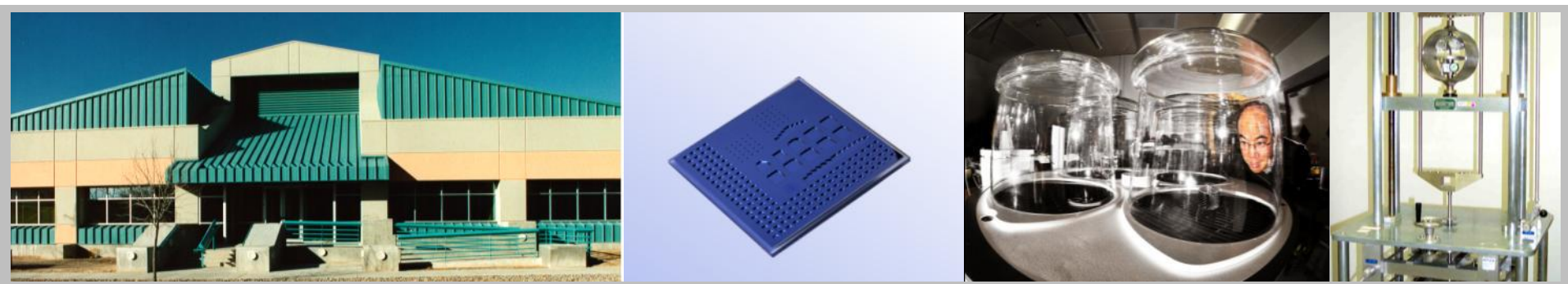


Exceptional service in the national interest



Calibration of Sinusoid Reference Standards Using a Coherence Scanning Interferometer

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Sandia National Laboratories
Primary Physical Standards
July 17, 2013



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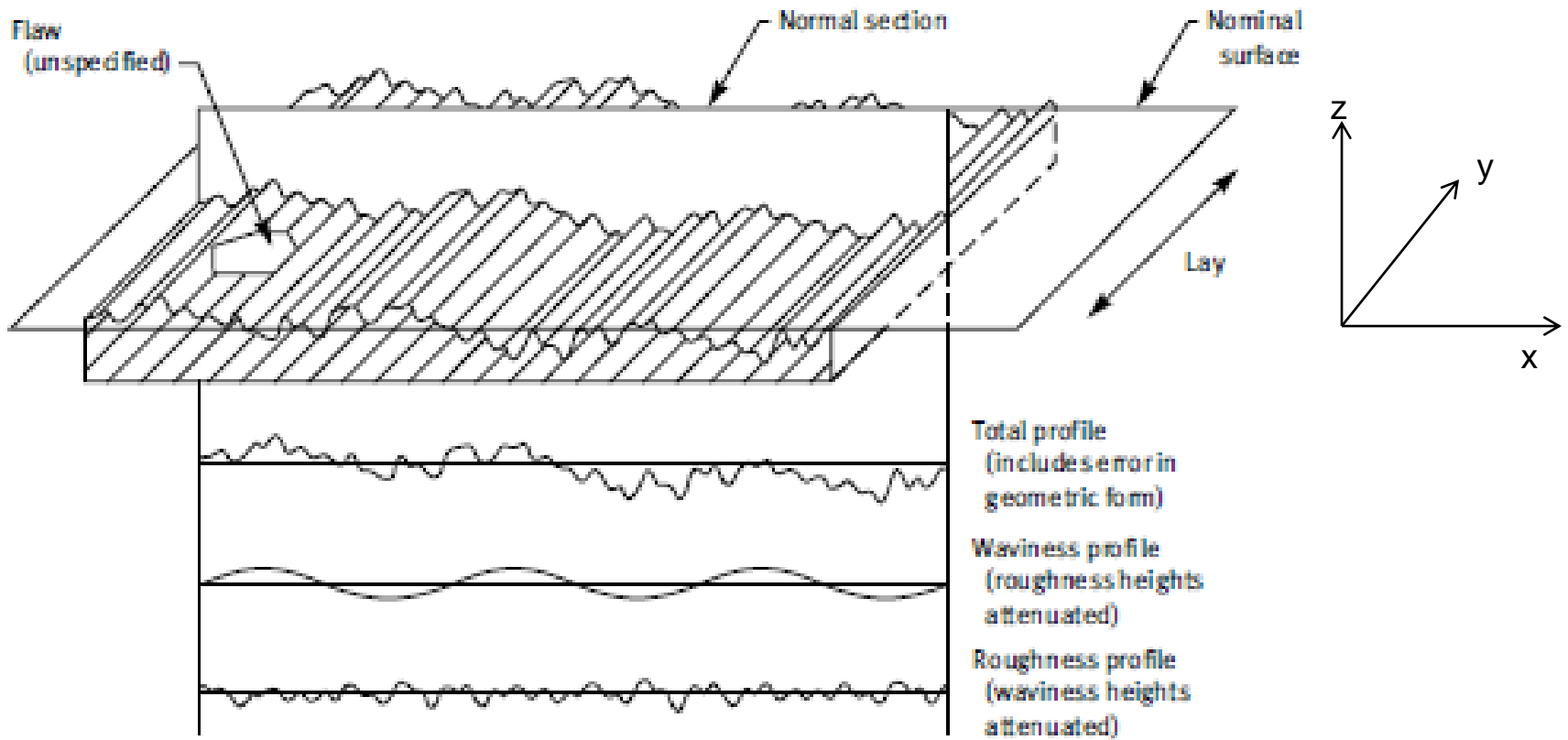
Objectives

- Surface texture, roughness, waviness, and lay
 - Why do we care?
- What are some of the existing standards, and how is texture generally measured?
- How do we calibrate instruments for measuring these characteristics? (How should we make calibrated measurements?)
- How do we calibrate optical instruments?
- What are some of the contributing factors to measurement uncertainty?
- Past work with the coherence scanning interferometer
- Calibration of a sinusoid/triangular/square wave standards on a coherence scanning interferometer

Why do we care?

- Surface texture and topography affect:
 - Wear and friction (sliding surfaces)
 - Electrical and thermal conductivity (contacts)
 - Corrosion properties
 - Fatigue (stress concentrators on surface)
 - Cost (excess cost to make a surface better than it needs to be, or costs due to poor product quality because surface properties were inadequately manufactured or specified)
 - Measurement (especially form: More difficult to meet a tight form requirement if you have too much topography)
 - O-ring seals (be careful if you specify too good a surface finish! Some seal designs actually require that your roughness is in a range between a minimum and maximum value!)
 - etc.

Surface texture, roughness, waviness, and lay



From ASME B46.1:2009

List of published standards

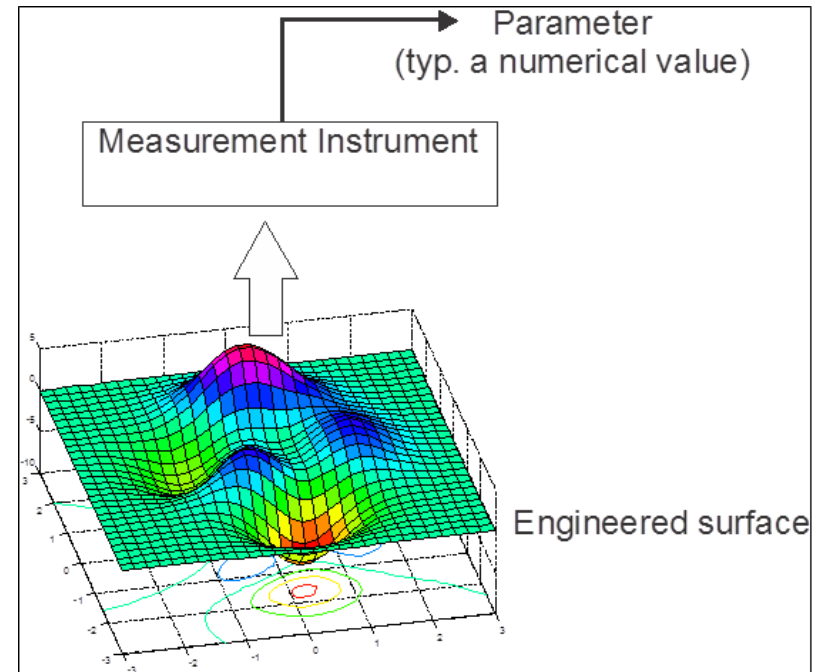
Standard number	Short title (GPS→Geometrical Product Specifications)
ASME Y14.36M:1996	Surface texture symbols
ASME Y14.5:2009	Dimensioning and Tolerancing
ASME B46.1:2009	Surface Texture (Surface Roughness, Waviness, and Lay)
ISO 1302:2002	GPS-Surface texture-Indication of texture in product documentation
ISO 4287:1997	GPS-Surface texture-Profile method-terms, definitions...
ISO 4288:1996	GPS-Surface texture-Profile method-Rules and procedures
ISO 5436-1:2000	GPS-Surface texture-Profile method-measurement stds
ISO 5436-2:2000	GPS-Surface texture-Profile method-software
ISO 8785:1998	GPS-Surface imperfections-terms, definitions ...
ISO 12085:1996	GPS-Surface texture-Profile method-Motif parameters
ISO 12179:2000	GPS-Surface texture-Profile method-Calibration of stylus instruments
ISO 13565-1:1996	GPS-Surface texture-Profile method-stratified functional-filtering
ISO 13565-2:1996	GPS-Surface texture-Profile method-stratified functional-height ratio
ISO 13565-3:1996	GPS-Surface texture-Profile method-stratified functional-material prob
ISO 16610-1:2006	GPS-Filtration-overview
ISO 16610-20:2006	GPS-Filtration-linear filters-basic concepts
ISO 16610-21:2011	GPS-Filtration-linear filters-Gaussian filters
ISO 16610-22:2006	GPS-Filtration-linear filters-Spline filters
ISO 16610-28:2010	GPS-Filtration-linear filters-end effects
ISO 16610-30:2009	GPS-Filtration-Robust profile-basic concepts
ISO 16610-31:2010	GPS-Filtration-Robust profile-Gaussian regression
ISO 16610-32:2009	GPS-Filtration-Robust profile-Spline
ISO 16610-40:2006	GPS-Filtration-Morphological-basic concepts
ISO 16610-41:2006	GPS-Filtration-Morphological-Disk and horizontal line segment filters
ISO 16610-49:2006	GPS-Filtration-Morphological-Scale space techniques
ISO 25178-2:2012	GPS-Surface texture-Areal-Terms, definitions
ISO 25178-6:2010	GPS-Surface texture-Areal-Classification of methods
ISO 25178-601:2010	GPS-Surface texture-Areal-characteristics of stylus instruments
ISO 25178-602:2010	GPS-Surface texture-Areal-characteristics of confocal chromatic probe
ISO 25178-701:2010	GPS-Surface texture-Areal-Calibration and standards for stylus instr.

Measurement methods

- Visual/tactile inspection
 - Not recommended
- Stylus based equipment
 - Portable, shop floor
 - Benchtop
- Non-contact
 - Optical “stylus”
 - Scanning microscopy (including confocal, point autofocus, etc)
 - Scanning laser triangulation
 - Areal image
 - Focus variation
 - Scanning white light interferometry

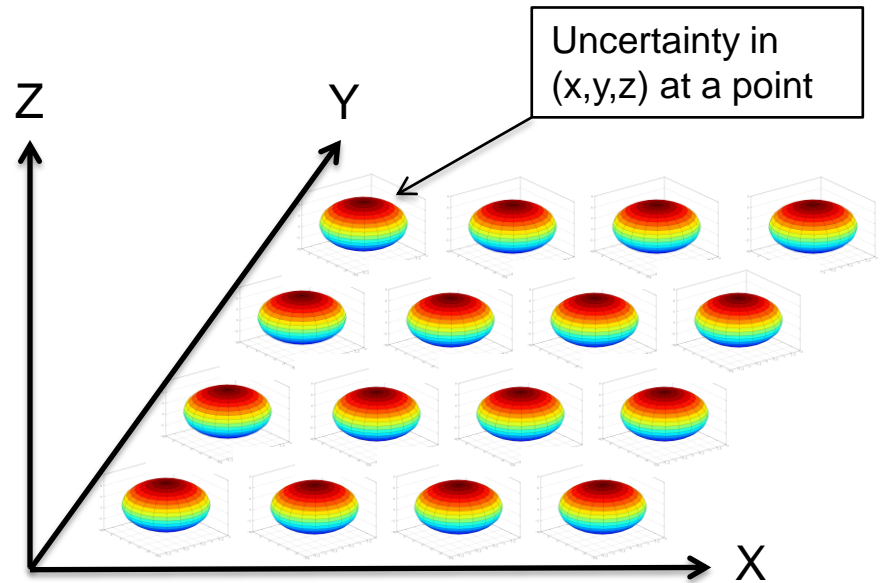
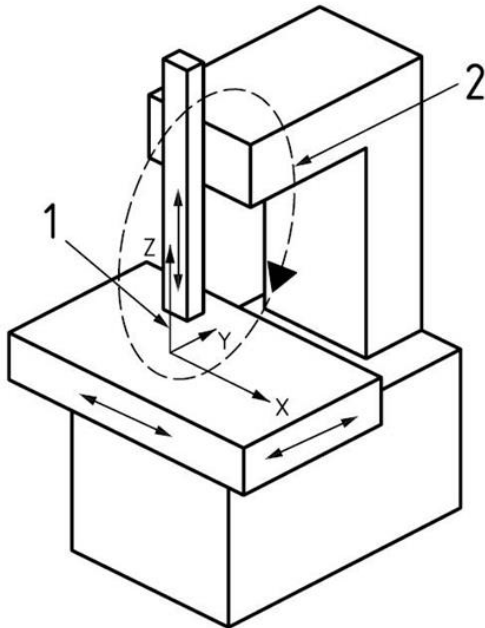
Measuring surface texture

