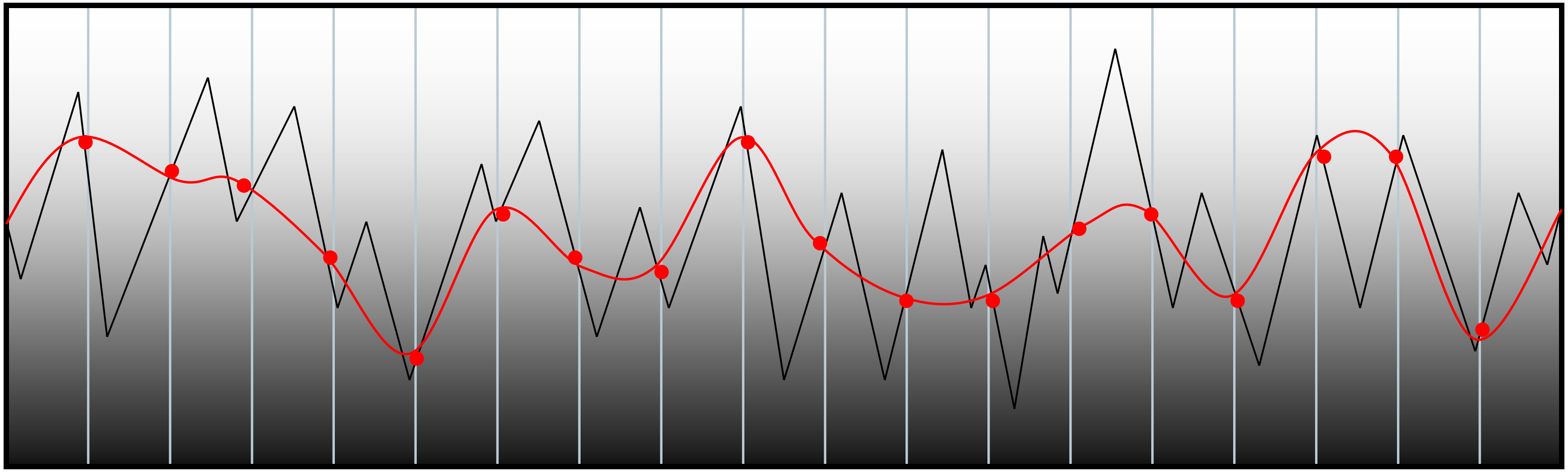
Lateral Resolution: Stylus Size Matters



- 2um radius stylus with 60º cone angle specified for surface texture measurements (ISO & ANSI)
- Larger tips such as 12.5um radius act as a filter to smooth data

- DektakXT offers tips as small as 50nm radius
- High aspect ratio tips also available for narrow trenches

Lateral Resolution: Data Point Density



Scoring Points:

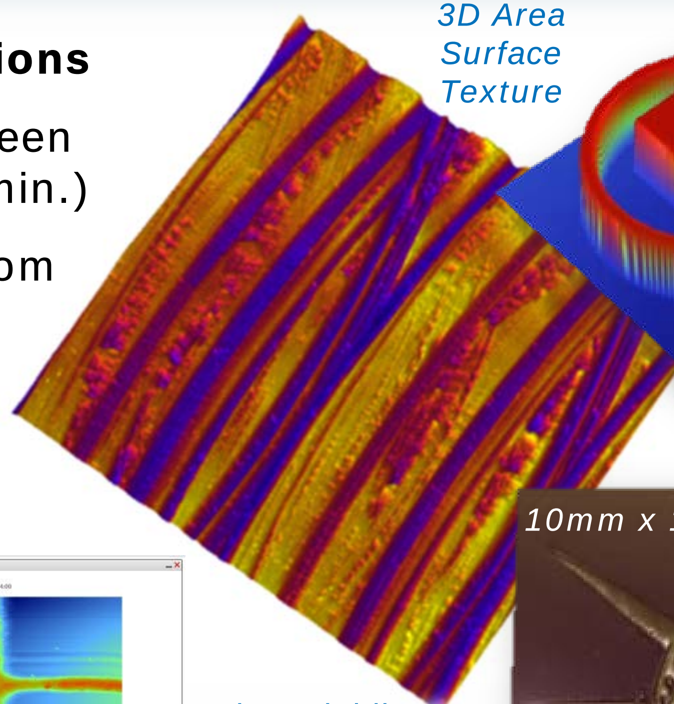
- Too few data points can act to smooth surface profile
- DektakXT offers up to 120,000 data points per scan
- DektakXT maximum data point density = 0.003um/data point

