**Bandwidth characteristics and comparisons of surface
texture measuring instruments**

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1. Introduction

- Function of a surface critically depends on surface texture; proper measurement is critical; especially in 2.5-D
- In intercomparisons spread is often larger than inhomogeneity of the surface and claimed uncertainties
- Intercomparisons mainly held between profile measuring instruments, hardly on areal measuring instruments
- Many discrepancies can be explained afterwards
- Because of this it would be better to take proper precautions beforehand

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1. Introduction; Historical developments

- For workshop: tactile profile measurement: since 1935
- Optical probe (cf CD-Player) since 1985
- Areal surface measurements optical (interferometric, confocal)
Digital evaluation: boost since 1990

- Areal (semi-) tactile measurements: AFM since 1981

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1. Introduction

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Tactile probing:

Hand-held
Semi-mass product !!!!

Laboratory type
With y-table for 2.5D surface measurements

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1. Introduction

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Unifications/smooth transitions needed:

Profile

Areal

Optical

Tactile

Semi-tactile

Point

Areal

e.g. AFM, tapping mode

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2. Past and recent comparisons

Haitjema (1997): Groove depth (simplest, most accurate)

Comparison between NMI's; both tactile and optical

- Small grooves: ok within few nm
- Deeper grooves (few μm): not ok, even for uncertainty of 2%

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2. Recent comparisons

Leach (2002) sinusoidal surface; $\lambda = 8 \mu\text{m}$ $A = 0.5 \mu\text{m}$

- Mechanical probe form may affect measurement
- Structure may be close to lateral resolution of optical instruments
- Result is rather dramatic
- Differences can somehow be explained, but what about an instrument user who just takes a measurement ?

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2. Past and recent comparisons

Rubert (Chemnitz, 2008) sinusoidal surface; $\lambda = 100 \mu\text{m}$ $A = 5 \mu\text{m}$

Ranges of values for R_a / S_a

Mechanical probe	: 304 – 323 nm
Chromatic sensor	: 272 - 302 nm
Confocal	: 311 – 324 nm
White-light Interferometer	: 78 – 368 nm

Also here:

Discrepancies can be explained, but one would prefer not to need to

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3. Bandwidth limitations when comparing stylus instruments

General influencing factors:

- Instrument calibration in relevant vertical and horizontal axes
- Noise and drift levels
- Stylus speed low enough to prevent stylus flight
- Stylus force low enough as not to damage the surface.

SEM-picture of damaged probe

Probe Traces in Cu-Ni; Morel, 2006

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3. Bandwidth limitations when comparing stylus instruments

Bandwidth and stylus size as standardized:

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3. Bandwidth limitations when comparing stylus instruments

Bandwidth and stylus size as standardized:

Table 1 Relationship between cut-off wavelengths (λ_s and λ_c), tip radius (r_{tip}) and maximum sampling spacing

λ_c /mm	λ_s / μm	Roughness cut-off wavelength ratio λ_c/λ_s	r_{tip} max / μm	Maximum sampling spacing / μm
0.08	2.5	30	2	0.5
0.25	2.5	100	2	0.5
0.8	2.5	300	2	0.5
2.5	8	300	5	1.5
8	25	300	10	5

Note: sampling spacing such that there are 5 samples in one λ_s cut-off

Note: ISO 4288 recommends taking measurement length of 5 λ_c cut-offs

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3. Bandwidth limitations when comparing stylus instruments

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Bandwidth and stylus size considerations:
Geometrical probe effect

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3. Bandwidth limitations when comparing stylus instruments

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Connecting probe size to bandwidth

Taking for granted that probe effects are non-linear

Bandwidth and stylus size considerations:

Geometrical probe effect

Ball probe with radius, R , can measure the top and bottom of a sinusoidal profile if

$$R \leq \frac{\lambda^2}{4\pi^2 A}$$

λ : wavelength; A amplitude of sinusoidal profile.