- Instruments measure points (coordinates) on surface, and convert a set of points into a single numerical parameter
- Parameter has some correlation with a functional characteristic (design intent for texture)



Instruments collect point data

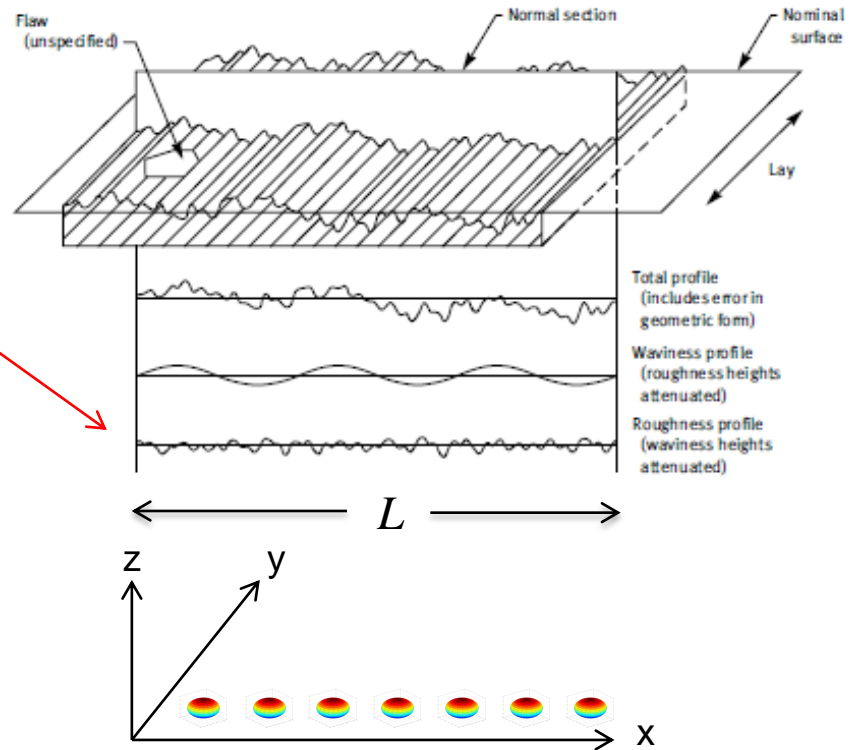
- Instrument measures points on surface
- Instrument is anisotropic (typically much better resolution in z than x and y)
- Mathematical operations performed to obtain parameter



Ra (Roughness average)

- ASME B46.1 Ra (aka arithmetic average, centerline average) is one of the oldest quantitative surface texture standards

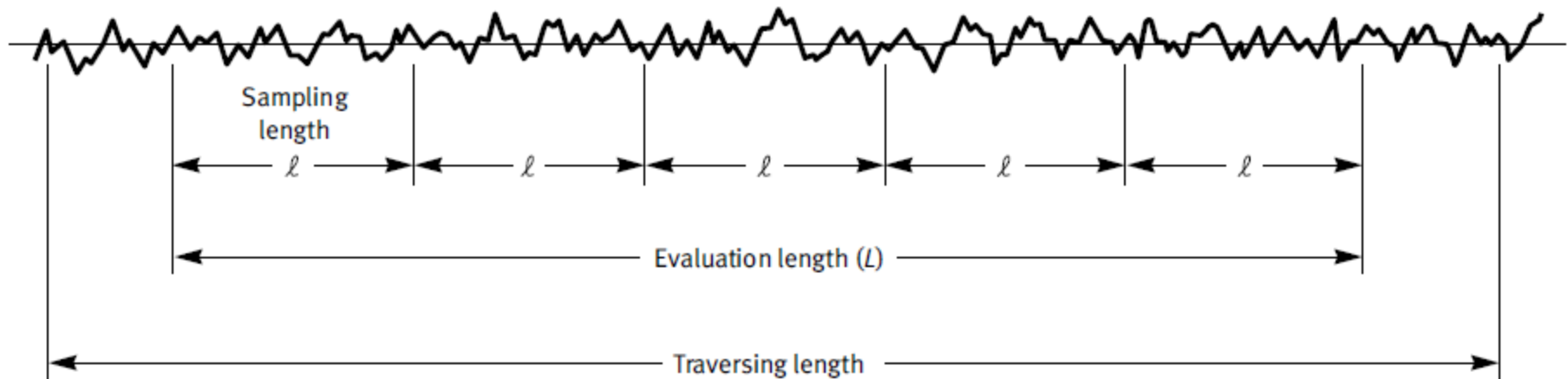
$$Ra = \frac{1}{L} \int_0^L |z(x)| dx$$



Parameters for the parameters

- Ra (and other parameters) are defined over a length “L”
- Other parameters for calculation are generally prescribed (for example, how to filter to separate profile from waviness, etc.)

Fig. 1-7 Surface Profile Measurement Lengths



How do you calibrate surface texture instruments?

- Instruments measure z and x , but also perform filtering and other (sometimes fairly complicated) mathematical operations
- Calibration of z
- NPL “Good Prac”
 - Calibrated “ z ” (standard)
 - Means of checking z artifact (unless you have another means of checking linearity. Stylus check specimens should not be used for this purpose. If the R_a measurement on either specimen differs by more than 10% of the calibrated value, instrument recalibration is required. For additional system
- Note that uncertainty requirements are not spelled out
- Analysis suggests that the z -direction measurement is the most critical for getting good results in measuring surface texture

4-4.8 Instrument Accuracy. The R_a indication of an instrument to a sinusoidal mechanical input of known amplitude and frequency within the amplitude and the cutoff range of the instrument shall not deviate by more than $\pm 7\%$ from the true R_a value of the input.

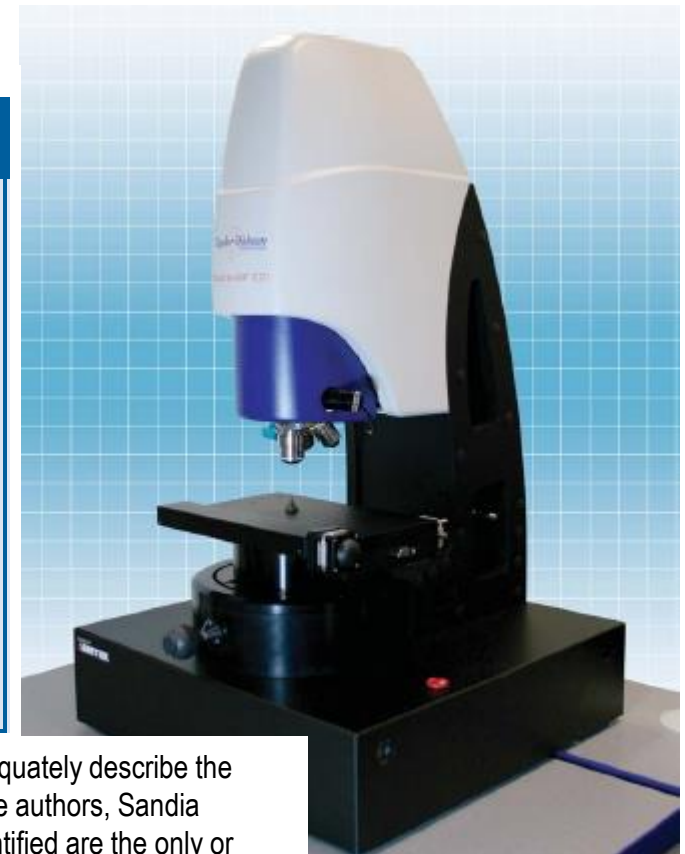
From ASME B46.1:2009

Let's focus on non-contact for sinusoids (type C reference stds)

- Limited to areal image, “scanning white light interferometry”
 - Most instruments nowadays are “coherence scanning”
 - Example: Taylor-Hobson CCI-Lite

Talysurf CCI Lite System Specifications

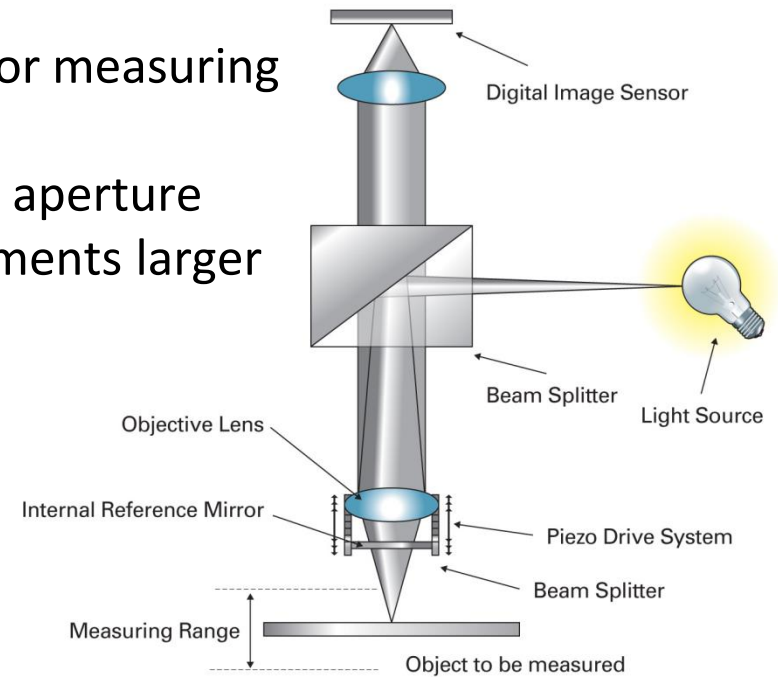
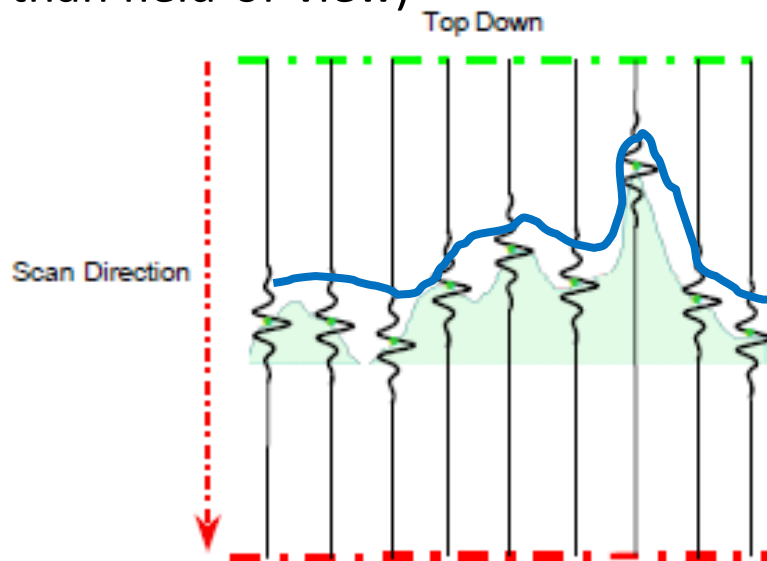
Measurement technique	Coherence Correlation Interferometry
Vertical range (Z)	2.2 mm as standard (>10 mm with Z-stitching)
Vertical resolution (max)	0.01 nm (0.1 Å)
Noise floor (Z)	<0.08 nm (0.8 Å) ¹
Repeatability of surface RMS (Z)	<0.02 nm (0.2 Å) ²
Max. Measurement area (X, Y)	6.6 mm (>75 mm with X, Y stitching)
Number of measurement points	1024 x 1024 standard
Optical resolution (X, Y)	0.4 - 0.6µm (surface dependent)
Step height repeatability	<0.1%
Surface reflectivity	0.3% - 100%
Measurement time	5-40 seconds (typical)



Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the authors, Sandia National Laboratories, or NCSL International, nor does it imply that the materials or equipment identified are the only or best available for the purpose.