3D Resolution – Its About Time

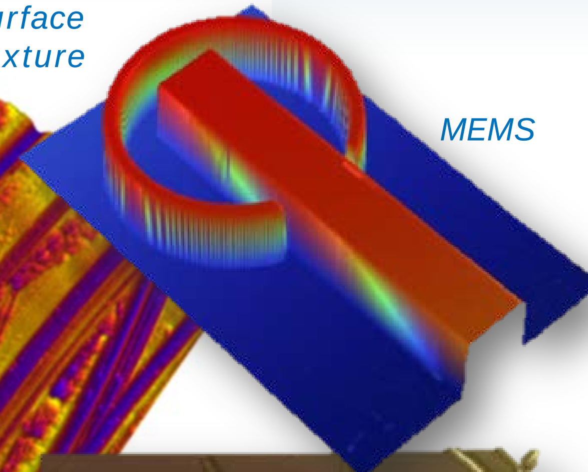
Lateral 3D Resolution Limitations

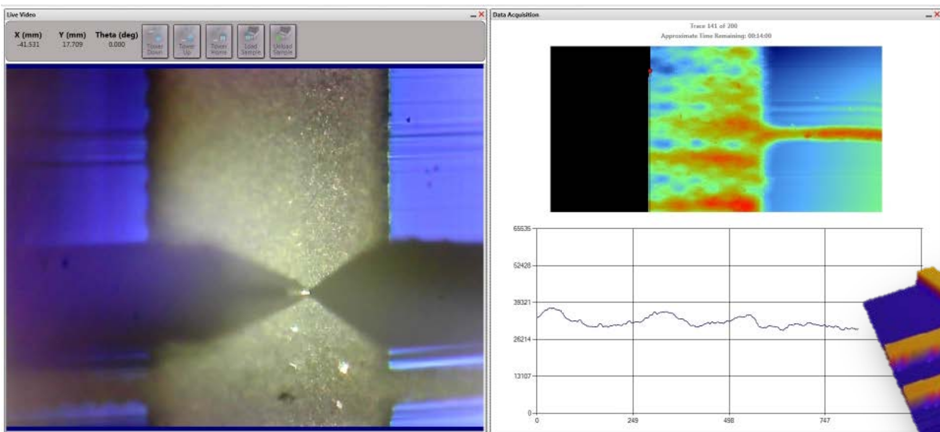
- Depends on the spacing between each individual profile (1um min.)
- 3D maps can be generated from 10 or 10,000 profiles
- High resolution 3D maps can take hours to complete

3D Area Surface Texture



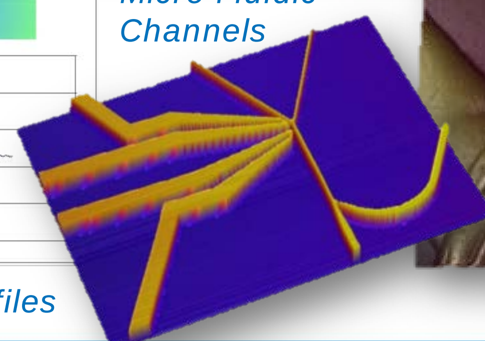
MEMS





3D images created from multiple individual profiles

Micro Fluidic Channels



Large Map Areas

Noise – The Resolution Killer

Improved Resolution Through:

- Lower noise floor achieved with stable sensor support (DektakXT Exclusive Single-Arch design)
- Vibration isolation (built-in)
- “Smart Electronics” establish new low-noise benchmark
- Environmental enclosure design reduces affects of acoustic noise and air currents
- Improved baseline stability by referencing all scans to thermally stable, glass optical flat, polished to Lambda-over-ten (λ/10)

