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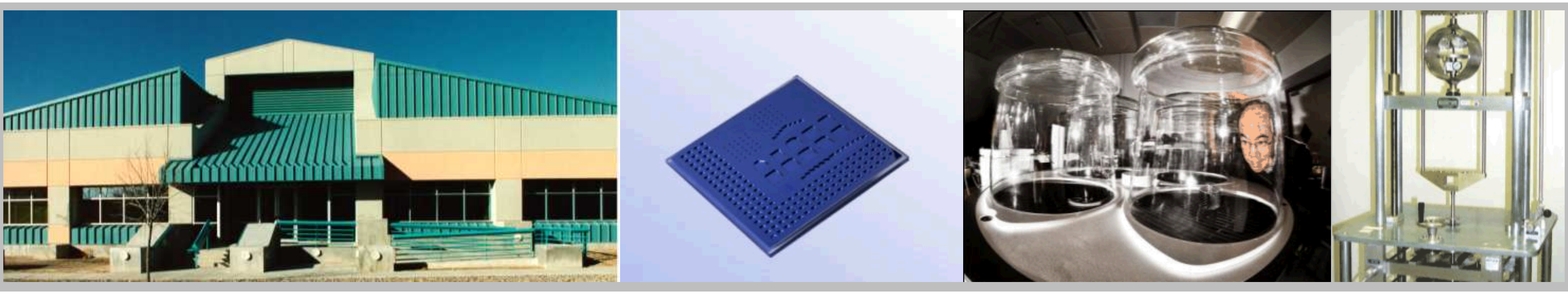

Qualification of a Coherence Scanning Interferometer for Calibration of Step Height Standards

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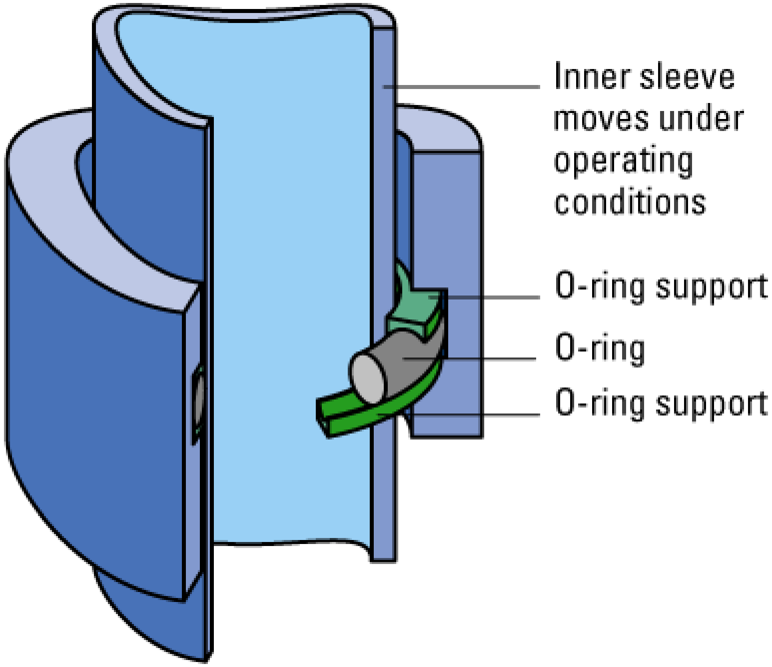
Sandia National Laboratories
Primary Physical Standards
July 31, 2012

Objectives

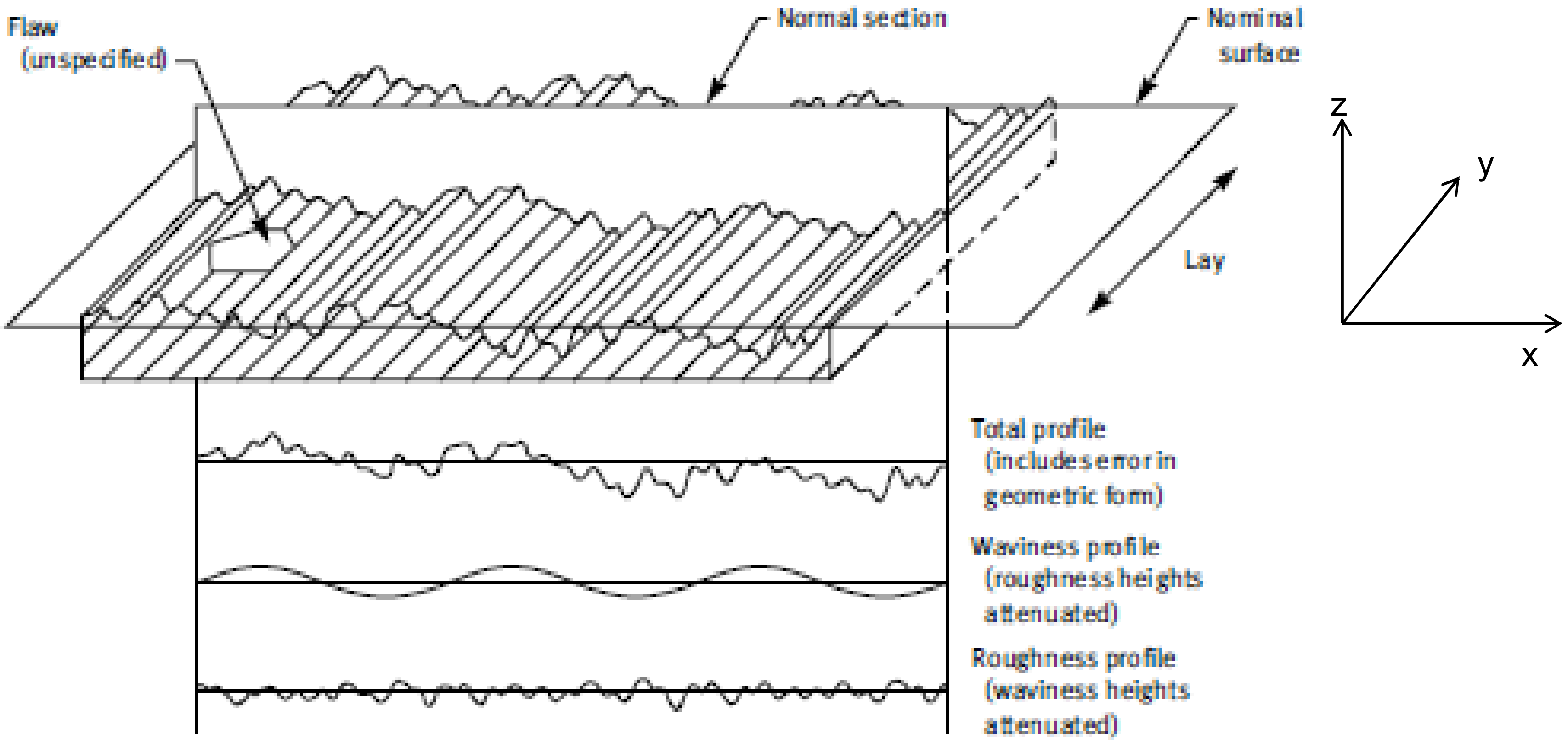
- Surface texture, roughness, waviness, and lay
  - Why do we care?
- What are some of the existing standards?
- How is surface texture generally measured?
- How do we calibrate instruments for measuring these characteristics? (How should we make calibrated measurements?)
- What are some of the contributing factors to measurement uncertainty?
- Calibration of a step height standard 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
  - Cost (excess cost to make a surfa or costs due to poor product qua properties were inadequately m
  - Measurement (especially form: form requirement if you have to
  - O-ring seals (be careful if you sp Some seal designs actually requi range between a minimum and maximum value.)
  - etc.