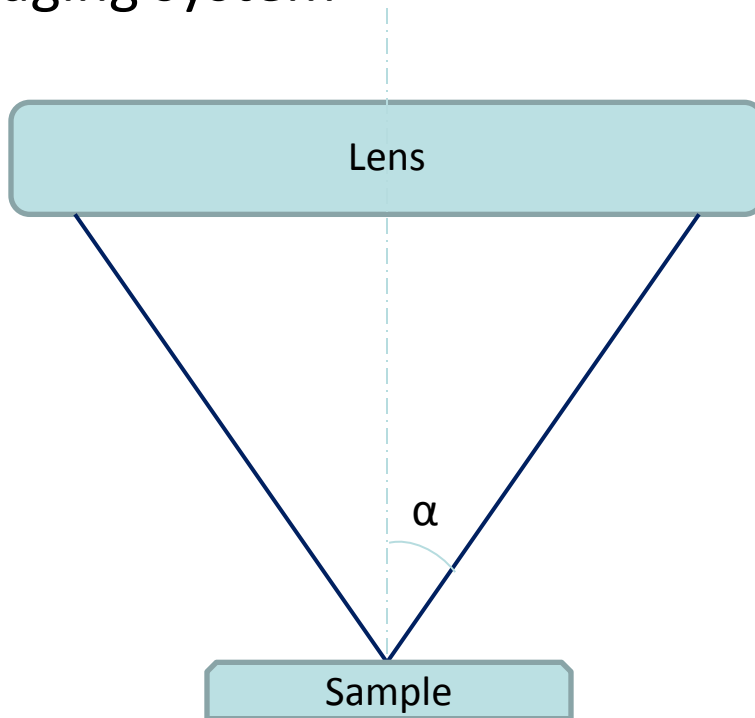
Coherence Scanning Operating Principles

- Measures vertical (z) features
- x,y (lateral) are like conventional microscope (image/pixel)
- Resolves vertical to 0.1 nm (or better)
- Software (both embedded and workflow) for measuring and analyzing surface geometry map
- Slope limitation due to objective numerical aperture
- Computer control for “stitching” (measurements larger than field-of-view)



Numerical Aperture

- The numerical aperture (NA) designates the spread of angles over which light illuminates a sample and the spread of angles over which light is accepted by the objective of the optical imaging system

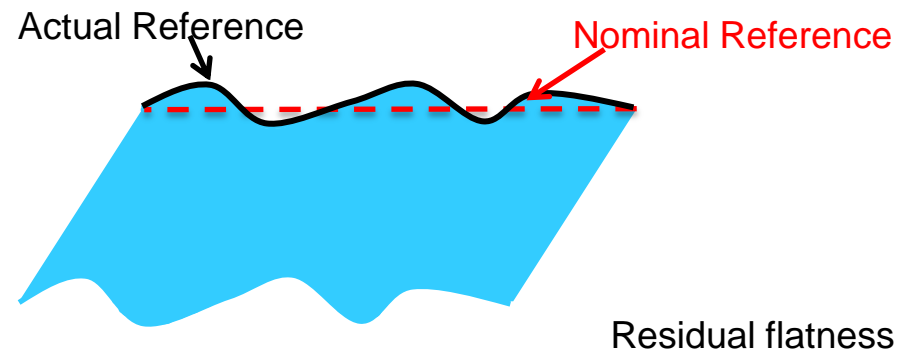
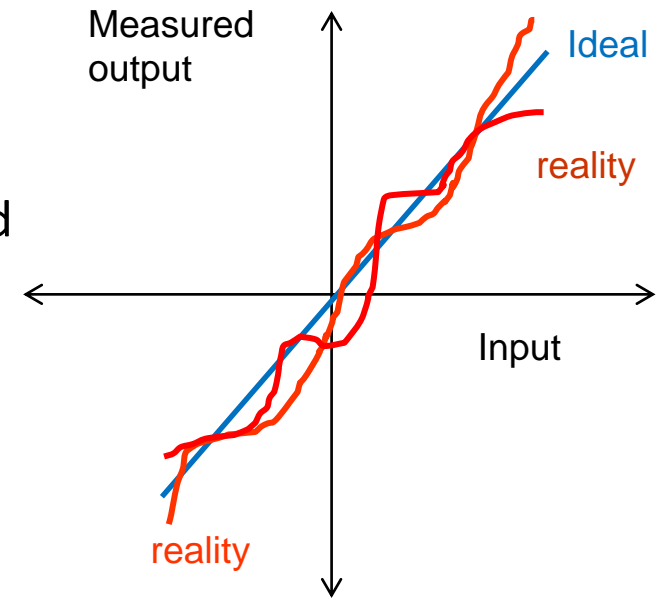


$$NA = n \sin \alpha$$

Lens	NA	α
10X	0.30	17°
20X	0.40	24°
50X	0.55	33°

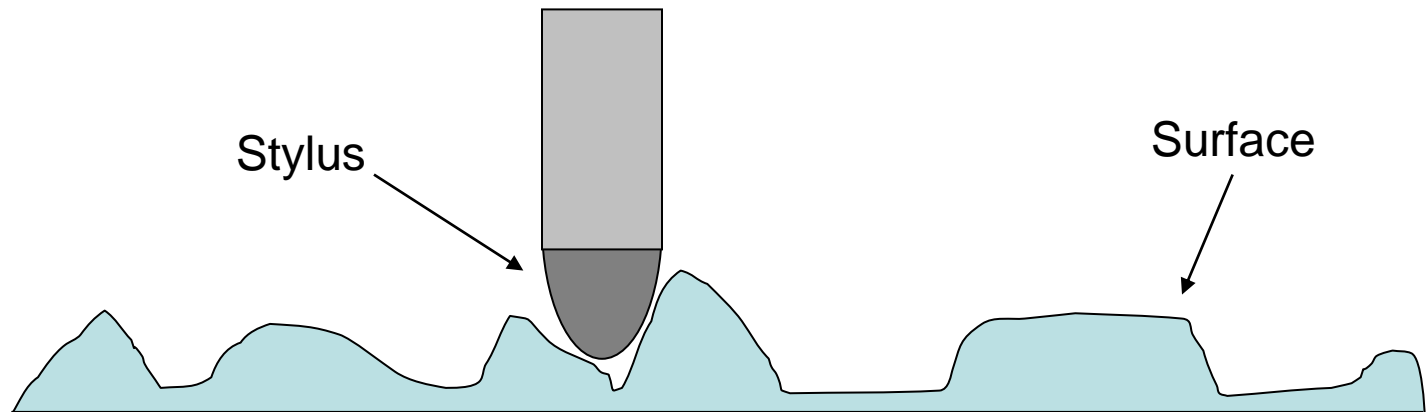
How do you calibrate optical (and stylus) instruments?

- Calibration of optical instrument:
 - Establish x,y,z output vs. reference standard
 - Establish orthogonality of the axes
 - Verify functionality
- Metrological characteristics
 - Amplification coefficients
 - Linearity deviation
 - Residual flatness
 - Measurement noise
 - Lateral period limit
 - Perpendicularity



Micro-Roughness

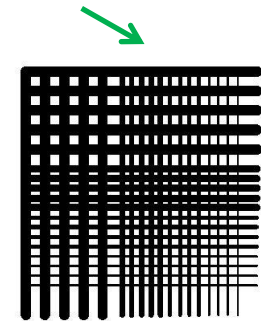
- The radius of the stylus tip for stylus instruments acts as a low-pass filter
- Optical instruments do not filter out micro-roughness automatically since they are non-contact, but Sparrow limit acts as a micro-roughness filter



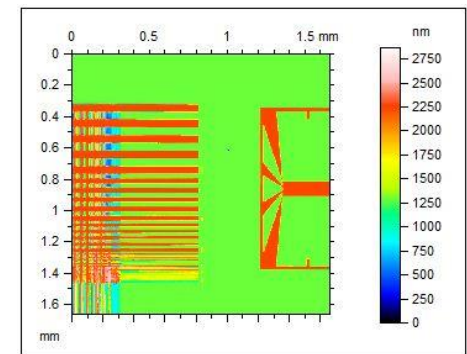
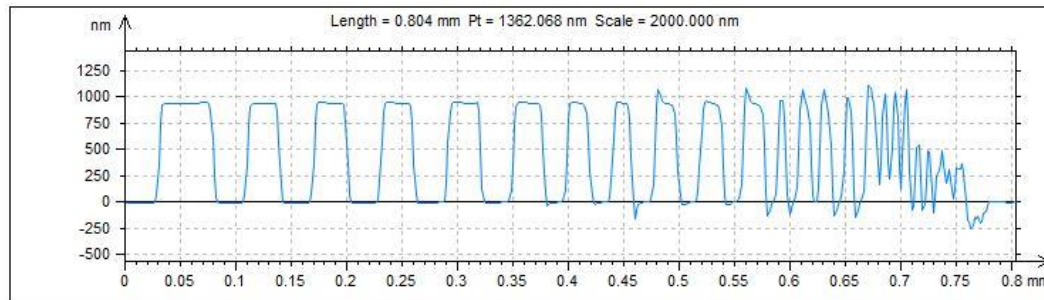
Lateral Period Limit

- The spatial or lateral resolution of a surface topography measuring instrument and its ability to distinguish and measure closely spaced surface features

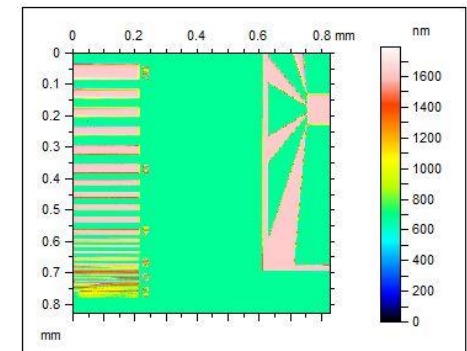
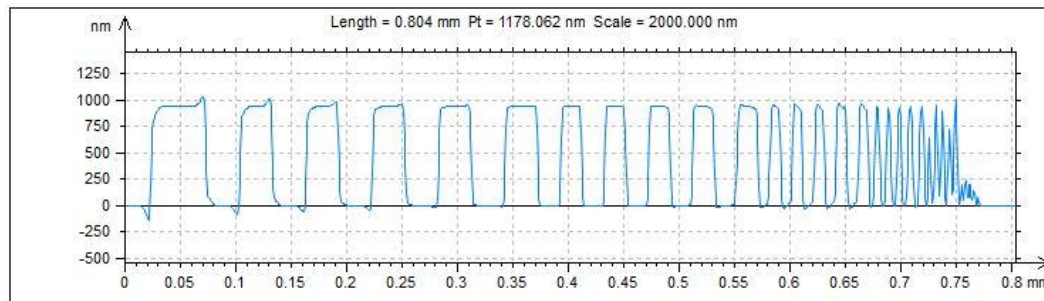
Incremental Pitch Area



10X



20X



Measurement uncertainties

- Uncertainties of what? Suppose R_a ?

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

- ISO GUM:

- y (measurand) = $f(x_1, x_2, x_3, \dots, x_n)$
- Type A (statistical data) + Type B
- partial derivatives, etc.

$$u_{R_a} = \left(\left(\frac{\partial R_a}{\partial L} \right)^2 u_L^2 + \left(\frac{\partial R_a}{\partial z} \right)^2 u_z^2 + \left(\frac{\partial R_a}{\partial x} \right)^2 u_x^2 \right)^{\frac{1}{2}}$$

- Just for R_a :

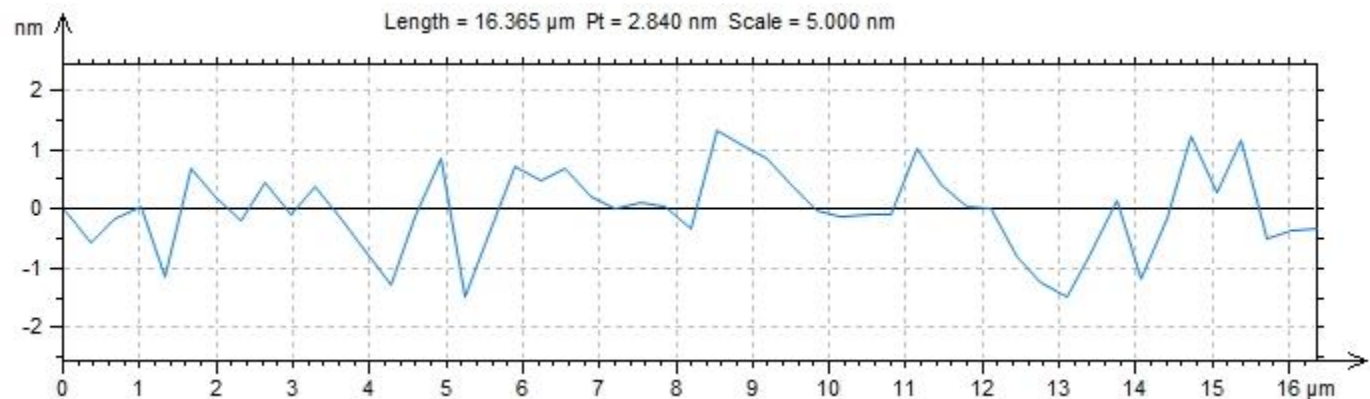
- λ_s Filter (mechanical? optical? signal processing?) uncertainty from filtering?
- λ_c Filter (electrical? signal processing?) uncertainty from filtering?
- Uncertainty in x direction measurement
- Uncertainty in z direction measurement
 - Effect of leveling the mean line?
 - Effect of lay direction?
- Uncertainty in mathematical algorithm for integral?