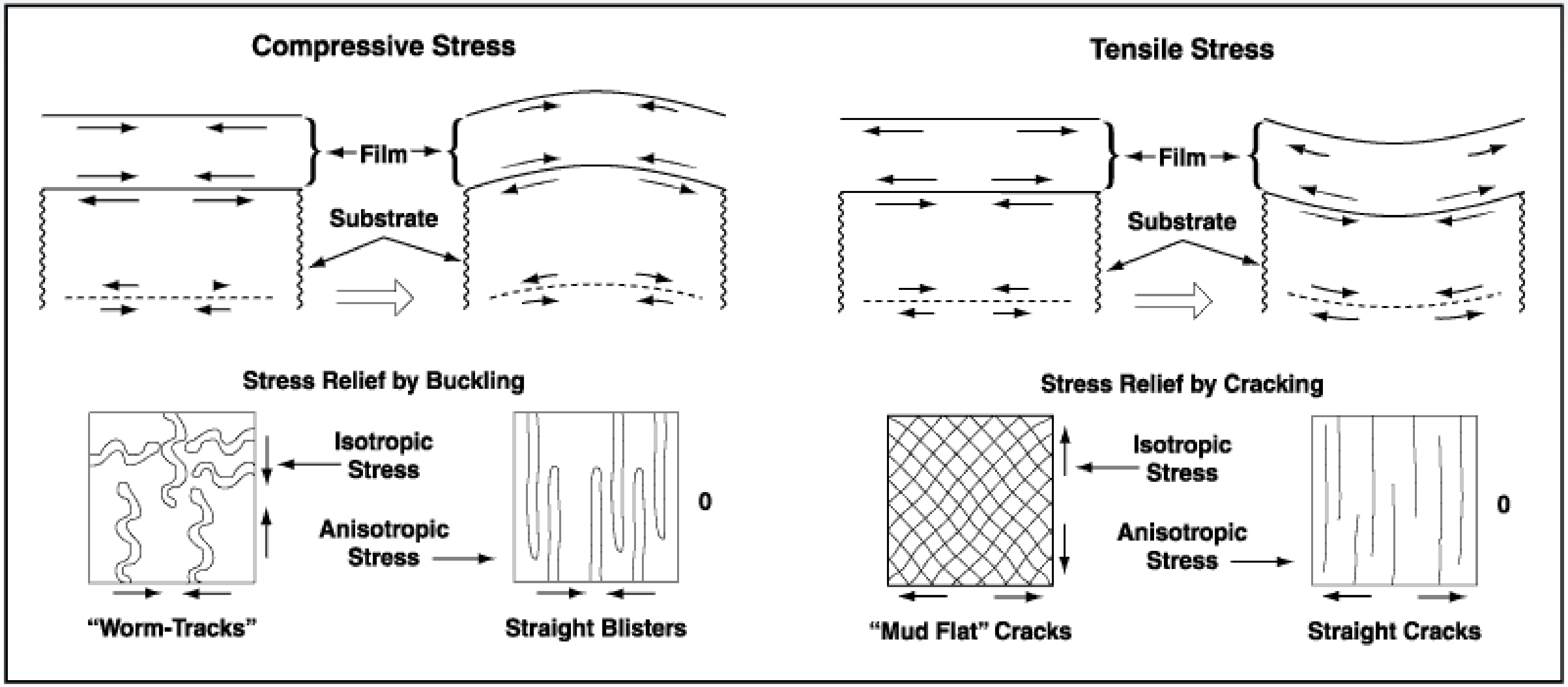
Enables step height repeatability of better than 5 Angstroms!

Built-In Vibration Isolators

Low Noise Single-Arch Support

Environmental Enclosure

Stress – Don’t Stress Over Resolution

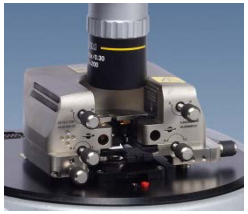


- Stress causes bowing or warping of substrate leading to de-lamination of layers, cracking or lithography problems
- Stylus profilers perform long scans (up to 200mm) before and after deposition to compare wafer bow caused by thin film stress
- Stylus profiler calculates tensile and compressive stress in MPa

Thin Film Measurement Applications

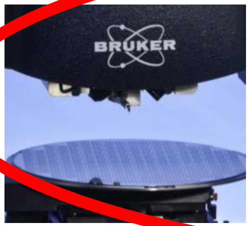
White Light Interferometers

- Dissimilar materials with different refractive index
- Thin films less than 2um become transparent
- Slopes greater than 30°



AFMs

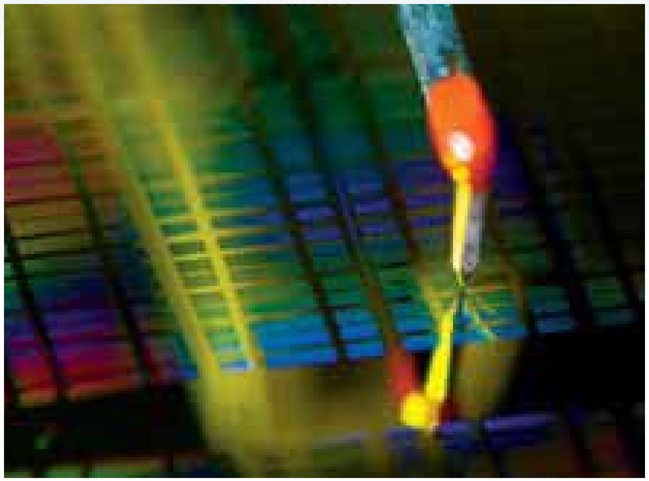
- Vertical range limited to 10 microns
- XY scan range limited to 100 microns
- Results can be operator dependent