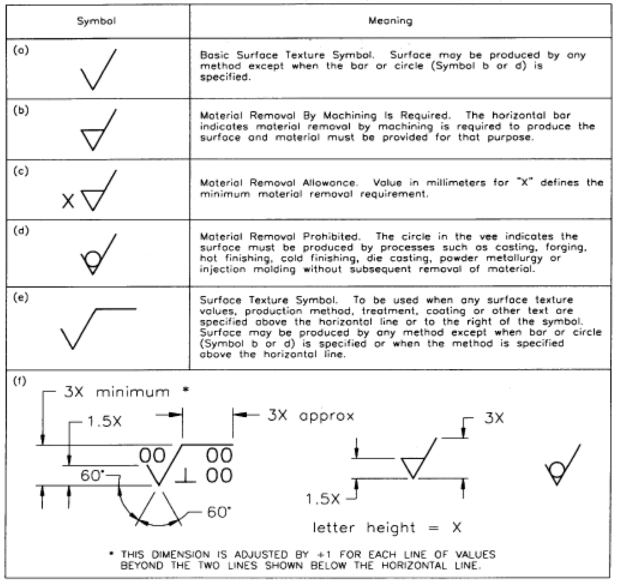
Surface texture, roughness, waviness, and lay



From ASME B46.1:2009

Specifications and Standards

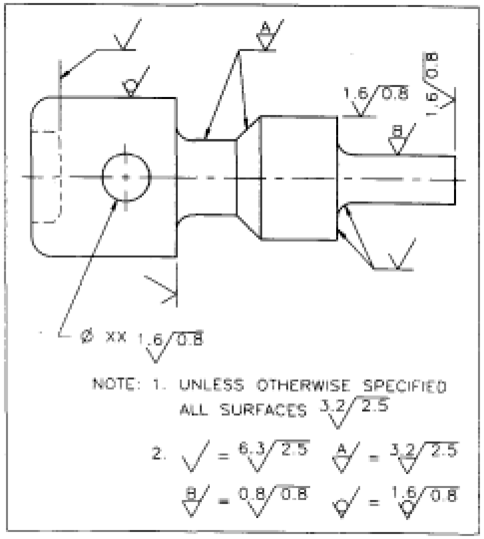
From ANSI/ASME Y14.36M:1996



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) X	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

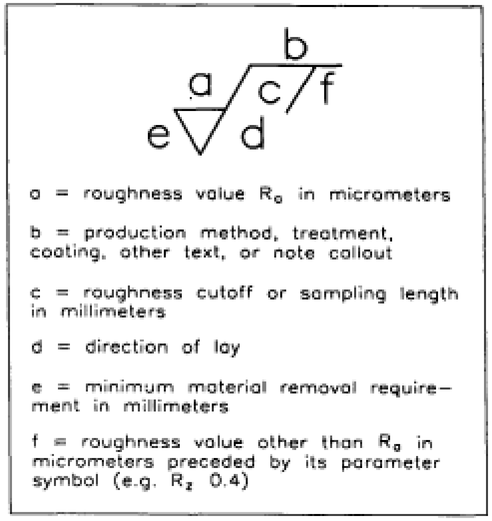


NOTE: 1. UNLESS OTHERWISE SPECIFIED ALL SURFACES 3.2/2.5

2. = 6.3/2.5 A = 3.2/2.5

B = 0.8/0.8 = 1.6/0.8

FIG. 2 LOCATION OF SURFACE TEXTURE SYMBOLS



a = roughness value R_a in micrometers

b = production method, treatment, coating, other text, or note callout

c = roughness cutoff or sampling length in millimeters

d = direction of lay

e = minimum material removal requirement in millimeters

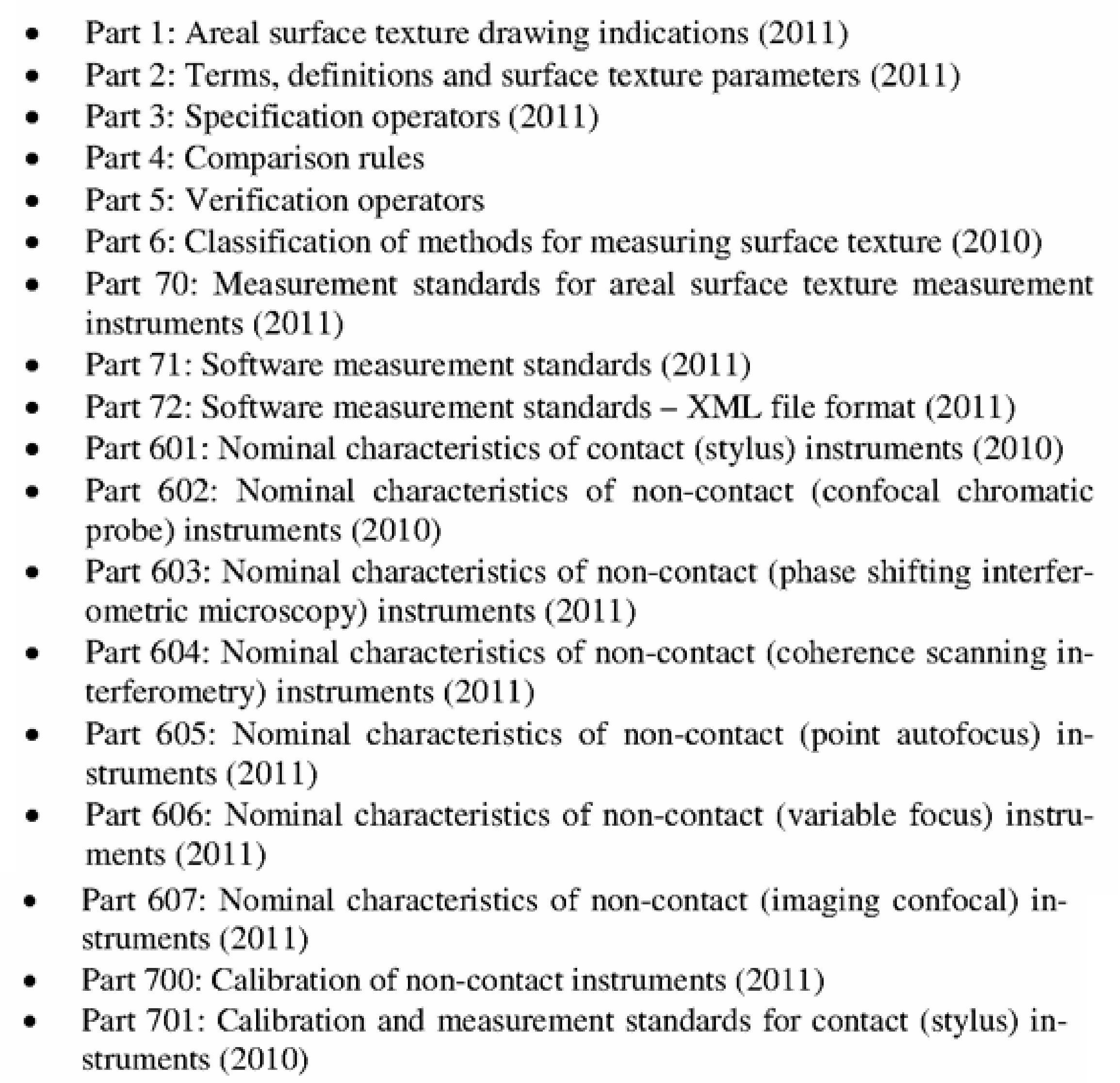
f = roughness value other than R_a in micrometers preceded by its parameter symbol (e.g. R_z 0.4)

FIG. 3 SYMBOL VALUE APPLICATION

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

ASME standards

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

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-characterisitics 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.