- Mathematical estimate of measurement uncertainty following GUM is complicated!

Measurement equation; uncertainty for z

- use calibrated step height (CV) to calibrate vertical scale (measure MV, calculate scale factor SF $SF = \frac{CV}{MV}$)
- measure UUT (measurement m).
- Calibrated value of z of UUT is: $z = m \times SF$

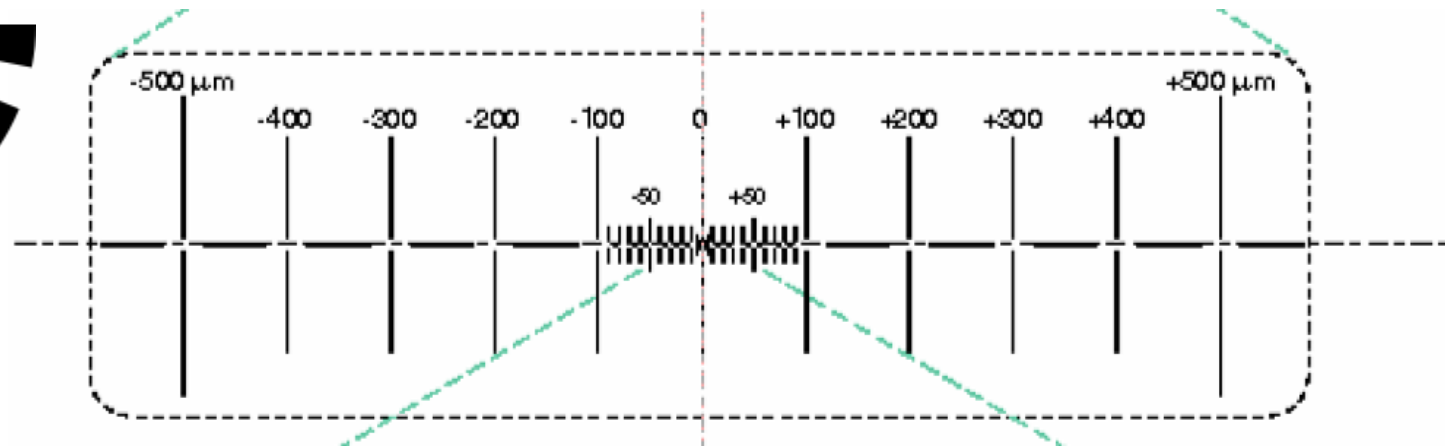
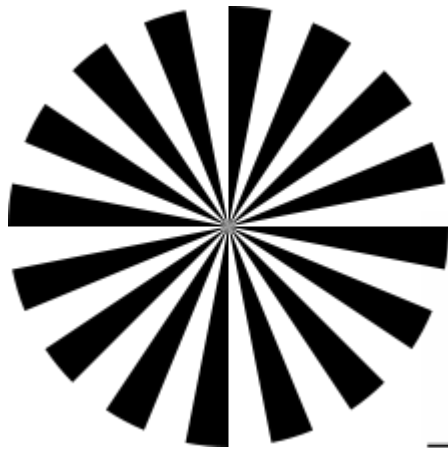
- Uncertainties: $u_z = \left[\left(\frac{\partial z}{\partial m} u_m \right)^2 + \left(\frac{\partial z}{\partial SF} u_{SF} \right)^2 \right]^{1/2}$



Non-linearity & non-uniformity study

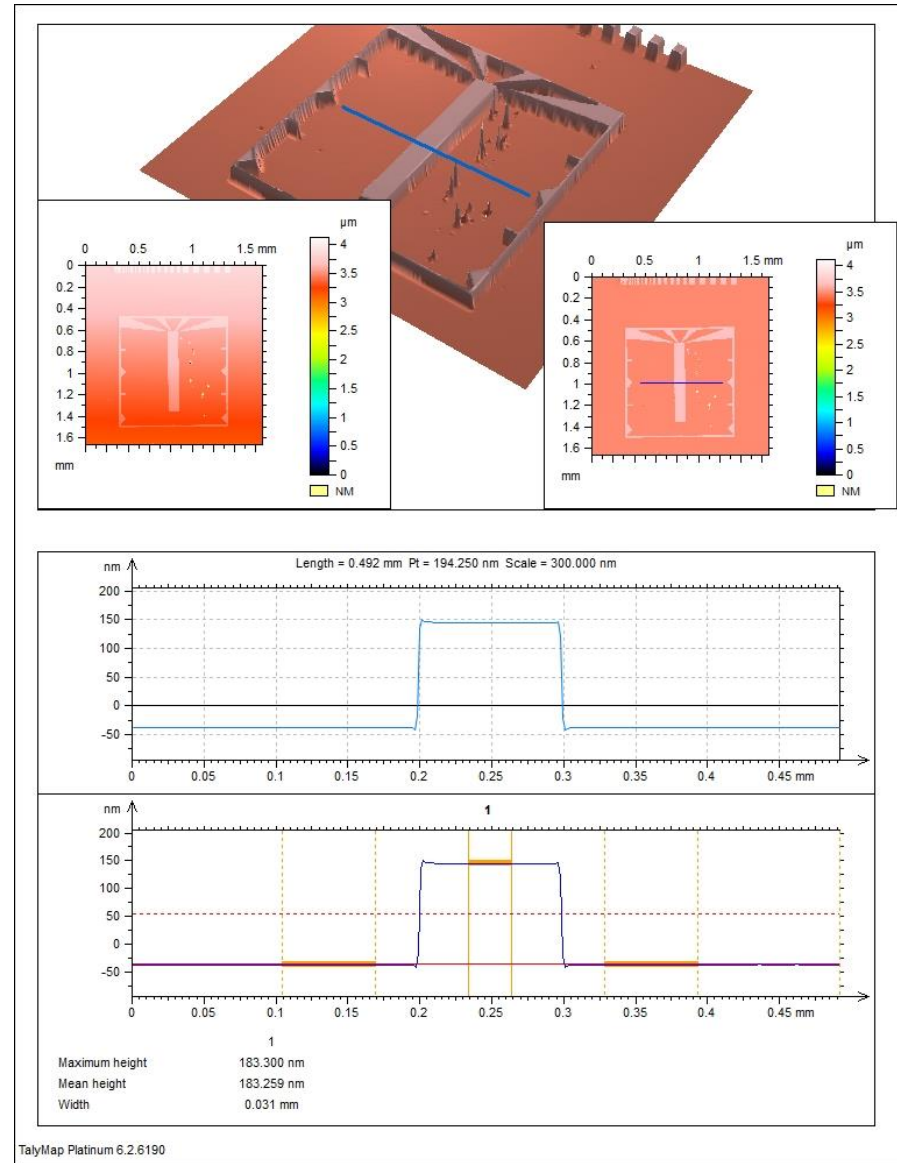
Calibration of x,y, orthogonality, etc. Sandia National Laboratories

- Stage micrometer; also use multiple orientations
- Siemens star for resolution (lateral period)
- What about mathematical operations & software?

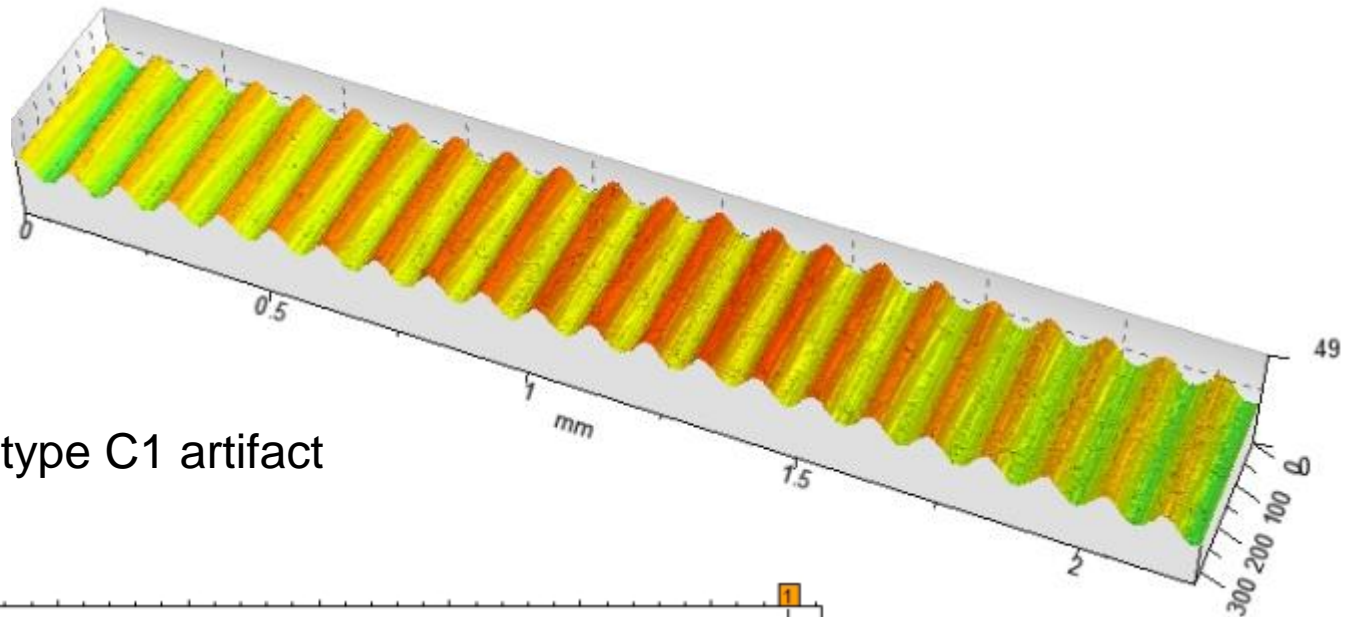


Typical measurement process

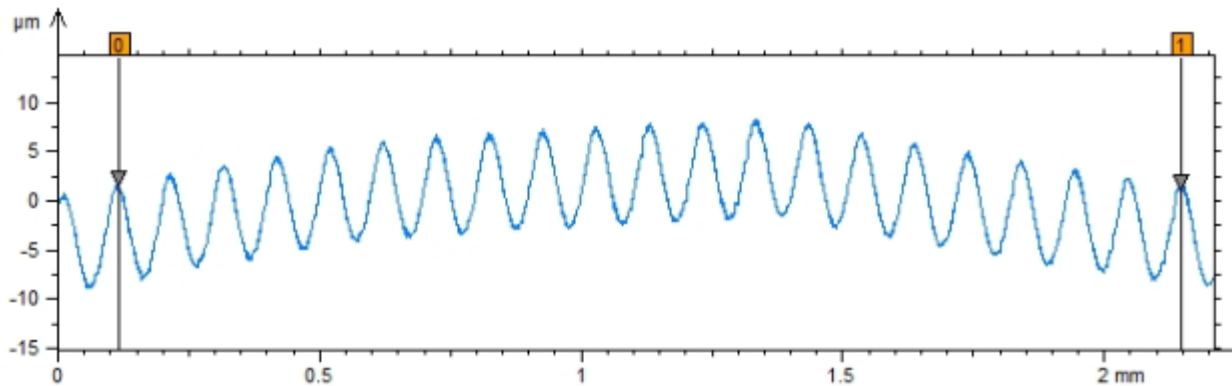
- Set up sample
- Measure
- Send topographic data to software
- Analyze topographic data in software
- Analysis software also capable of S parameters (surface, or areal) and fractal parameters
- We have previously qualified CSI to calibrate step height