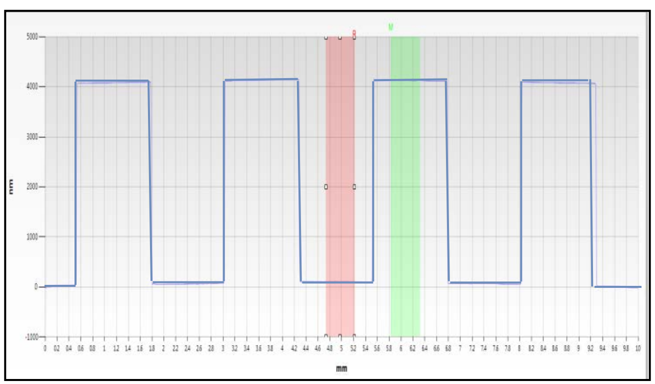


Stylus Profilers

- 3D mapping can be time consuming
- Contact method can damage soft samples
- Resolution can be tip dependent

Advantages of Stylus Profilometry





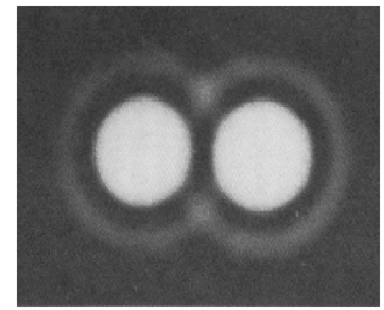
To Monitor Thin Film Deposition:

- Excellent measurement repeatability
- Resolve thin films below 50Å (5nm)
- Thin transparent films or dissimilar optical characteristics
- Long scan measurements up to 200mm to analyze thin film stress
- Ease of use (fast, simple, step heights)
- Lower cost, long life, durable and upgradeable

Resolution in 3D Optical Microscopy

Lateral Resolution of Microscopes Are Determined by the Optics and the Camera

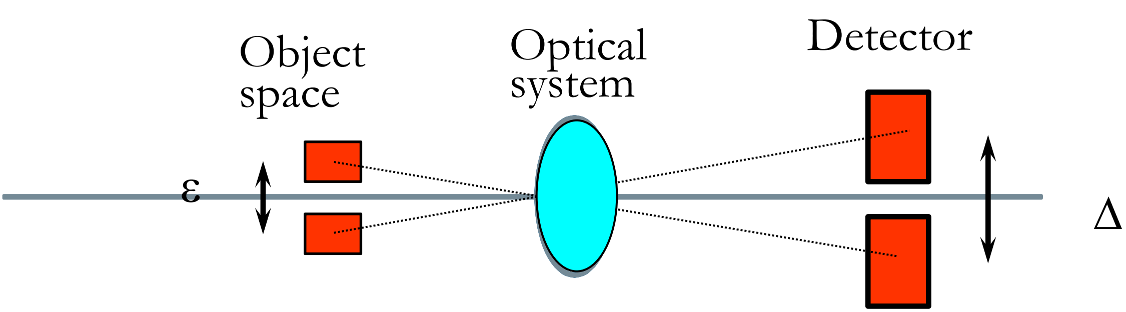
System is called:

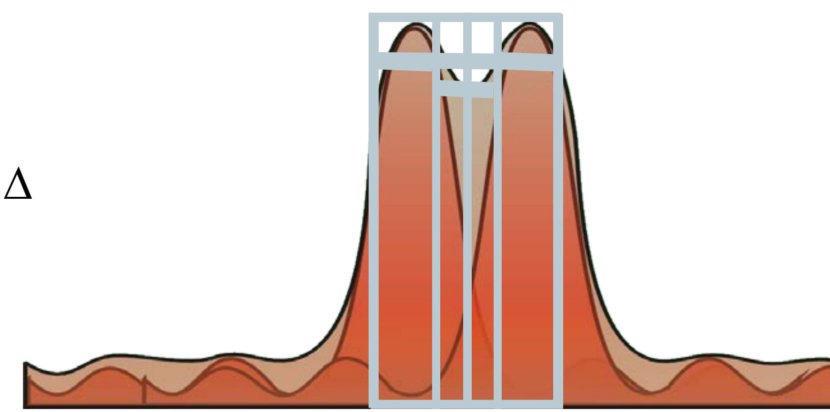


- "**detector limited**" if $\varepsilon >> 0.6\ \lambda / NA$
- "**optics limited**" if $\varepsilon << 0.6\ \lambda / NA$

Effective lateral spatial sampling = $\varepsilon = \Delta / M$

where Δ = pixel spacing & M = magnification





Resolution Limiting Element Changes Depending on the Optics Selected

Objective Magnification	Zoom	High Resolution Camera
2.5X	0.5	
	1	
	2	
5X	0.5	
	1	
	2	
10X	0.5	
	1	
	2	
20X	0.5	
	1	
	2	
50X	0.5	
	1	
	2	
115X	0.5	
	1	
	2	