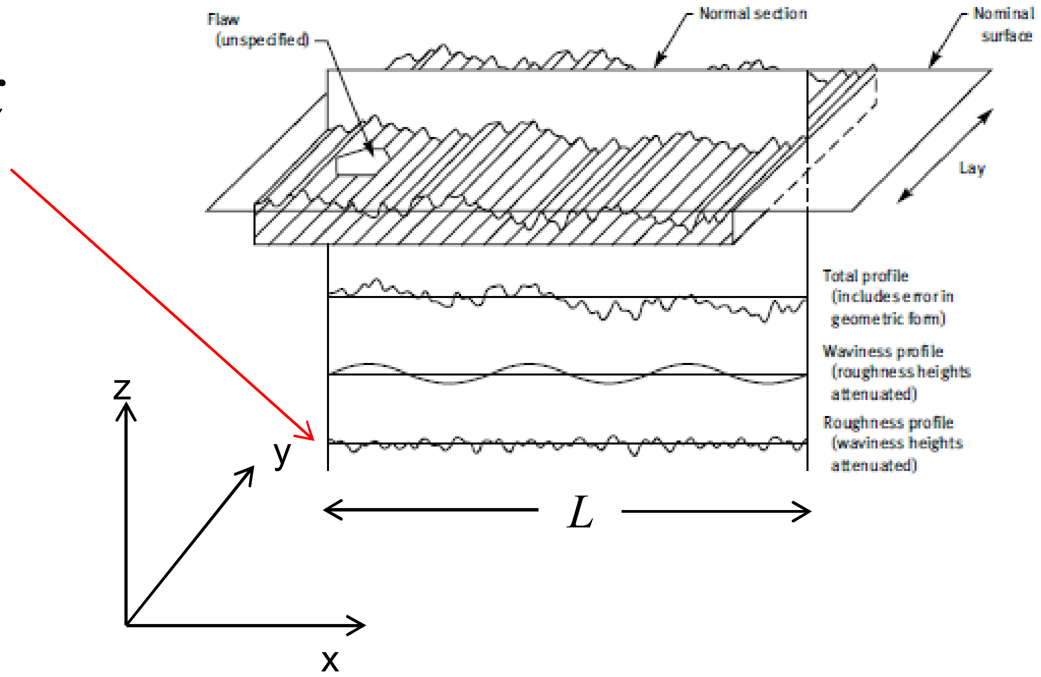
Measurement methods

- 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

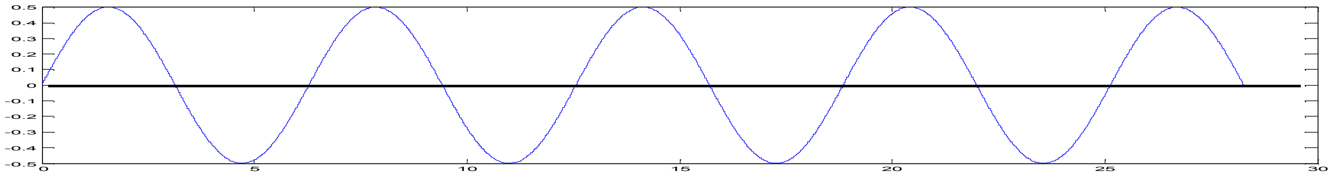
Ra (Roughness average)

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

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

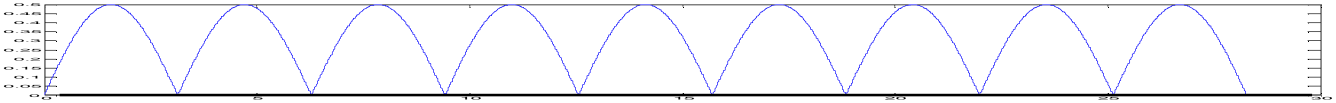


Commonly used parameters:



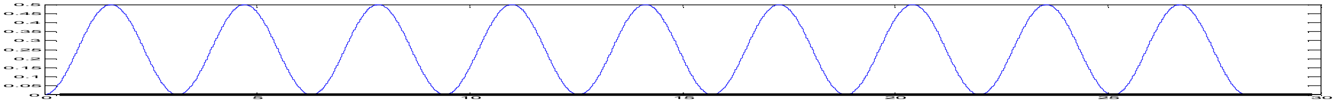
Ra

For a pure sinusoid, peak-valley= π Ra



Rq (rms)

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

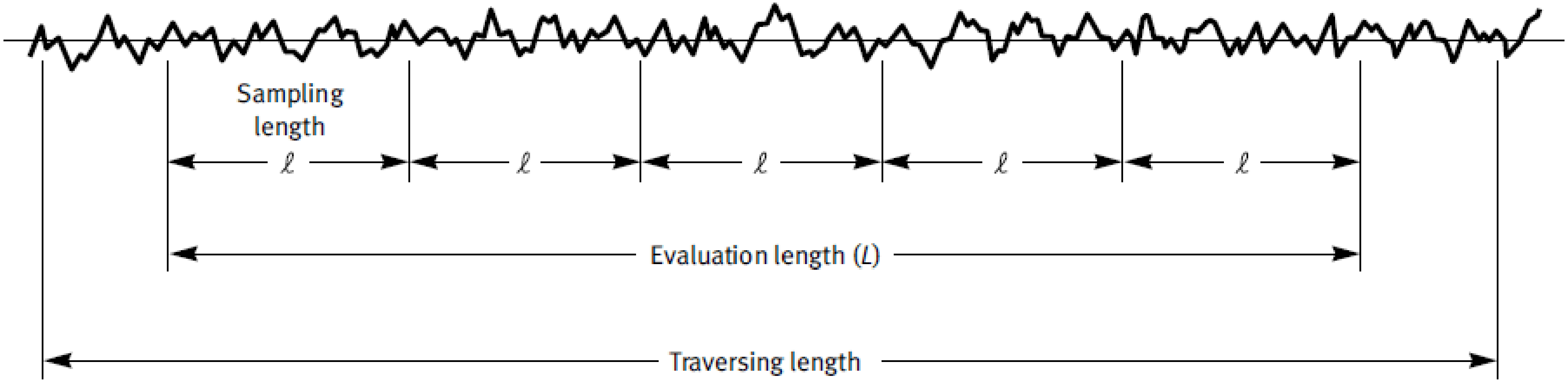


Others include:
Rt: peak-valley
Rz: avg peak-valley

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.)

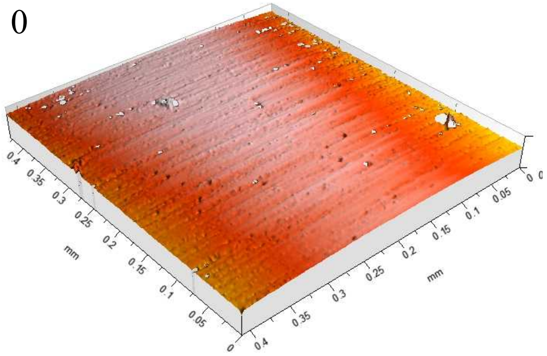
Fig. 1-7 Surface Profile Measurement Lengths

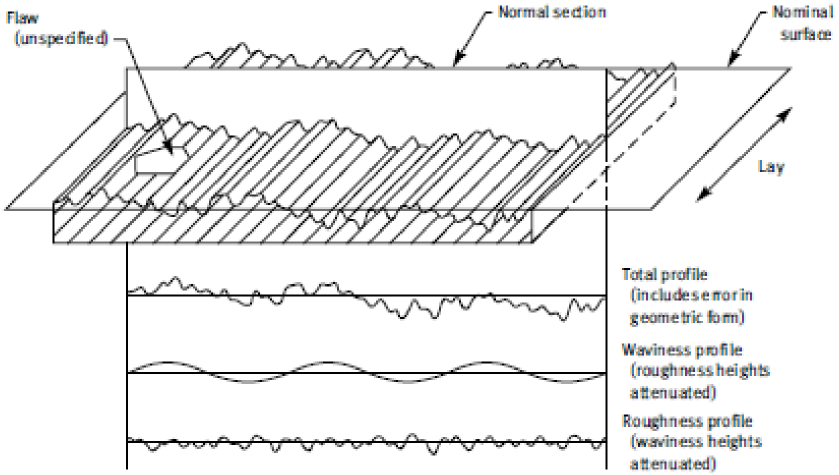


Measurement of surface texture

- 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

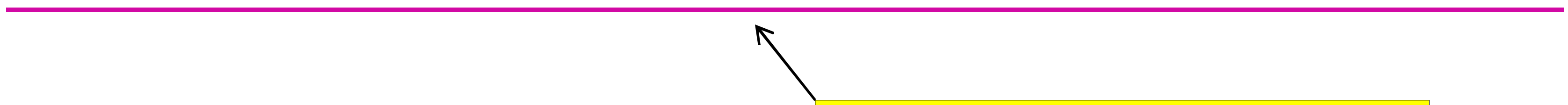
$$S_q = \sqrt{\frac{1}{A_e}\int_0^{L_x}\int_0^{L_y}\left(z(x,y)\right)^2 dydx}$$





Visual miscues

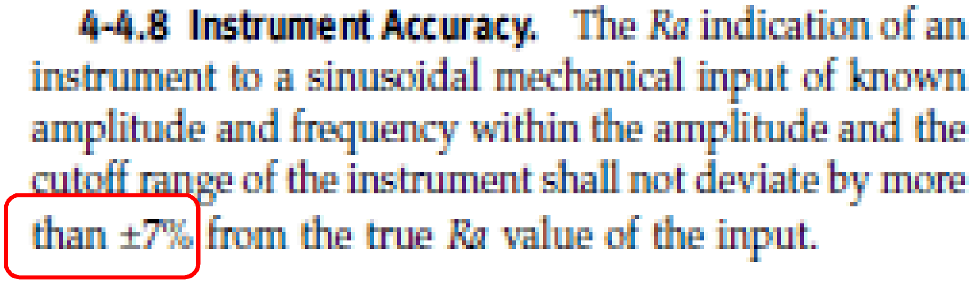
- For a sinusoid profile, Ra= $\frac{1}{\pi}(\mathrm{P\text{-}V})$
- Let’s consider Ra=3 μm (roughly 120 μin) over a 4 mm length (roughly 0.16 in) (P-V ≈ 9.4 μm for sinusoid; P-V ≈ 12.1 μm for triangle.
    - I’m passing around a “×1000” “pseudo-strip chart” (1 mm→1m)
    - Don’t let visual distortions of typical surface profile equipment mislead you!