Sinusoid profile reference

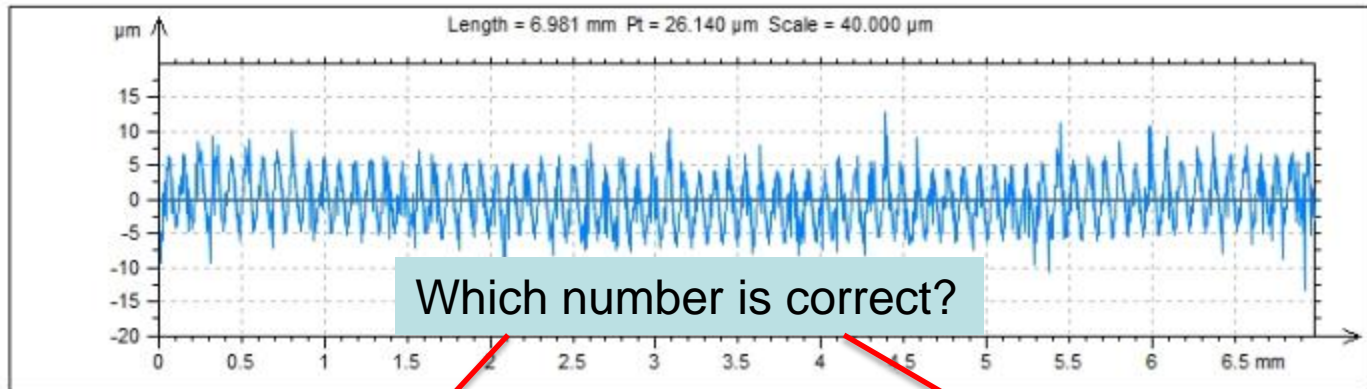
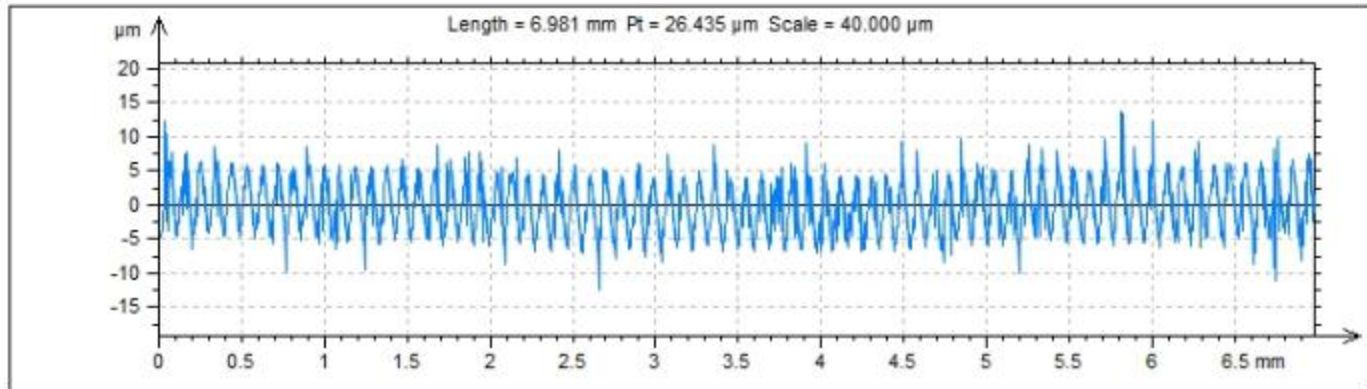


ASME or ISO type C1 artifact



0-1
Horizontal distance 2.035 mm
Height difference -0.464 μm

Another reference profile (C1 type)

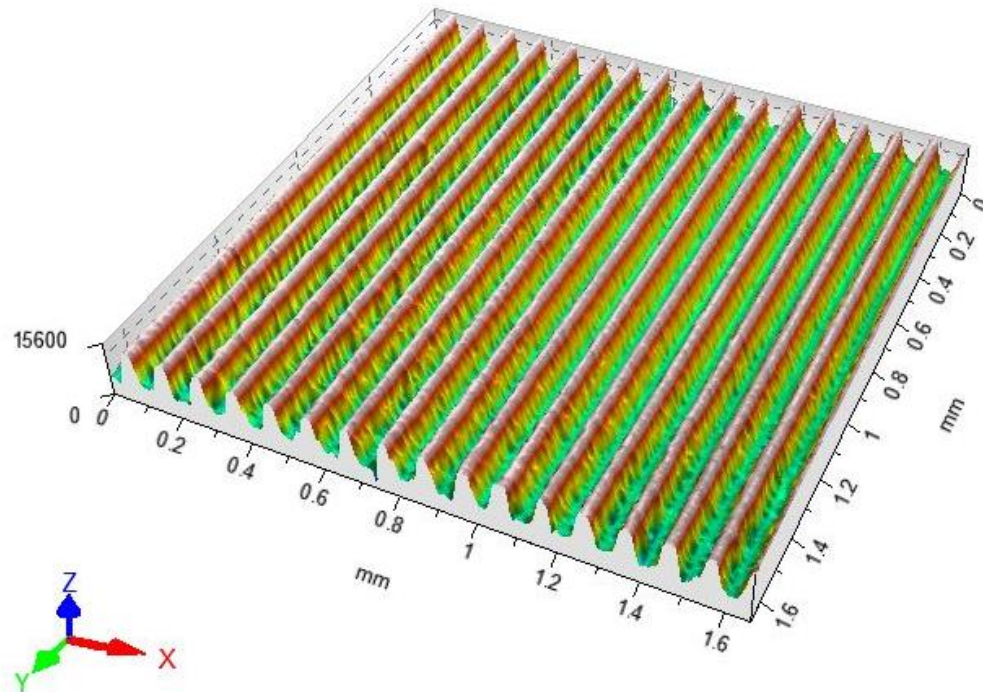


Which number is correct?

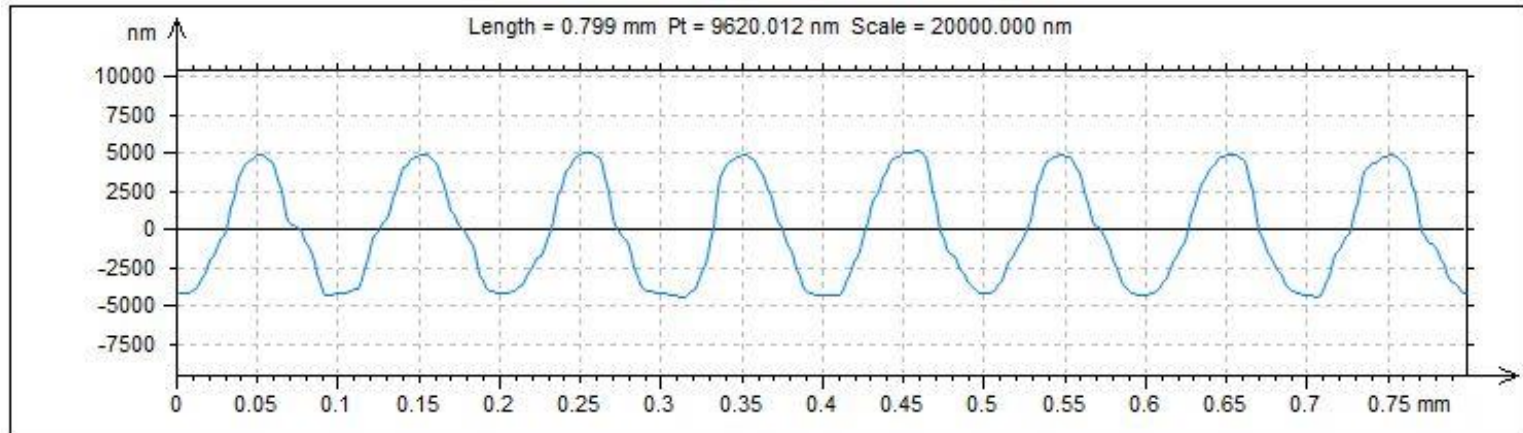
ASME B46.1			
2D Parameters			
Rz	16.596	μm	Gaussian filter, 0.8 mm
Ra	3.022	μm	Gaussian filter, 0.8 mm
ISO 4287			
Amplitude parameters - Primary profile			
Pz	26.435	μm	

ASME B46.1			
2D Parameters			
Rz	16.176	μm	Gaussian filter, 0.8 mm
Ra	2.951	μm	Gaussian filter, 0.8 mm
ISO 4287			
Amplitude parameters - Primary profile			
Pz	26.140	μm	

Measurement of sinusoid standards

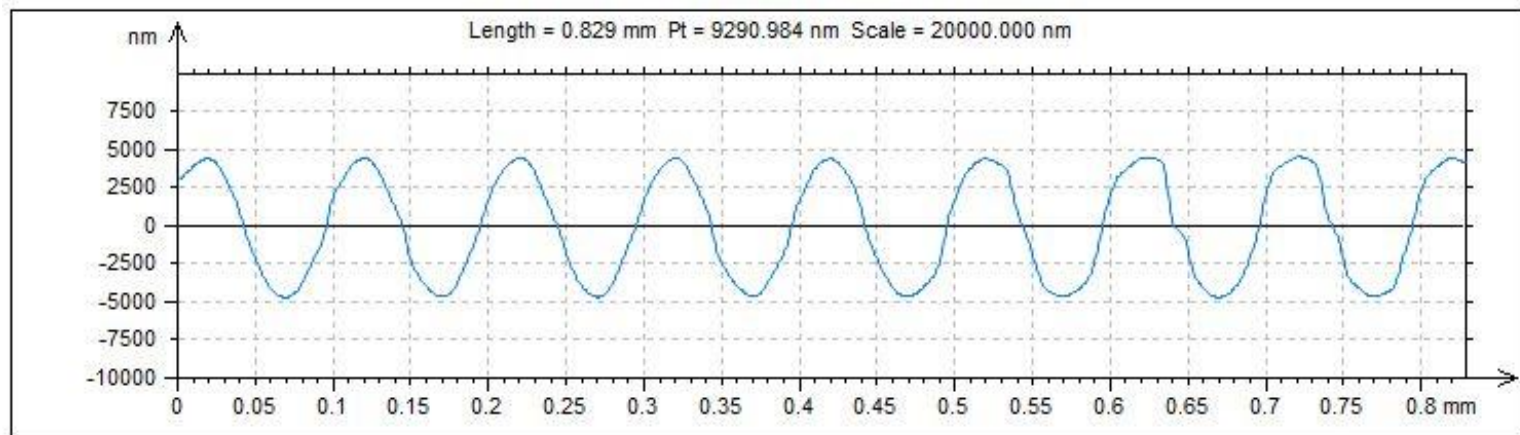
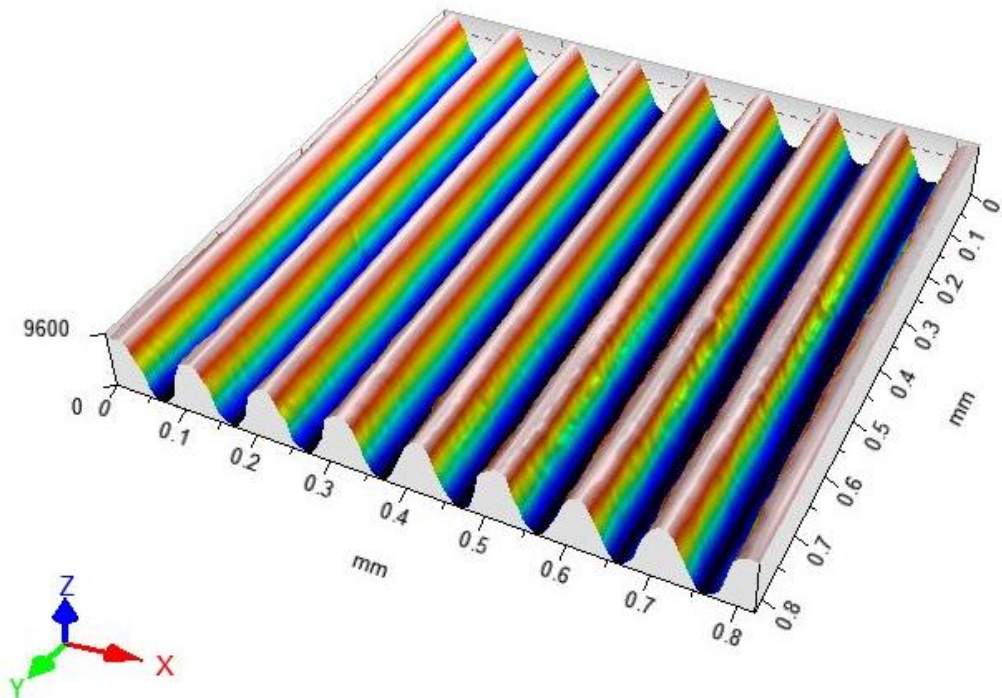