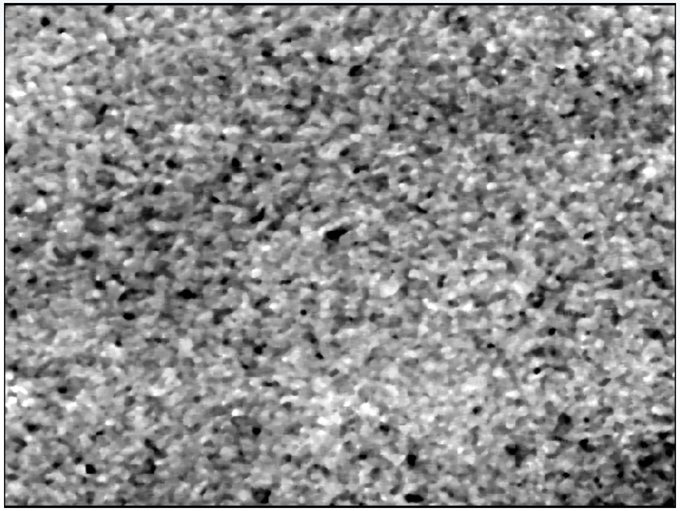
Optics Limited

Camera-Limited

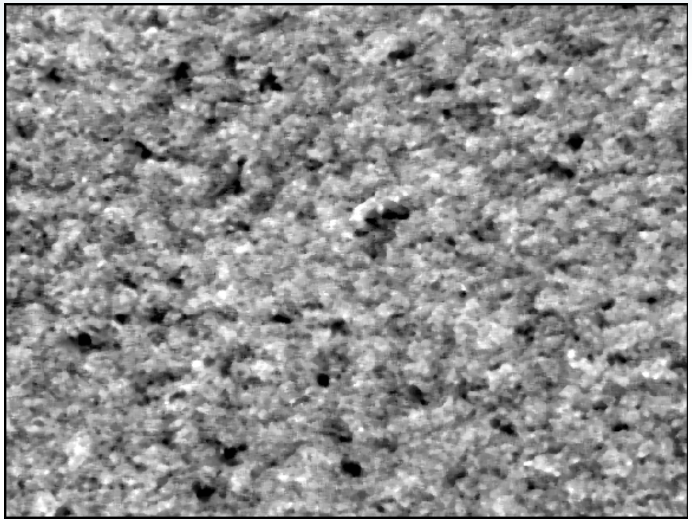
Optics Must Provide the Required Detail and Sampling