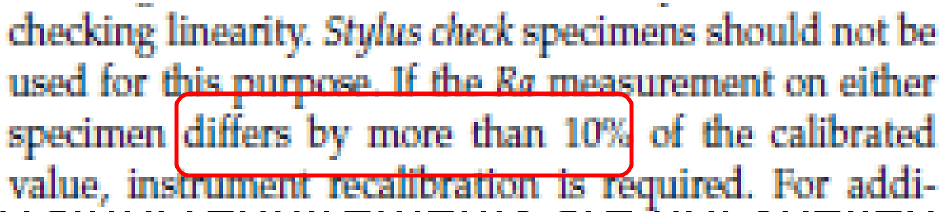
This line, scaled down to 4 mm length, would have Ra ≈ 3 μm (120 μin)

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 and x sensors are not too difficult
- NPL "Good Pra
  - Calibrated ndard)
  - Means of c
  - Calibrated "x" artifact (unless you have another means of checking x (
  - Calibrated ' e and 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 *Ra* 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 ±7% from the true *Ra* value of the input.



checking linearity. *Stylus check specimens should not be used for this purpose.* If the *Ra* measurement on either specimen differs by more than 10% of the calibrated value, instrument recalibration is required. For addi-

From ASME B46.1:2009

Measurement uncertainties

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

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

- Uncertainties of what? Suppose Ra?
- ISO GUM:
  - y (measurand) = f($x_{1,}$ $x_{2,}$ $x_{3,}$ … x_n)
  - Type A (statistical data) + Type B
  - partial derivatives, etc.
- Just for Ra:
  - λs Filter (mechanical? optical? signal processing?) uncertainty from filtering?
  - λc 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!

Uncertainty of surface texture measurements

- Determination of uncertainty for step height, Rp, Rv, Rt (Rt≡(Rp-Rv)) is straightforward
- Determination of uncertainty for Ra, Rq, 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

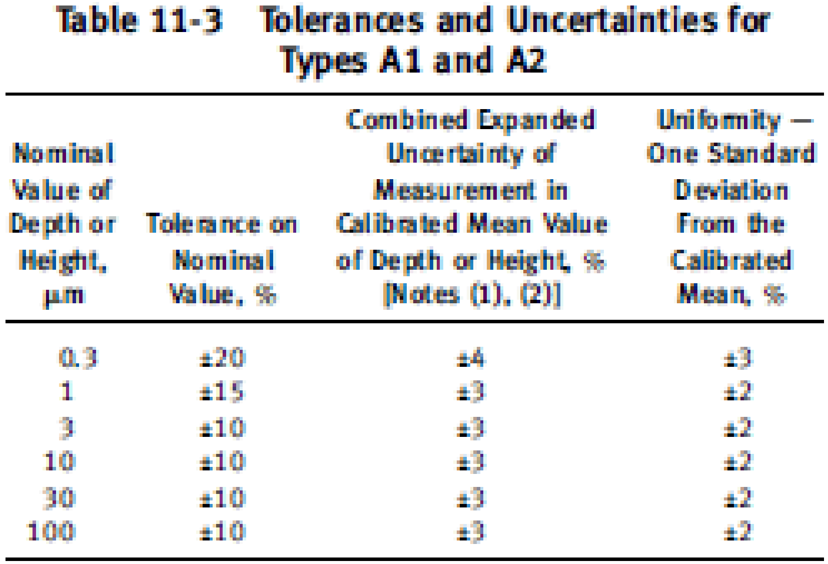


Table 11-3 Tolerances and Uncertainties for Types A1 and A2

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

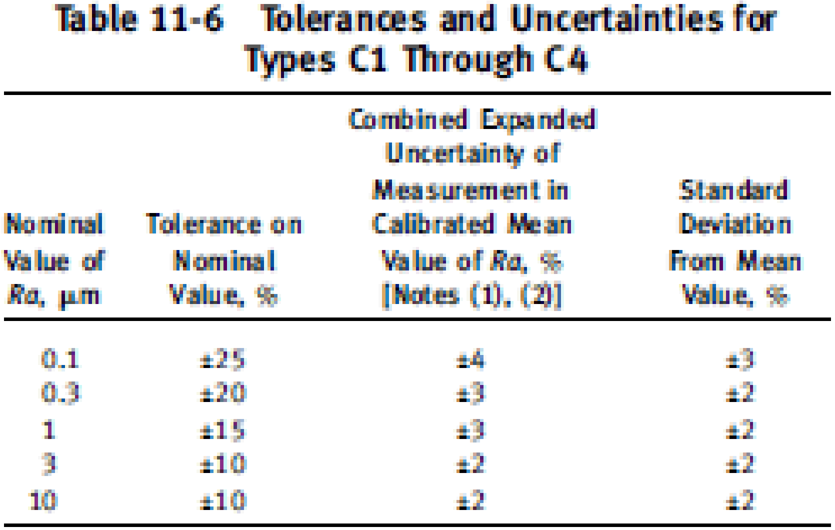
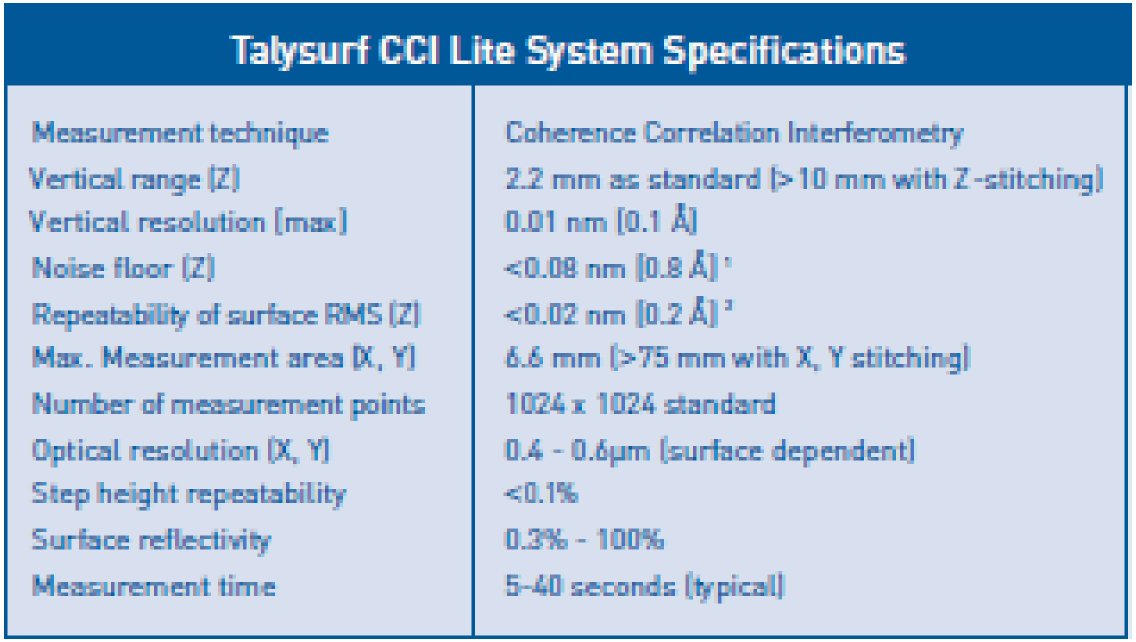


Table 11-6 Tolerances and Uncertainties for Types C1 Through C4

Nominal Value of *Ra*, µm	Tolerance on Nominal Value, %	Combined Expanded Uncertainty of Measurement in Calibrated Mean Value of *Ra*, % [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

Let’s focus on non-contact for step height (type A reference stds)