10X objective

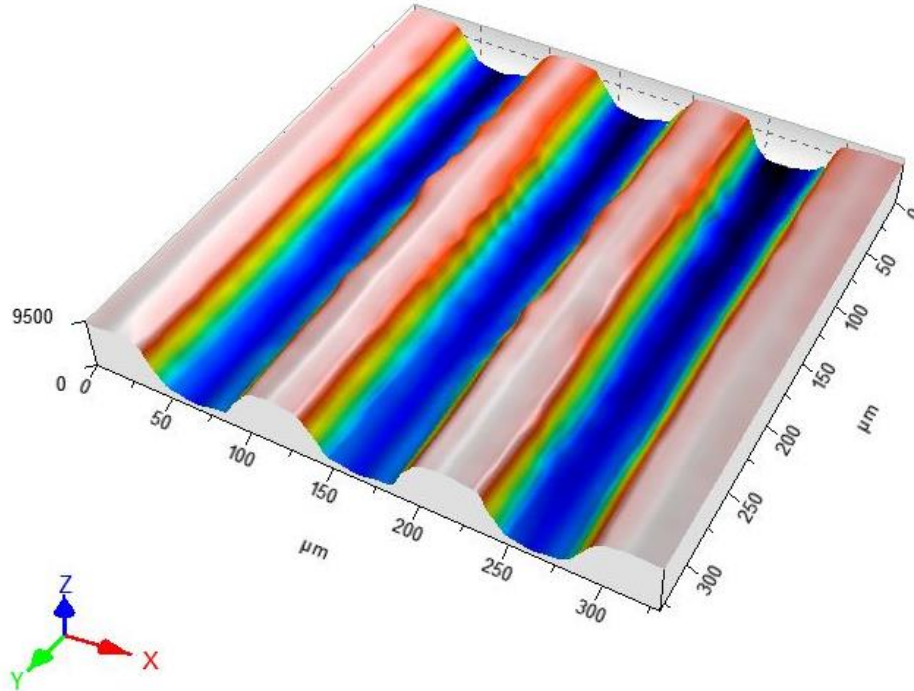


Measurement of sinusoid standards

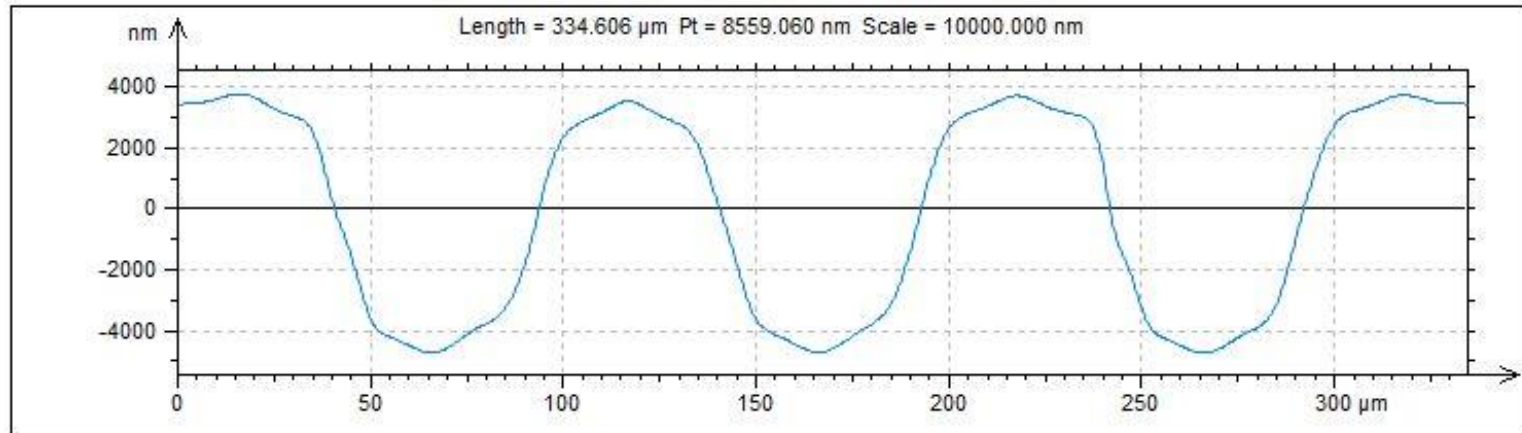
20X objective



Measurement of sinusoid standards

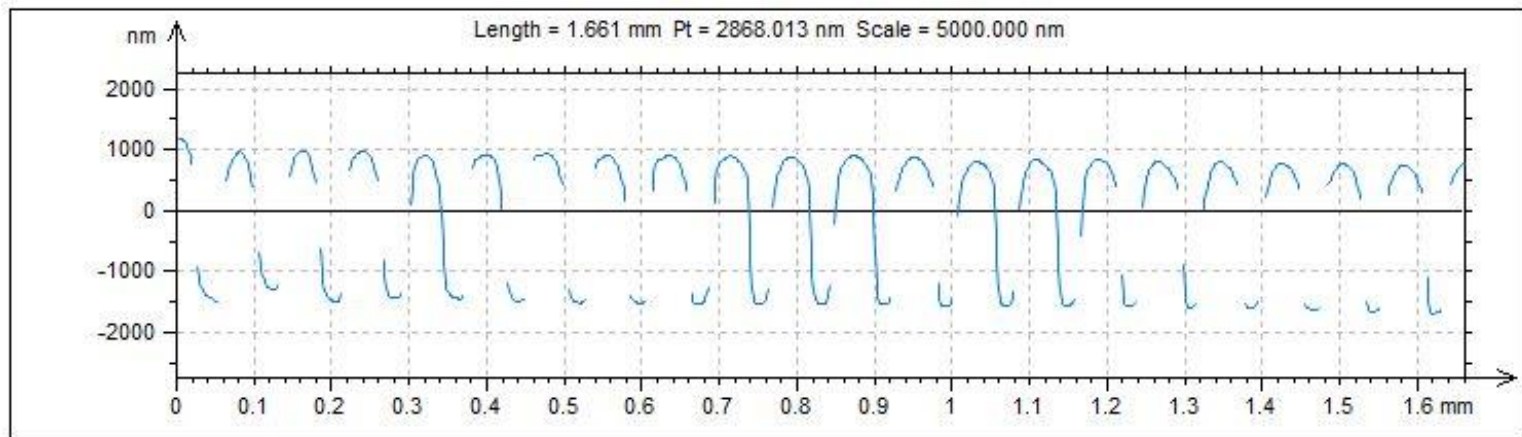
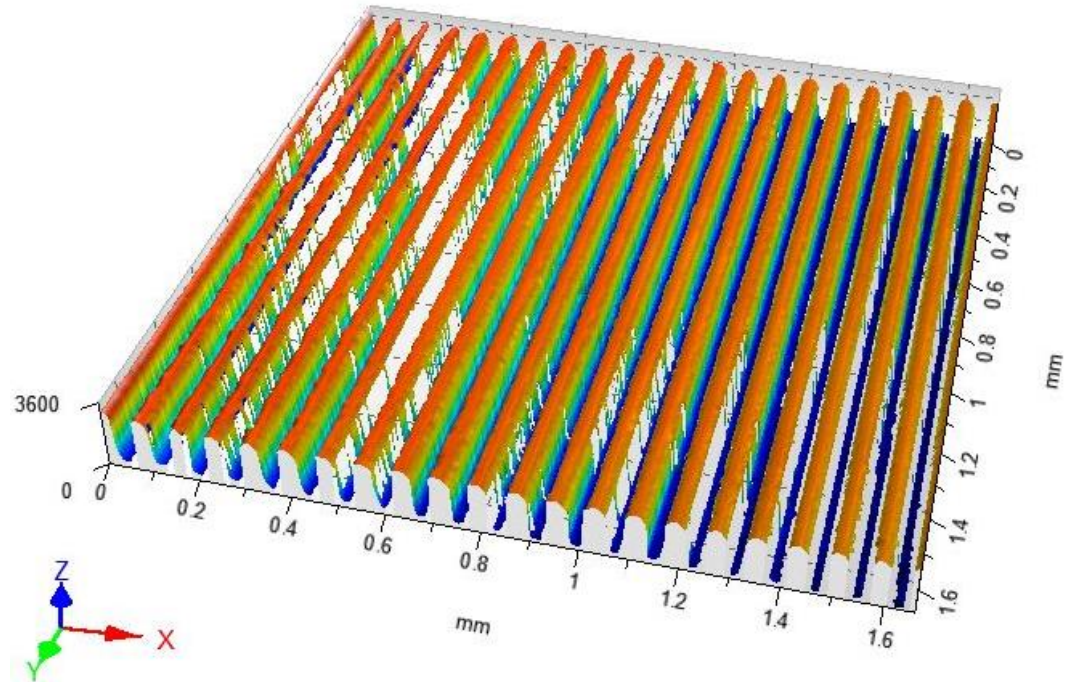