Monocrystalline Solar Cell

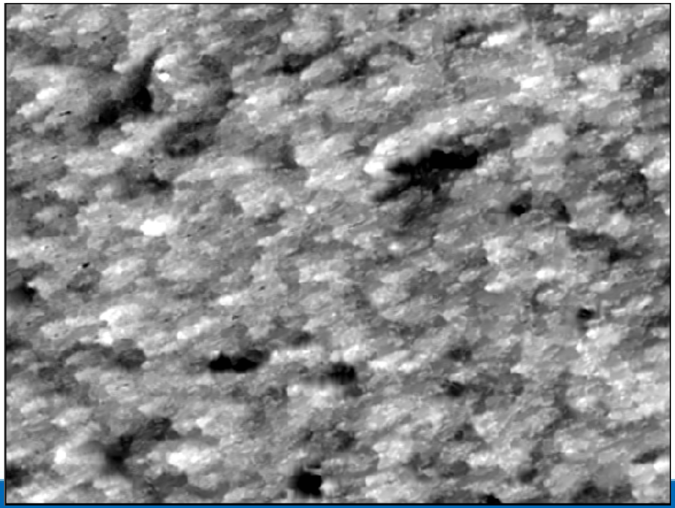
5X



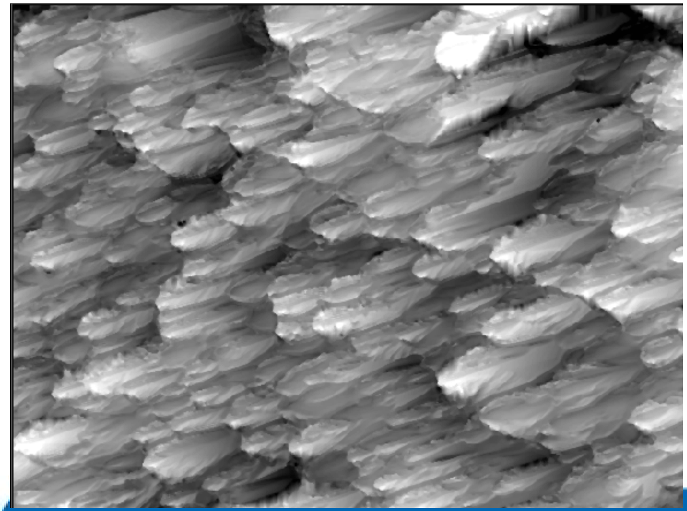
10X



20X

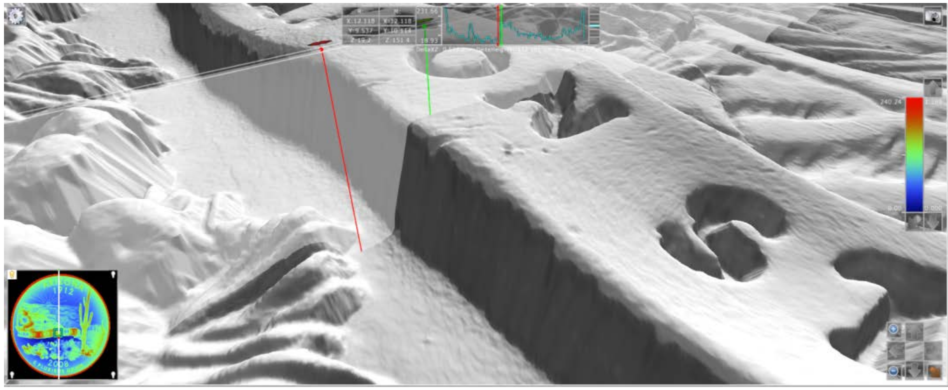


50X



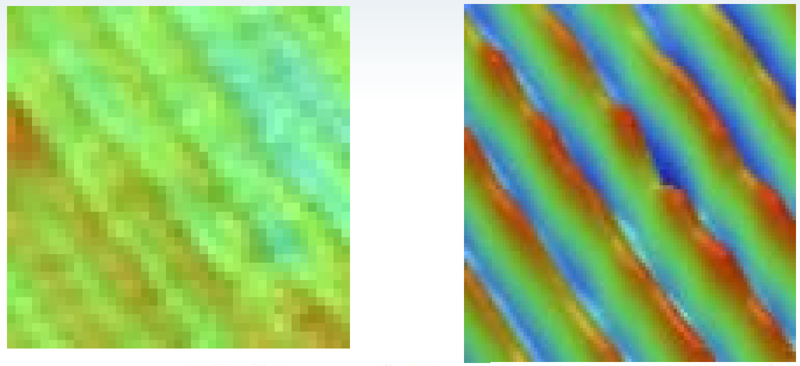
Stitching Allows Large Areas to be Measured at High Resolution

- 64 bit architecture allows thousands of files to be stitched together
- Each measurement overlaps its neighbors so that alignment can be achieved
- Errors of just a few nm are typically observed in stitched datasets
- For ultra-smooth surfaces, averaging and subtraction of systematic errors are key considerations

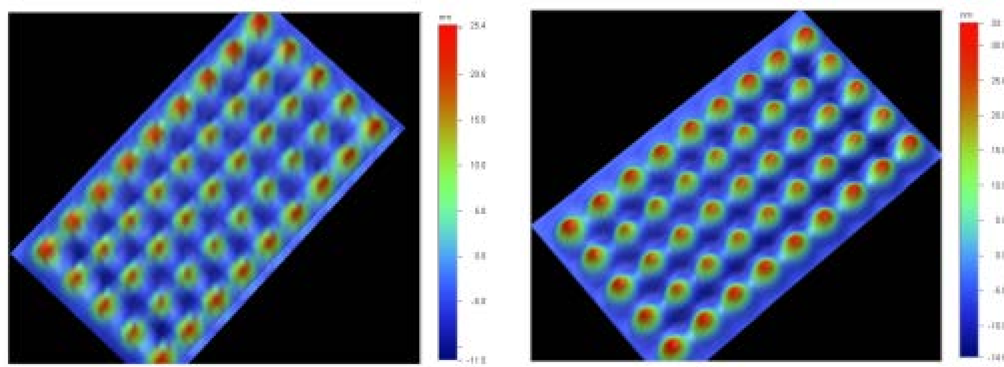


Specialized Measurements Employing Modeling Such as AcuityXR Can Improve Resolution