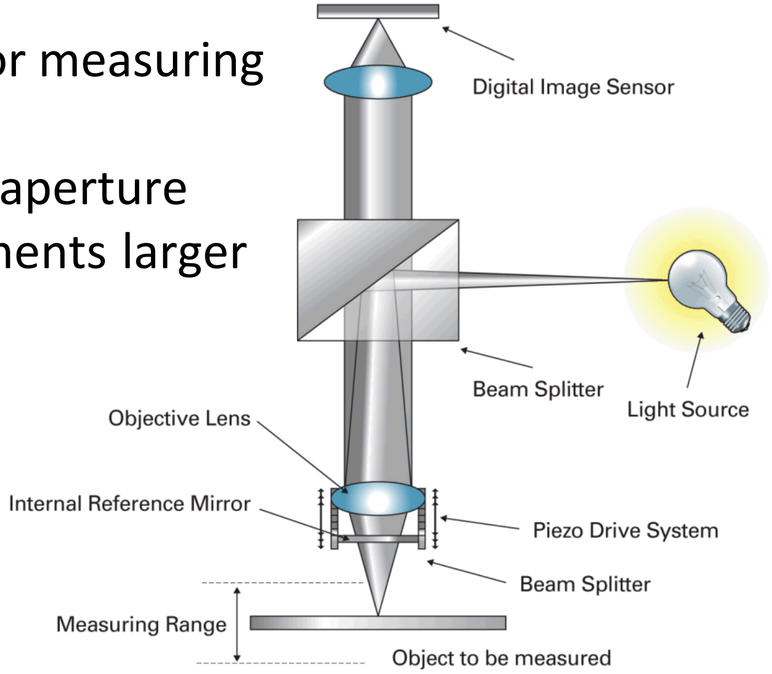
- Limited to areal image, “scanning white light interferometry”
  - Most instruments nowadays are “coherence scanning”
  - Example: Taylor-Hobson CCI-Lite

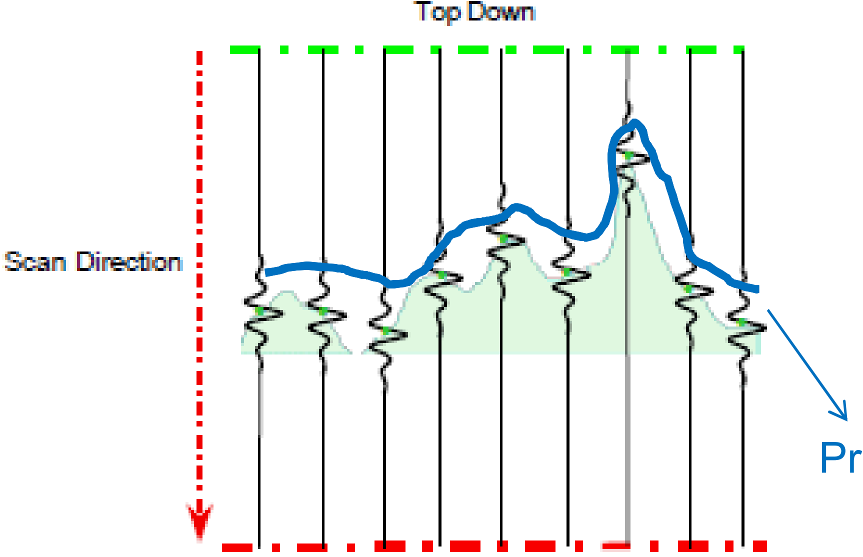


Talysurf CCI Lite System Specifications	
Measurement technique	Coherence Correlation Interferometry
Vertical range (Z)	2.2 mm as standard (>10 mm with Z-stitching)
Vertical resolution (max)	0.01 nm (0.1 Å)
Noise floor (Z)	<0.08 nm (0.8 Å) [1]
Repeatability of surface RMS (Z)	<0.02 nm (0.2 Å) [2]
Max. 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)

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)

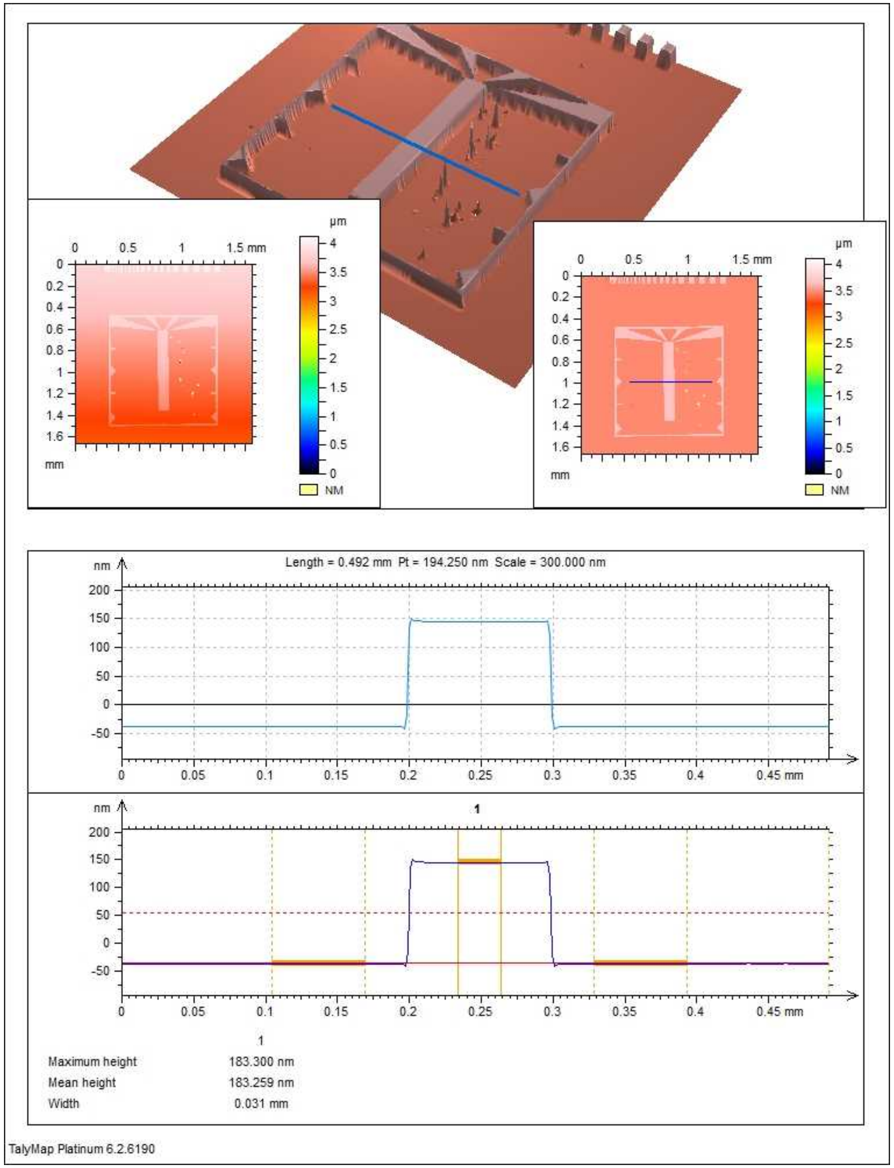




Profile extracted by software

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



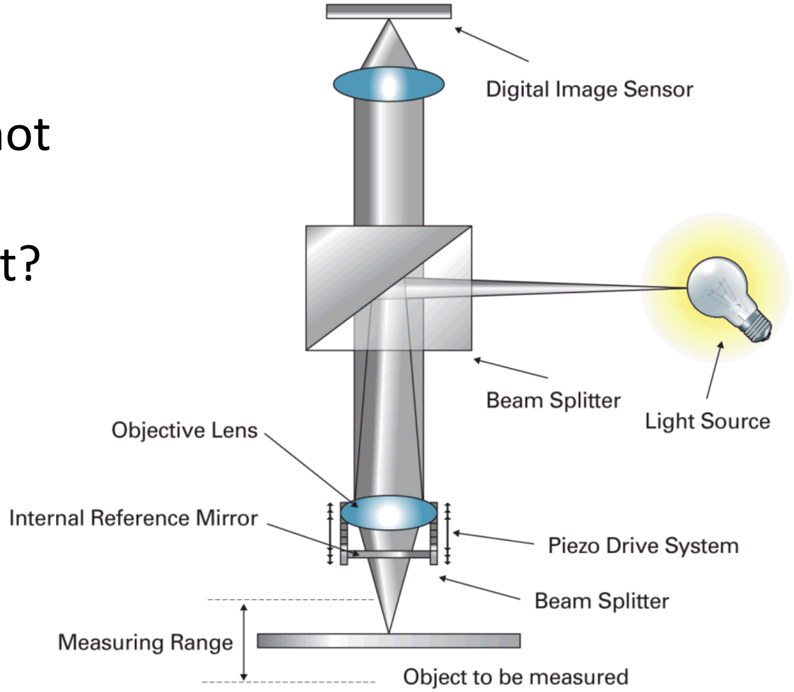
Length = 0.492 mm Pt = 194.250 nm Scale = 300.000 nm

	1
Maximum height	183.300 nm
Mean height	183.259 nm
Width	0.031 mm

TalyMap Platinum 6.2.6190

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?