50X objective

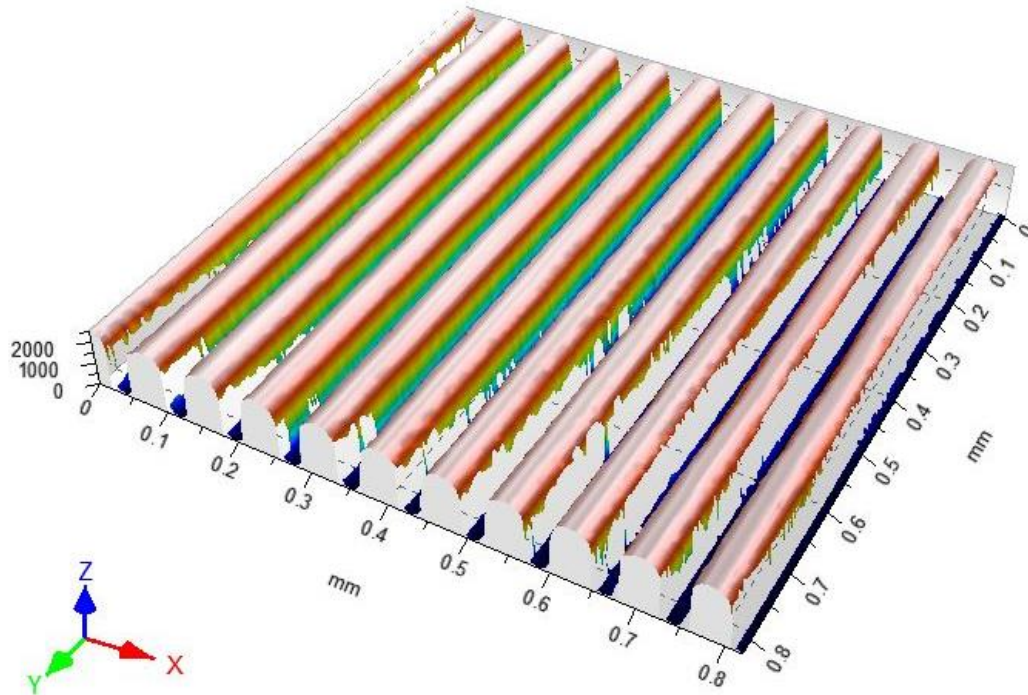


Measurement of square wave standards Sandia National Laboratories

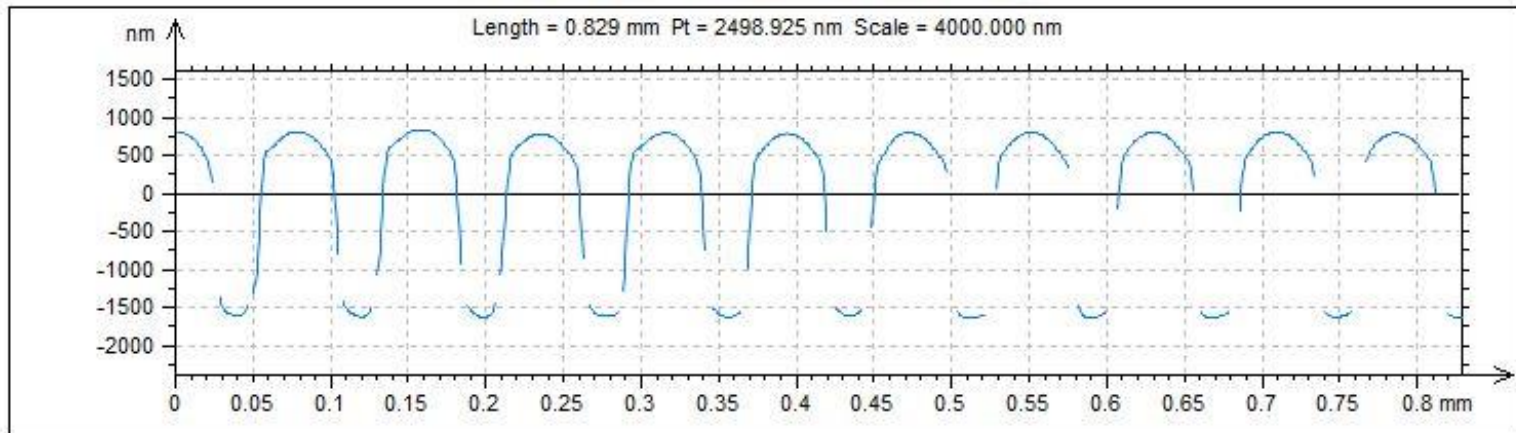
10X objective



Measurement of square wave standards Sandia National Laboratories

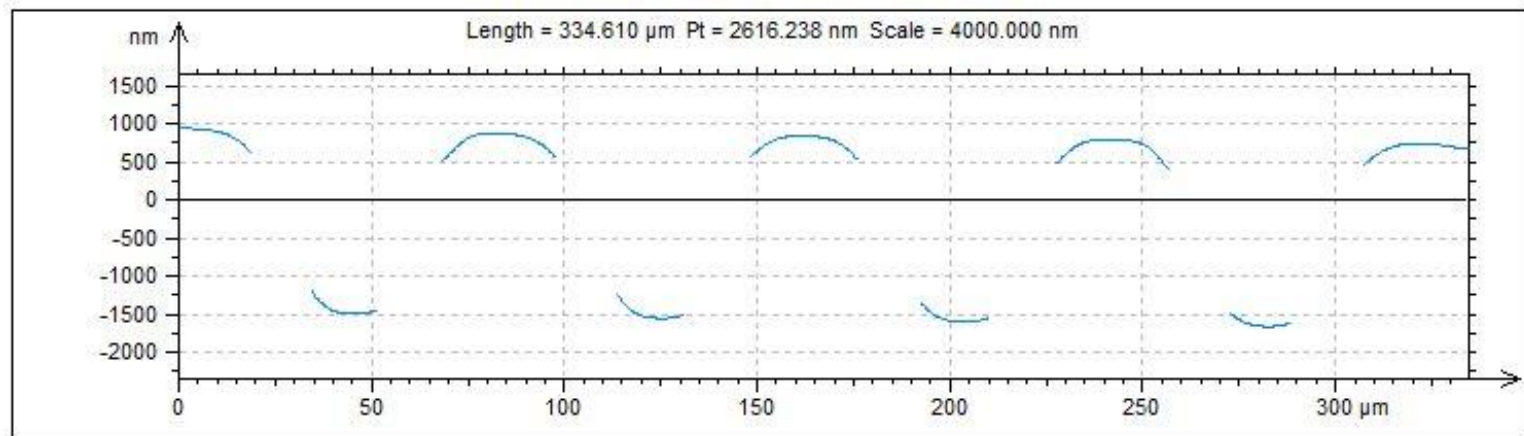
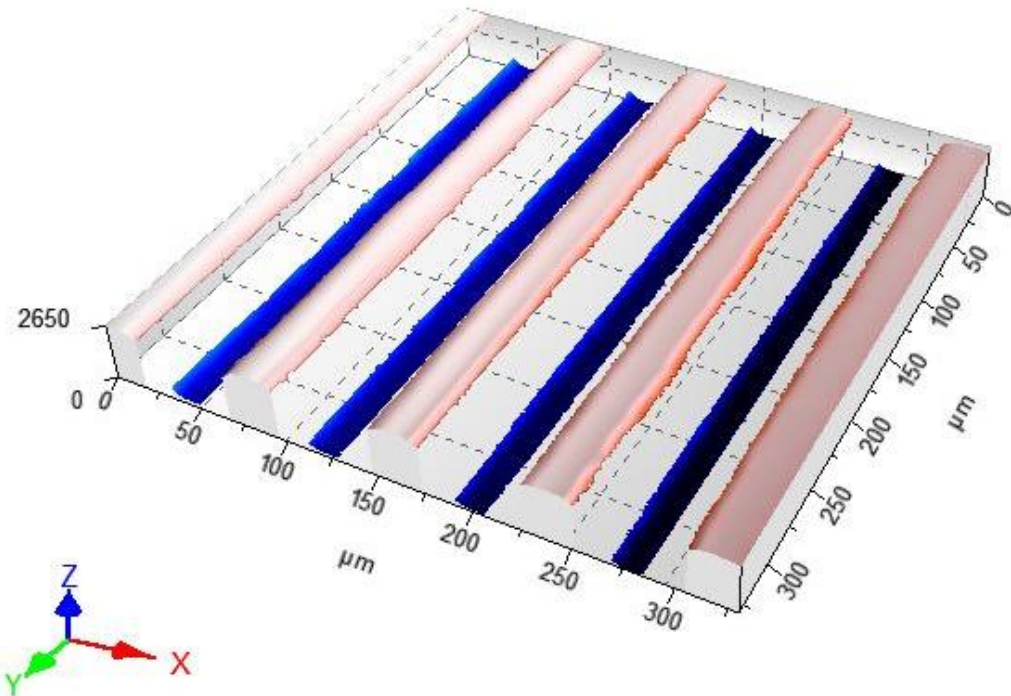


20X objective



Measurement of square wave standards Sandia National Laboratories

50X objective



Preliminary Evaluations

Standard Description	Historical Calibration with Expanded Uncertainty	Measurement w/ CSI (2 std devs)	Calculated Ra from p-v
Sinusoid Ra = 3 μm 10X objective	2.975 \pm 0.011 μm	3.245 μm (0.061 μm)	2.709 μm
Sinusoid Ra = 3 μm 20X objective	2.975 \pm 0.011 μm	3.054 μm (0.103 μm)	2.585 μm
Sinusoid Ra = 3 μm 50X objective	2.975 \pm 0.011 μm	3.492 μm (0.177 μm)	3.339 μm
Square Wave Ra= 0.86 μm 10X objective	0.856 \pm 0.028 μm	1.056 μm (0.034 μm)	1.136 μm
Square Wave Ra= 0.86 μm 20X objective	0.856 \pm 0.028 μm	0.954 μm (0.017 μm)	1.125 μm
Square Wave Ra= 0.86 μm 50X objective	0.856 \pm 0.028 μm	1.068 μm (0.006 μm)	1.185 μm

Conclusions

- To calibrate surface texture instruments, individual axes need to be calibrated
- Instrument operation should be verified
- Step-heights can be used to calibrate z-axis
- Period gratings or stage micrometers can be used to calibrate x and y axes
- Structured surfaces can be used for validation/verification of instrument function
- We have not yet successfully correlated stylus measurements and CSI measurements for periodic structures

Resources

- ASME and ISO standards
- NPL Good Practice Guide 108 (smooth surfaces with CSI)
- NPL Good Practice Guide 116 (rough surfaces with CSI)
- NPL Good Practice Guide 37 (stylus instruments)
- *Optical Measurement of Surface Topography*, Richard Leach, ed. Springer 2011
- *Handbook of Surface and Nanometrology*, David Whitehouse, CRC Press 2011
- *Surfaces and their Measurements*, David Whitehouse, Hermes Penton Science, 2002
- Giusca, Leach, et al., “Calibration of the scales of areal surface topography-measuring instruments...”, parts 1 & 2, *Meas. Sci. Tech.* 23 (2012)

Place holder for extra slides

Initial data

- Uncertainty is limited by master
- Optical instrument has demonstrated < 1 nm repeatability and much faster operation
- Optical instrument has demonstrated $\sim \pm 0.9$ nm scale nonlinearity (over span of ~ 20 μm)
- Instrument qualified for:
 - Step height standards (Type A reference specimens)
 - Ongoing work: Structured (square wave, sinusoid, and triangular) profiles (Type B and Type C reference specimens)
- Limitations: Inhomogeneous surfaces; coated surfaces

Current BMC (k=2) ≈ 21 nm + 1.2% of rdg (0-3200 nm)

Proposed BMC (k=2) ≈ 1.0 nm + 1% of rdg (0-50000 nm)

Working recommendations






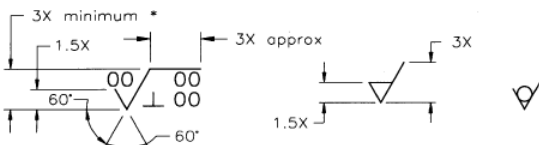
- Calibrate your instrument x,y,z scales using appropriate methods and standards
 - Verify functioning for z (largest influence)
 - Verify appropriate instrument functions (based on the parameters you're interested in)
 - Verify regularly!
- Agree with your customer on acceptance methods
- Report uncertainty as follows:
 - “Expanded measurement uncertainty in the z-axis is ...” (base on instrument calibration)
 - “Expanded measurement of the parameter XYZ is estimated to be ..., based on n repeated measurements at p locations ...”
 - Report all the evaluation conditions

How do you know your measurements are good?

- Are you measuring the desired parameter?
 - or are you specifying a smaller value of R_a because you think that will make your supplier do a better job?
- What is the impact if your values are non-conforming?
 - What is the impact if your product actually conforms, but your instrument tells you to reject?
 - What is the impact if your product should be rejected, but your instrument passes?
- We ***calibrate**** measurement and test equipment to establish traceability of measurement results (not to be confused with verification and validation of equipment or results)
- Traceability is implied in specifications & requirements (commerce, subcontracts, etc.)
- Measurement results (without an evaluation of the uncertainty) are meaningless

Specifications and Standards

From ANSI/ASME Y14.36M:1996

Symbol	Meaning
(a) 	Basic Surface Texture Symbol. Surface may be produced by any method except when the bar or circle (Symbol b or d) is specified.
(b) 	Material Removal By Machining Is Required. The horizontal bar indicates material removal by machining is required to produce the surface and material must be provided for that purpose.
(c) 	Material Removal Allowance. Value in millimeters for "X" defines the minimum material removal requirement.
(d) 	Material Removal Prohibited. The circle in the vee indicates the surface must be produced by processes such as casting, forging, hot finishing, cold finishing, die casting, powder metallurgy or injection molding without subsequent removal of material.
(e) 	Surface Texture Symbol. To be used when any surface texture values, production method, treatment, coating or other text are specified above the horizontal line or to the right of the symbol. Surface may be produced by any method except when bar or circle (Symbol b or d) is specified or when the method is specified above the horizontal line.
(f) 	

* THIS DIMENSION IS ADJUSTED BY +1 FOR EACH LINE OF VALUES BEYOND THE TWO LINES SHOWN BELOW THE HORIZONTAL LINE.

FIG. 1 SURFACE TEXTURE SYMBOLS AND CONSTRUCTION

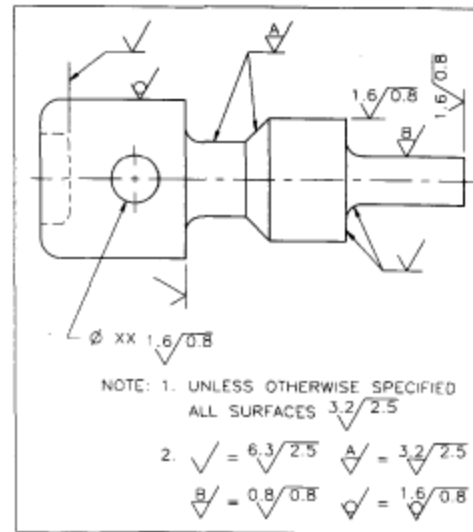


FIG. 2 LOCATION OF SURFACE TEXTURE SYMBOLS

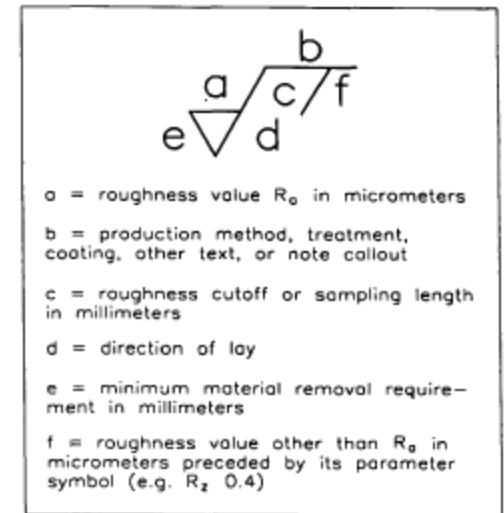
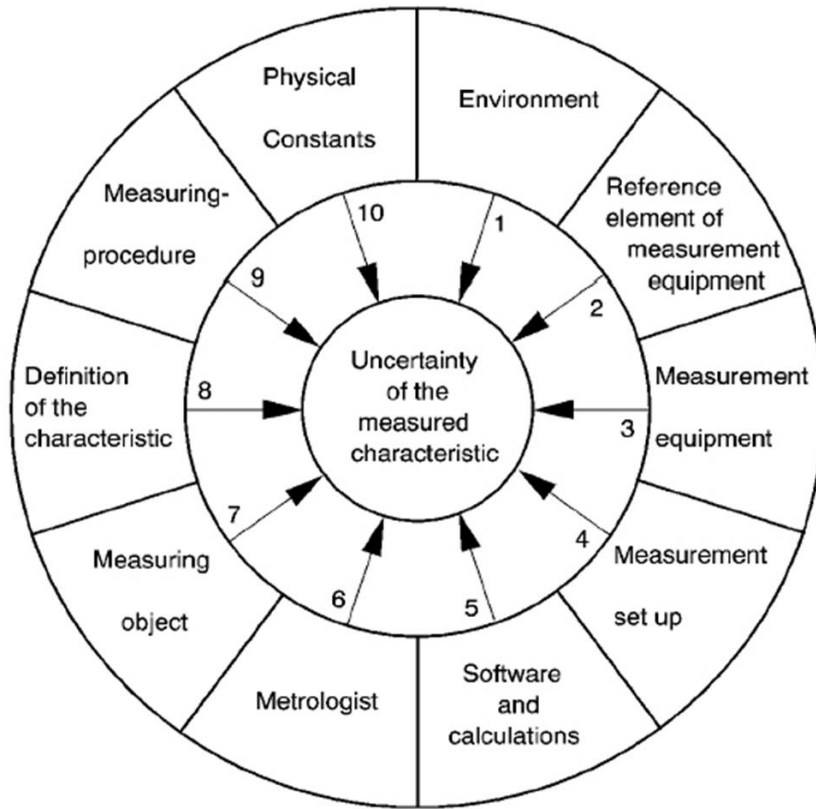


FIG. 3 SYMBOL VALUE APPLICATION

A deeper dive into uncertainty



- When measuring R_a :
 - Specify evaluation length
 - Specify short spatial wavelength cutoff
 - Specify long wavelength cutoff
 - Specify type of filter for cutoff (nowadays, Gaussian)
- Then, calculate R_a
- Evaluate statistical data
 - Remember the influence of the UUT—you need statistics on that too!
- Evaluate influence parameters
- Fully rigorous evaluation is difficult

Uncertainty of surface texture measurements

- Determination of uncertainty for step height, R_p , R_v , R_t ($R_t \equiv (R_p - R_v)$) is straightforward
- Determination of uncertainty for R_a , R_q , etc. is more difficult
 - Allowable tolerances & uncertainties for reference specimens, per ASME B46.1 →
 - A1, A2: Step heights; C1-C4; precision sinusoid or other “shaped” grooves

Table 11-3 Tolerances and Uncertainties for Types A1 and A2

Nominal Value of Depth or Height, μm	Tolerance on Nominal Value, %	Combined Expanded Uncertainty of Measurement in Calibrated Mean Value of Depth or Height, % [Notes (1), (2)]	Uniformity — One Standard Deviation From the Calibrated Mean, %
0.3	± 20	± 4	± 3
1	± 15	± 3	± 2
3	± 10	± 3	± 2
10	± 10	± 3	± 2
30	± 10	± 3	± 2
100	± 10	± 3	± 2

Table 11-6 Tolerances and Uncertainties for Types C1 Through C4

Nominal Value of R_a , μm	Tolerance on Nominal Value, %	Combined Expanded Uncertainty of Measurement in Calibrated Mean Value of R_a , % [Notes (1), (2)]	Standard Deviation From Mean Value, %
0.1	± 25	± 4	± 3
0.3	± 20	± 3	± 2
1	± 15	± 3	± 2
3	± 10	± 2	± 2
10	± 10	± 2	± 2

Traceability path

- Lateral (x,y) is similar to typical microscope objective (use stage micrometer if necessary)
- Vertical comes **from the vertical sensor**, not the fringes
- How do I calibrate a span of vertical height?