R_t (R_z) is unaffected if probe satisfies this condition

Critical wavelength λ_t can be defined

$$\lambda_t = 2\pi\sqrt{AR}$$

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3. Bandwidth limitations when comparing stylus instruments

Connecting probe size to bandwidth

Simulations for sine-waves with $\lambda < \lambda_t$

Note there is no resolution limit: very small amplitudes can be measured with large probe

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4. Limitations of optical instruments

Basic problem;

Interaction of electromagnetic radiation with surface

Is far more complicated than mechanical probe-surface interaction

Issues:

- (internal) reflection
- Scattering
- Diffraction

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4. Limitations of optical instruments

Example: Ball measurement with an interference microscope

Mechanical reality

Objective

Ball

Mirror

Optical reality:

Hemisphere

Plane

Hemisphere

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4. Limitations of optical instruments

Common aspect for microscope-based instruments:

Lateral resolution r depends on Numerical Aperture (N.A.)

Fig. 7.62. Illustrating two monochromatic spectral components just resolved according to the RAYLEIGH criterion.

$$r = 0.61 \frac{\lambda}{\text{NA}}$$

Classical issue: see Born&Wolf: Principles of Optics

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4. Limitations of optical instruments

Common aspect for microscope-based instruments:
 Lateral resolution r depends on Numerical Aperture (N.A.)
 Additional: pixel array in camera

$$r = 0.61 \frac{\lambda}{NA}$$

Table 2 Typical data for microscope with CCD and different objectives

Magnification	NA	Resolution / μm	Pixel spacing / μm
10x	0.3	1.00	1.75
20x	0.4	0.75	0.88
50x	0.5	0.60	0.35

Combination (0.75 μm , 0.88 μm) may lead to worse effective resolution (1.16 μm)

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4. Limitations of optical instruments

However, surface measurement is not for brightness,
 but for surface (height) features.

ISO CD 25178-604
Specification of coherence scanning interference microscopes

chapter 3.4.12: lateral resolution
 <CSI>one-half the spatial period for which the instrument response (measured feature height to actual feature height) falls to 50%.

Characteristics:

- Can be generalised
- Compatible with Rayleigh criterion
- Disregards a-symmetry (peak vs valley) and size effects
- Implicit assumption: for heights << optical wavelength

(Maybe better call this 'spatial period limit')

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4. Limitations of optical instruments

For metals, light appears to penetrate in the surface before being reflected.

Mechanical surface: glass with 20 nm gold coating:
$$\delta = \arctan\left(\frac{2n_1k_2}{1-n_2^2-k_2^2}\right)$$

Mechanical measurement
(scratch, probe convolution at edge, indentation)

Optical measurement (artifact at edge, penetrates in metal)

Even more tricky: transparent coatings/A.R.-coatings

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5. Bandwidth matching

5.1 Bandwidth in profile comparisons:

Follow ISO: e.g. $\lambda_c = 0.8 \text{ mm}$, $\lambda_s = 2.5 \text{ }\mu\text{m}$, $L = 4 \text{ mm}$, spacing is $0.5 \text{ }\mu\text{m}$

● Shows at what points the filter is defined

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5. Bandwidth matching

5.1 Bandwidth in profile comparisons:

Follow ISO: e.g. $\lambda_c = 0.8 \text{ mm}$, $\lambda_s = 2.5 \text{ }\mu\text{m}$, $L = 0.8 \text{ mm}$, spacing is $2.5 \text{ }\mu\text{m}$

● Shows at what points the filter is defined

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5.2 Bandwidth in areal comparisons:

Bandwidth 1:300 and proper filter definition hard to achieve (8000 profiles of 8000 points)

Mechanical/Optical point probe: many lines; too long measurement time (hours; days)

Areal/Optical: Limitations in lateral resolution, sample amount and sample size.

Path taken by ISO-committee:

Default bandwidth 1:100; **saves factor of 9**

1 cut-off wavelength is enough (area 0.8×0.8 instead of $4 \times 4 \text{ mm}$); **saves factor of 25**

For optical measurements:

Optical lateral resolution limit may replace λ_s -filter (**may save factor of 3**)

3 measurement points instead of 5 within λ_s filter suffice (**saves factor of 3**)

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5.2 Bandwidth in areal comparisons:

Consequences:

For mechanical probing measurements: bandwidth 1:100 + 5 x sampling

Minimum 500 x 500 measurements. **For industry: forget it**

For typical optical microscopic measurement, 480x640 points

Magnification	Resolution /μm	Pixel spacing /μm	Bandwidth
10x	1.00	1.75	1 : 160
20x	0.75	0.88	1:160
50x	0.60	0.35	1:280

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5.3 Bandwidth matching criteria

For a proper data comparison, as a basic principle the bandwidth must match.