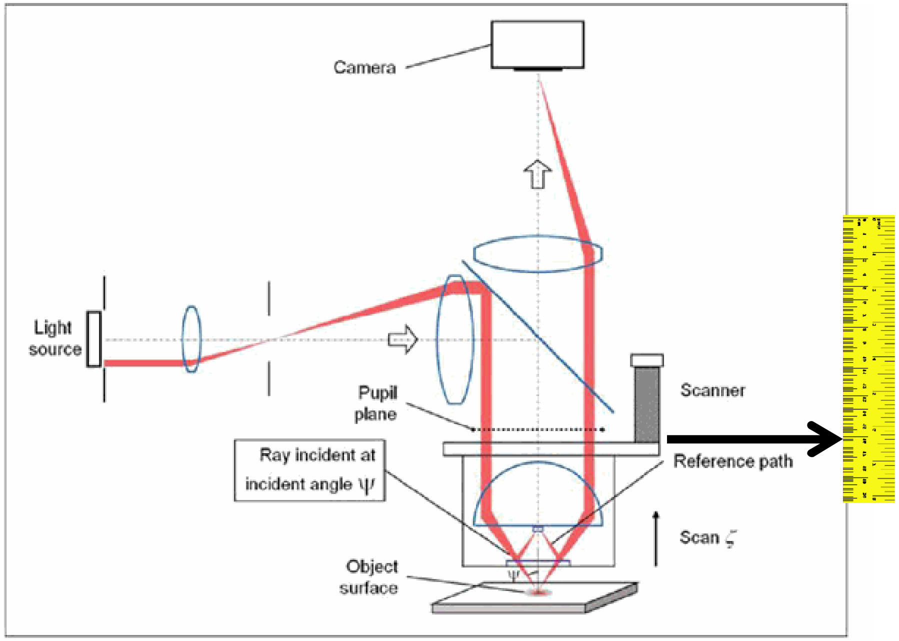


Fig. 9.4 Path of a single ray bundle through a CSI instrument

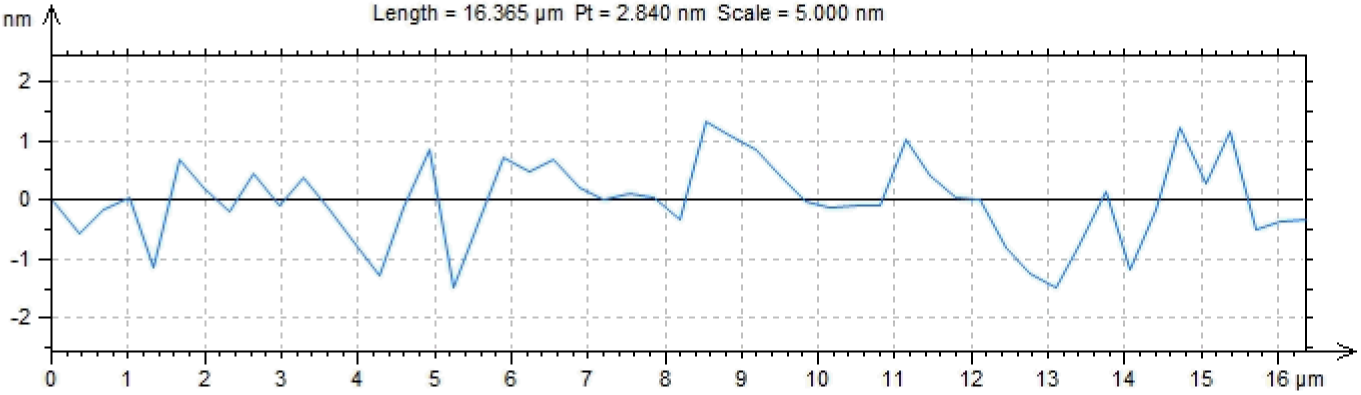
All boils down to yellow ruler (figuratively)

Calibration of step height standards

- Step height standards (Type “A” reference specimen per ASME B46.1:2009) are generally used to calibrate the vertical scale of instruments
  - Vertical scale has the greatest influence on texture parameters
- Calibration by comparison with certified reference specimens
  - It is possible to directly calibrate the motion of the *z* translation on the interferometer, but this is more difficult to perform!
- Direct comparison specimen to specimen? Or calibrate the z-translation?
  - We choose to calibrate the z-span, as if it were a graduated scale with subdivisions:
    - Span calibration (scale factor) and uncertainty of span
    - Nonlinearity of span

measurement equation; uncertainties

- use calibrated step height (CV) to calibrate vertical scale (measure MV, calculate scale factor SF $SF = \dfrac{CV}{MV}$
- measure UUT (measurement *m*).
- Calibrated value of y of UUT is: $y = m \times SF$
- Uncertainties: $u_y = \left[\left(\dfrac{\partial y}{\partial m} \cdot u_m \right)^2 + \left(\dfrac{\partial y}{\partial SF} \cdot u_{SF} \right)^2 \right]^{1/2}$



Non-linearity & non-uniformity study

Typical calibration results

	Value	Value	Value	Value	Units
CV	949.2	949.2	949.2	949.2	nm
MV	933.149	933.25	932.577	933.12	nm
SF	1.0172	1.0171	1.01782	1.01723	none
m	7.796	46.087	177.923	443.89	nm
y (UUT)	**7.93**	**46.874**	**181.094**	**451.538**	**nm**
UUT (previous cal, external source, k=2)	**8.7±0.75**	**47.4±0.90**	**180.1±3.0**	**449.5±4.4**	**nm**
1. $u_{CV\ (B)}$	4.792	4.792	4.792	4.792	nm
2. $u_{MV\ (A)}$	0.396	0.463	0.582	1.192	nm
u_{SF}	0.0052	0.0052	0.0052	0.0053	dim'less
3. $s_{m\ (A)}$	0.036	0.079	0.221	0.389	nm
4. $u_{z\ (B)}$	0.522	0.522	0.522	0.522	nm
$u_{m\ (RSS\ 3\text{-}4)}$	0.524	0.528	0.567	0.652	nm
$m \times u_{SF}$	0.04	0.238	0.921	2.351	nm
u_y	0.53	0.58	1.08	2.44	nm
$U_{y\ (k=2)}$	**1.1**	**1.2**	**2.2**	**4.9**	**nm**

Initial data

- Uncertainty is limited by master
- Optical instrument has demonstrated < 1 nm repeatability and much faster operation
- Optical instrument has demonstrated ~ ±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)