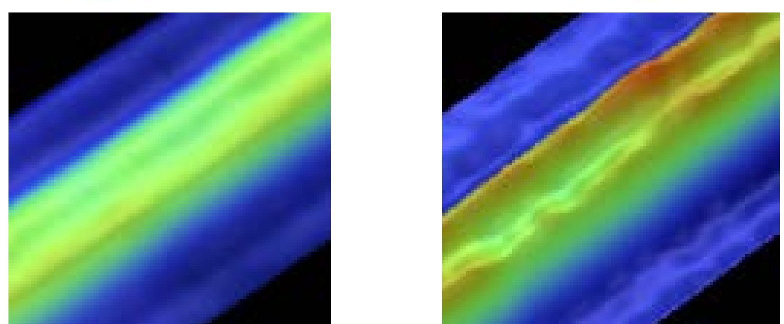
- **200nm grating**



- **5 µm semiconductor features**



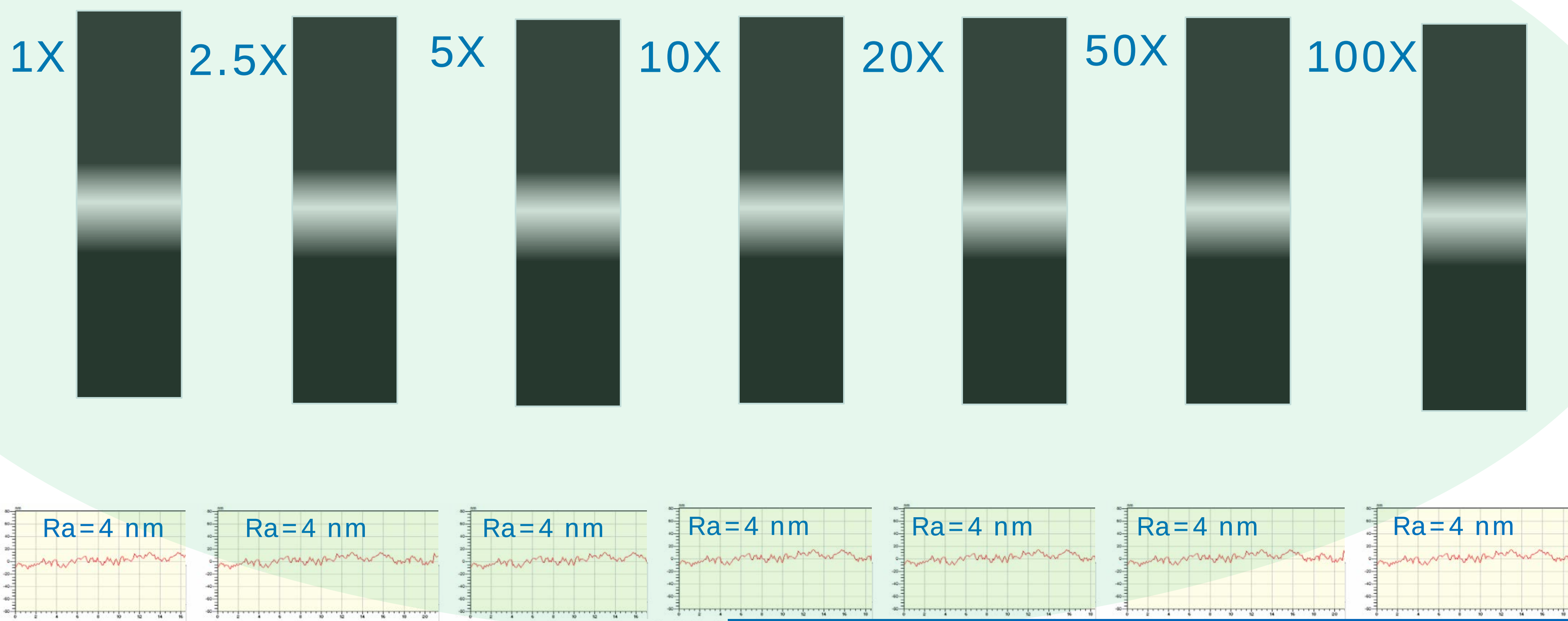
- **150nm line pair**



3D Interferometric Microscopes Always Provide Same Good Signal: Low noise, best roughness detection

- *Plots below show the signal used to determine the surface for a line of pixels as you go through focus.*
- *Signal is unchanged no matter the magnification.*