Explicitly:

Take same measurement length/area, filter type, filter cut-offs
Even better: define where in the surface to take the measurement

Implicitly:

Take same filters/lateral resolution and measurement length or long-wavelength cut-off

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5.4 Measurement example:

Halle type D standard; $R_a = S_a = 0.55 \mu\text{m}$
Measured under default conditions, bandwidth 1:300:

Measured effect of bandwidth related issues:

Changed parameter	Effect on R_a/S_a
Single λ_c cut-off instead of five i.e. measurement length 0.8 mm instead of 4 mm	-4 %
Single λ_s cut-off instead of five i.e. measurement spacing $2.5 \mu\text{m}$ instead of $0.5 \mu\text{m}$	+0.1 %
No λ_c filter in single λ_c cut-off	+6.5 %
No λ_c filter in five λ_c cut-offs	+39 %
No λ_s filter	+0.11 %
Bandwidth 1:100, $\lambda_s = 8 \mu\text{m}$	-0.5 %
Bandwidth 1:100, $\lambda_c = 250 \mu\text{m}$	-32 %
Bandwidth 1:30, $\lambda_s = 25 \mu\text{m}$, $\lambda_c = 800 \mu\text{m}$	-2.2 %
Bandwidth 1:30, $\lambda_s = 8 \mu\text{m}$, $\lambda_c = 250 \mu\text{m}$	-33 %

For this example;

- λ_s has hardly influence
- Bandwidth can be reduced if λ_c is unchanged

Major effect: correlation of least-squares line with λ_c -filter

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5.4 Measurement example:

Halle type D standard; $R_a = S_a = 0.55 \mu\text{m}$

Cut-off length

5 cut-offs in one measurement
 $R_a = 0.546 \mu\text{m}$

5 separate measurements
 $R_a = 0.524$ (4% less)

Mean (filter) line in green

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5.4 Measurement example:

Halle type D standard; $R_a = S_a = 0.55 \mu\text{m}$

Bandwidth 1:300

$R_a = 0.547 \mu\text{m}$

Bandwidth 1:30; λ_s changed

$R_a = 0.535 \mu\text{m}$ (2% less)

Bandwidth 1:30; λ_c changed

$R_a = 0.123 \mu\text{m}$ (77% less)

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5.4 Measurement example:

Halle type D standard; $R_a = S_a = 0.55 \mu\text{m}$

Provisional conclusions for Roughness amplitude parameters:

- λ_s limitation and sampling resolution is important in theory but not in practice
- Longer wavelengths are most important in technical surfaces
- Bandwidth can safely be reduced if λ_c is unchanged
- Reducing measurement length to $1 \times \lambda_c$ reduces roughness
- Reducing measurement length to $1 \times \lambda_c$ reduces homogeneity (with factor of 2 at least)

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6. Software Issues

Some ambiguities and lack of standardization may cause problems:

- Integral versus digital definition of parameters
- Taking least-squares reference and if so, how
- Taking measurement length larger than evaluation length
- Taking extra length into account when correcting for least-squares reference
- Some parameter definitions are ambiguous (e.g. *RSm*)

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6. Software Issues

Digital versus Integral definition of parameters

Note: only difference at zero-crossings, hard to notice in practice

Any other mathematics (FFT, filtering, least-squares) takes digital definition

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7. Comparison of profile and areal measurements/parameters

In standardisation it is tried to keep transition smooth e.g. $Ra \approx Sa$

In practice, there is seldom correspondence because:

- Areal filter works in a points areal environment vs in one line
- For peak parameters a line is likely to miss the peaks in a surface
- For some areal parameters there is no profile-equivalent

If you still want to give it a try:

- Align orientation with surface lay.
- Use Gaussian filter with same cut-off lengths
- Take same stylus tip and sample spacing
- Traverse length should be integer amount of cut-offs

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8. Summary and conclusions

When comparing surface measurements:

- Check homogeneity of specimen or define measurement area
- Understand limitations of the instruments involved
- Make sure the bandwidths match
- Minimize effects of software differences (e.g. level surface)
- Make sure relevant measurement axes are calibrated

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