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

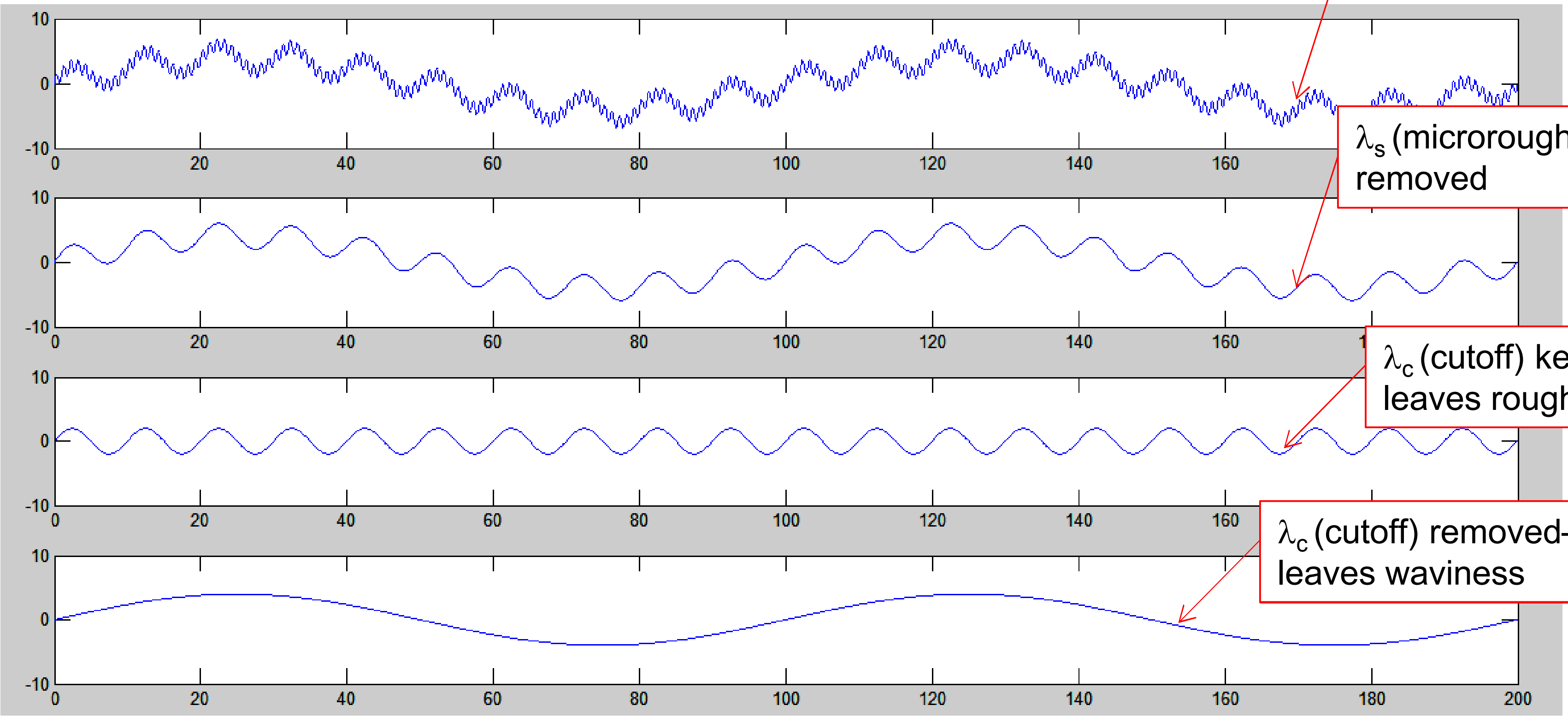
Backup slides below

Conclusions

- Surface texture is complicated! (How many standards do you need to buy?)
- Don’t create new requirements without proper study (if Ra=0.8 µm is good, then Ra=0.4 µm is not necessarily better!)
    - You may not be using the right surface texture parameter!
    - Be aware of a whole raft of ISO standards!
- Areal parameter family (S family) and fractal parameters may provide better description (and maybe correlate better with function) than R family of parameters

Filtering of profiles

- **Filters** remove undesired frequencies (or wavelengths)
  - Low pass→removes high frequencies; etc.
- Total profile: “unfiltered” (raw “z” vs “x” data)
  - May be “mechanically” filtered because of the stylus
- Filtering performed by electronics or software



Total profile

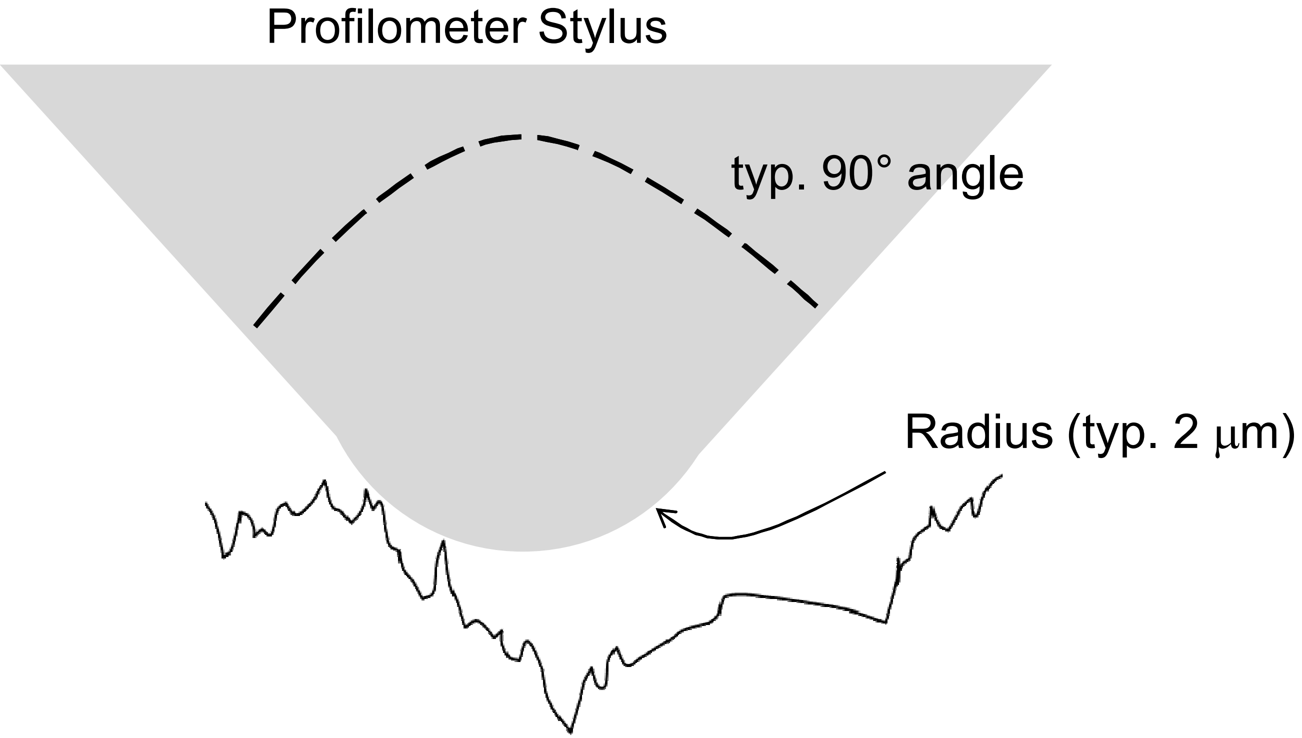
λ_s (microroughness) removed

λ_c (cutoff) kept—leaves roughness

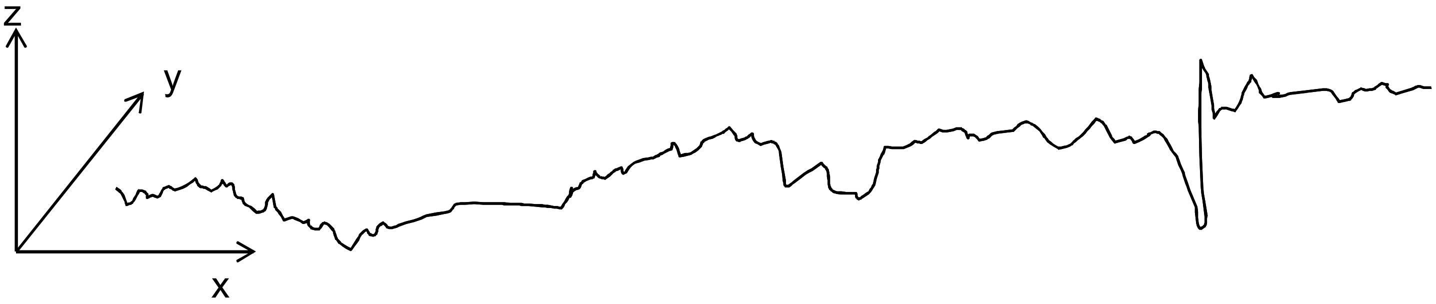
λ_c (cutoff) removed—leaves waviness

Filtering due to mechanical stylus

- Because of stylus radius (typ. 2 μm, but 5 μm and 10 μm also used), wavelengths < 2 μm typically not seen. Stylus mechanically acts like λ_s (microroughness) filter



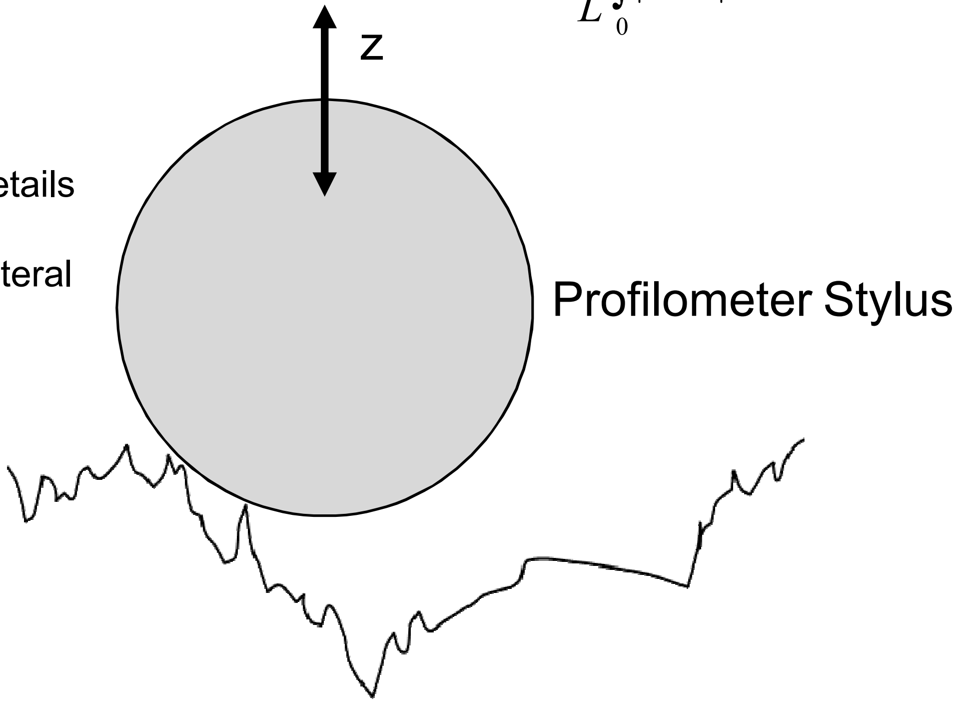
Roughness profiles, the (gory) details



- Remember that the profile goes ***across*** the direction of the lay
- Profile instruments measure z and x, and calculate:

$$Ra = \frac{1}{L}\int_{0}^{L} \left| z(x) \right| dx$$

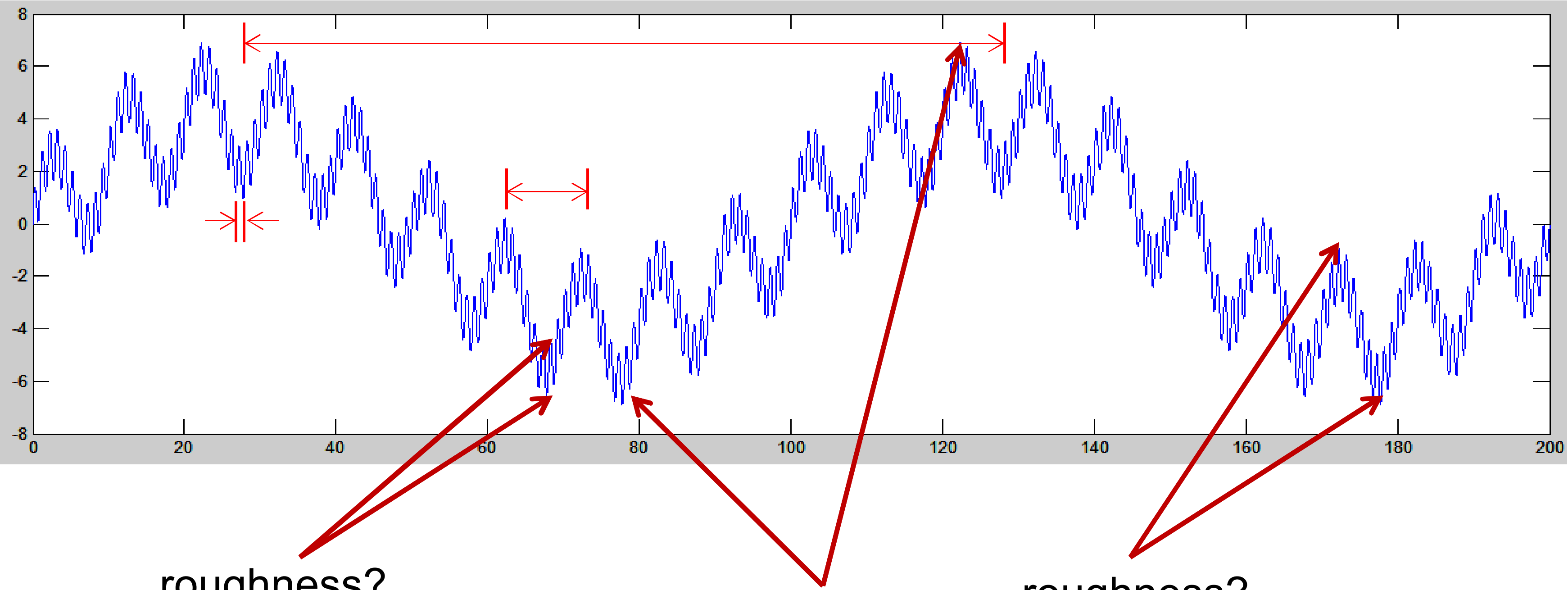
- Actual measurement?



- Stylus cannot physically measure fine details of surface
- Stylus effectively *averages* over some lateral space

More gory details

- Spatial frequency: “cycles/mm” or “cycles/μm”
- Spatial wavelength: “mm” or “μm”
- Short wavelength⇔high frequency



roughness?

roughness?

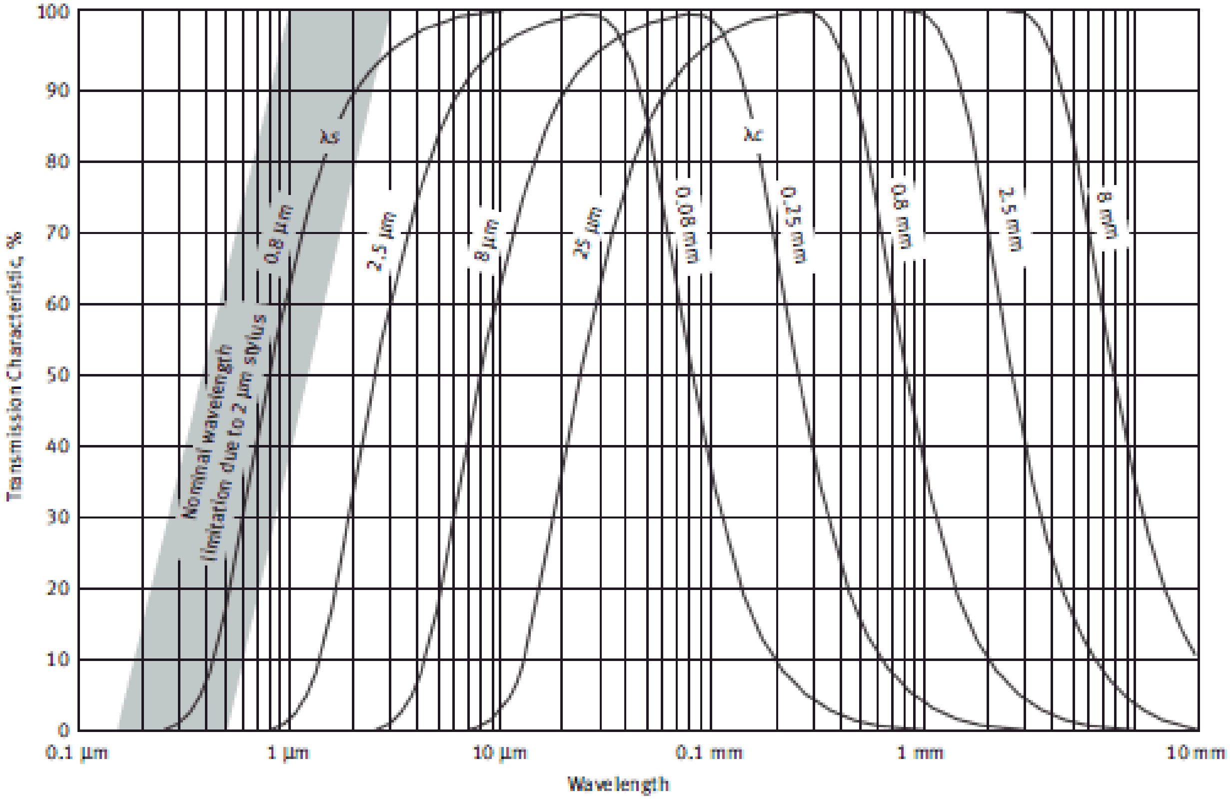
roughness?

Let’s just look at a filter

- Uncertainty in filter characteristics?
- Short wavelength (high pass); long wavelength (cutoff) location?
- Pass band variation?
- Steepness of rolloff?

Fig. 9-2 Gaussian Transmission Characteristics Together With the Uncertain Nominal Transmission Characteristic of a 2 μm Stylus Radius

(Paul Scott, Private Communication), modified



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More on uncertainty

- Remember that the instrument is typically “±7%” for Ra!
- For calculating uncertainty in Ra:
  - NPL GPG recommends only reporting the expanded type A (2 × standard error of the mean of ≥ 12 measurements)
- What functionality do you want to ensure, based on the surface texture specification?
  - Reflectivity?
  - Electrical contact resistivity?
  - Bearing ratio? (rotating O-ring seal?)
- How good do you really need to know your surface texture?