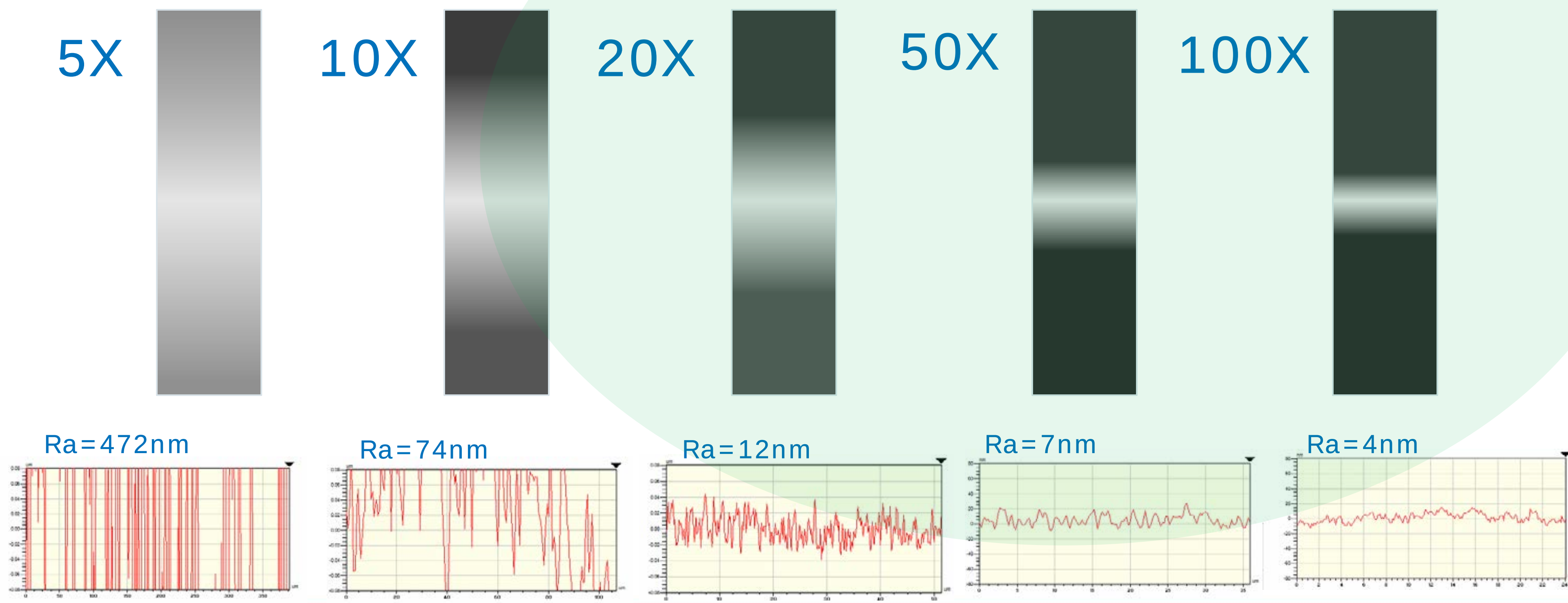
Any objective can be used for measurement



3D Confocal Microscopes Always Provide Variable Signal: Higher Noise at Lower Magnifications

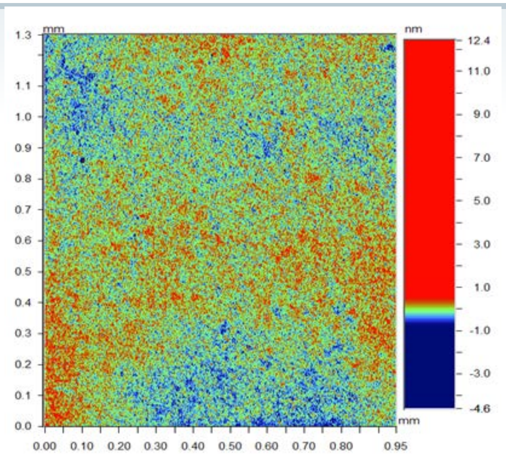
- *Plots below show the signal used to determine the surface for a line of pixels as you go through focus.*
- *Signal changes drastically with the magnification.*

Only a few objectives usable for measurement

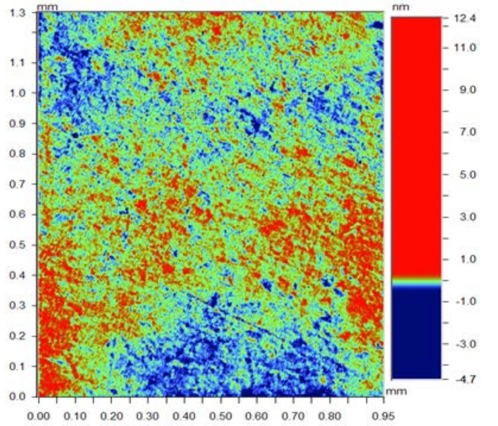


Optimizing Resolution is a Balancing Game

- Many Tradeoffs
  - Setup complexity
    - Reference subtraction
    - Alignments
    - Fixturing
  - Measurement time
    - Scan speed
    - Averaging
    - Sample spacing and field of view
  - Data processing choices
    - Filter selection
    - Data interpolation
  - Analysis results
    - How many calculations?
    - How is a part pass/failed?



0.5 seconds - .5nm noise floor



10 seconds - .02nm noise floor

How to Achieve the Resolution You Need

- AFM: Highest lateral resolution with multiple modes and applications
- 3D Microscopes: Highest Z resolution, non-contact high-speed 3D measurements
- Stylus: High Z with excel ... ment repeatability

Atomic Force Microscopy
Nanoscale characterization of electrical, magnetic, compositional and material properties

C ... g
N ... rement of
s ... ghness

Stylus Profiling
Measure thin film step heights, stress and surface texture

Questions?

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