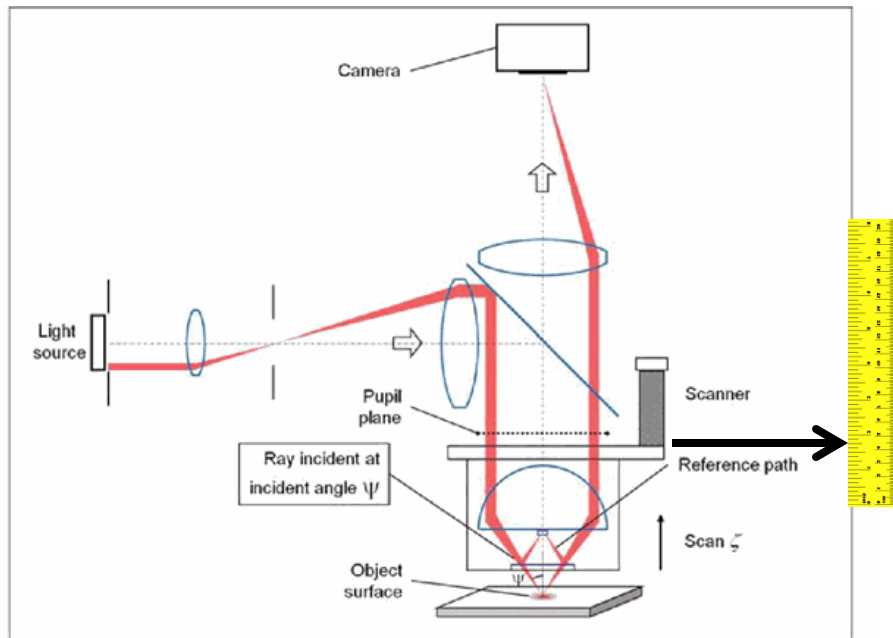
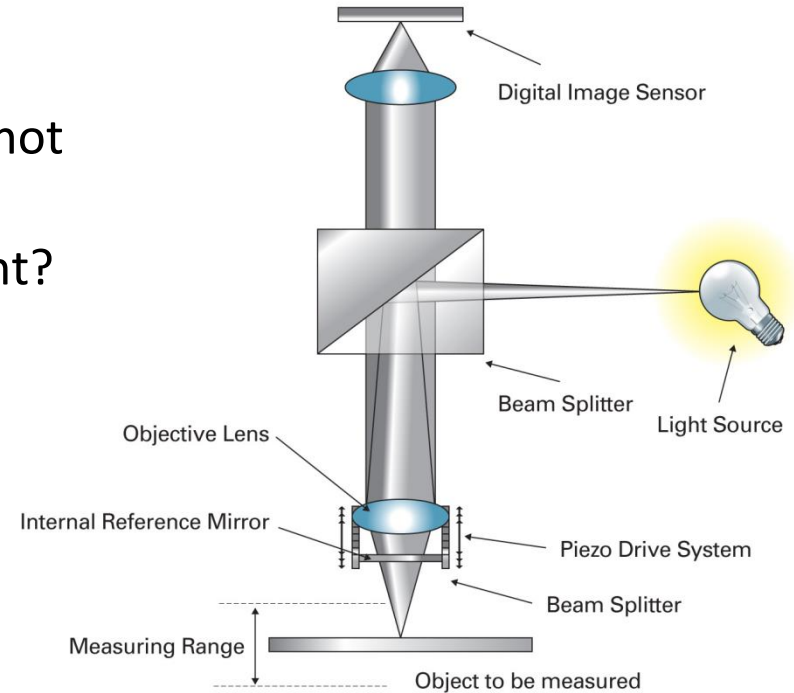


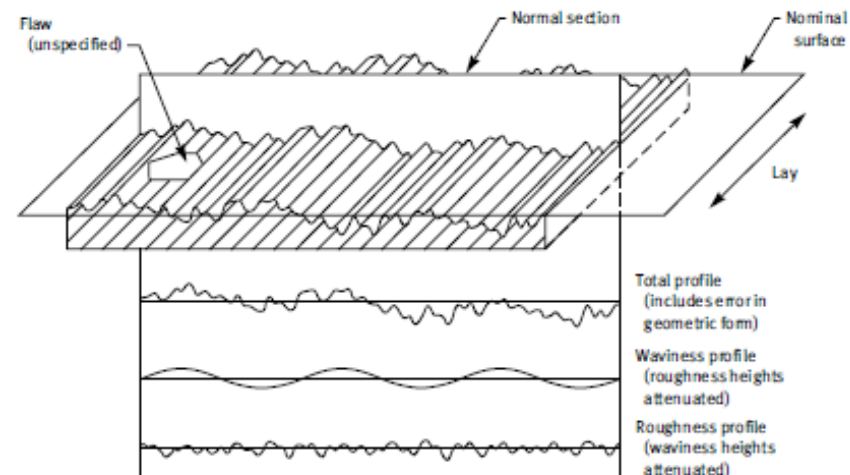
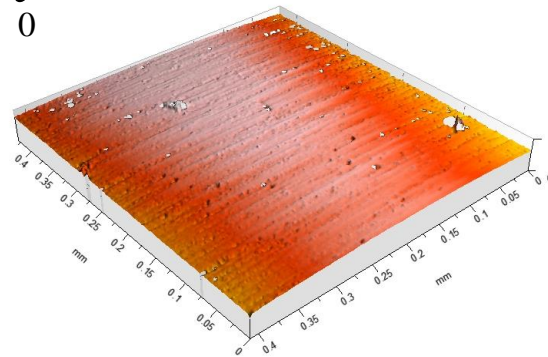
Fig. 9.4 Path of a single ray bundle through a CSI instrument

All boils down to yellow ruler (figuratively)

Measurement of surface texture

- Measure z, measure x, apply mathematical operations to obtain Ra
- Calibration and uncertainty?
- How does the specified texture actually relate to the desired functionality?
- What about 2-D (3-D?) surface. “R” parameters do not address those. “S” parameters for areal texture

$$S_q = \sqrt{\frac{1}{A_e} \int_0^{L_x} \int_0^{L_y} (z(x, y))^2 dy dx}$$



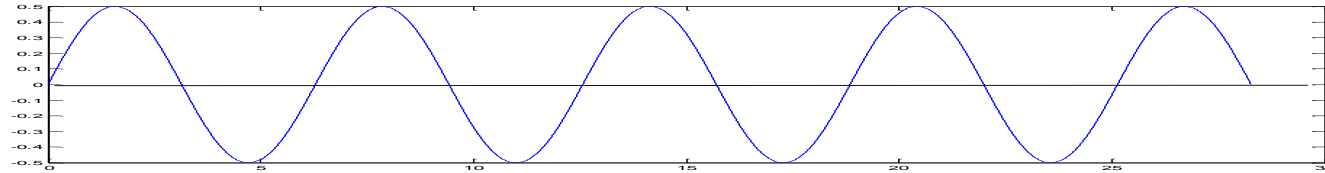
Some International Standards

- ISO 1302:2000
 - Graphical (drawing) symbols
- ISO 4287:1997
 - Definitions for profile
- ISO 4288:1996
 - Procedures for profiles
- ISO 5436:2000 (parts 1 & 2)
 - Profile measurement standards; materials; software
- ISO 11562:1996
 - Metrology filters
- ISO 13565: 1996
 - more filters
- ISO 25178 series of standards (next slide)

ISO 25178 series

- Part 1: Areal surface texture drawing indications (2011)
 - Part 2: Terms, definitions and surface texture parameters (2011)
 - Part 3: Specification operators (2011)
 - Part 4: Comparison rules
 - Part 5: Verification operators
 - Part 6: Classification of methods for measuring surface texture (2010)
 - Part 70: Measurement standards for areal surface texture measurement instruments (2011)
 - Part 71: Software measurement standards (2011)
 - Part 72: Software measurement standards – XML file format (2011)
 - Part 601: Nominal characteristics of contact (stylus) instruments (2010)
 - Part 602: Nominal characteristics of non-contact (confocal chromatic probe) instruments (2010)
 - Part 603: Nominal characteristics of non-contact (phase shifting interferometric microscopy) instruments (2011)
 - Part 604: Nominal characteristics of non-contact (coherence scanning interferometry) instruments (2011)
 - Part 605: Nominal characteristics of non-contact (point autofocus) instruments (2011)
 - Part 606: Nominal characteristics of non-contact (variable focus) instruments (2011)
 - Part 607: Nominal characteristics of non-contact (imaging confocal) instruments (2011)
 - Part 700: Calibration of non-contact instruments (2011)
 - Part 701: Calibration and measurement standards for contact (stylus) instruments (2010)
- From Leach, editor, Chapter 1 of *Optical Measurement of Surface Topography*, Springer, 2011.
 - Note that years listed are “projected”
 - A number of these are still in voting

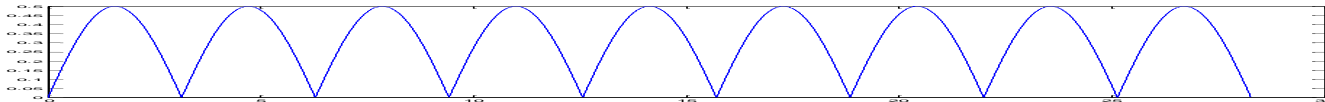
Commonly used parameters:



Ra

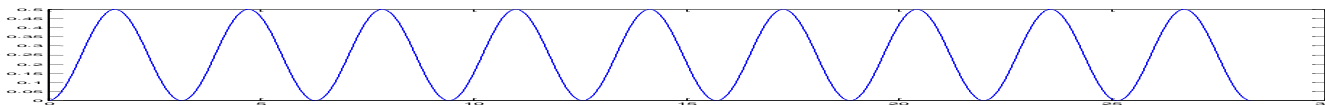


For a pure sinusoid, peak-valley = π Ra



Rq (rms)

For a pure sinusoid, $Rq = (\pi/\sqrt{8}) Ra$



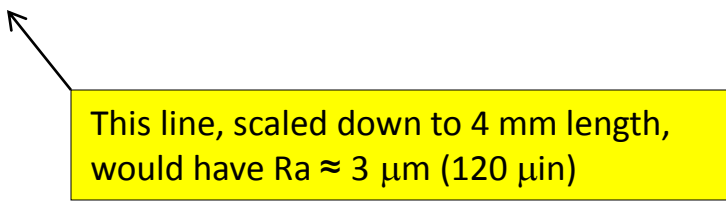
Others include:

Rt: peak-valley

Rz: avg peak-valley

Visual miscues

- For a sinusoid profile, $Ra = \frac{1}{\pi} (P-V)$
- Let's consider $Ra = 3 \mu\text{m}$ (roughly $120 \mu\text{in}$) over a 4 mm length (roughly 0.16 in) ($P-V \approx 9.4 \mu\text{m}$ for sinusoid; $P-V \approx 12.1 \mu\text{m}$ for triangle).
 - I'm passing around a " $\times 1000$ " "pseudo-strip chart" (1 mm \rightarrow 1m)
 - Don't let visual distortions of typical surface profile equipment mislead you!



This line, scaled down to 4 mm length,
would have $Ra \approx 3 \mu\text{m}$ ($120 \mu\text{in}$)

ASME standards

- **ANSI/ASME Y14.36M**
 - Drawing symbols
- **ASME B46.1:2009**
 - Definitions for texture (mainly profile, but has some coverage of aerial texture)