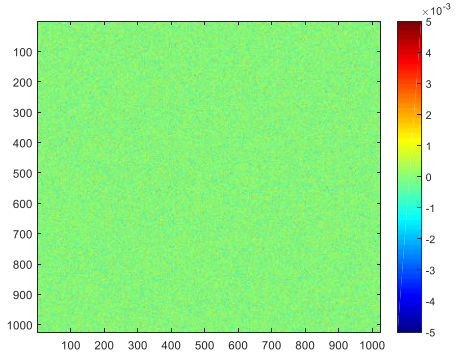
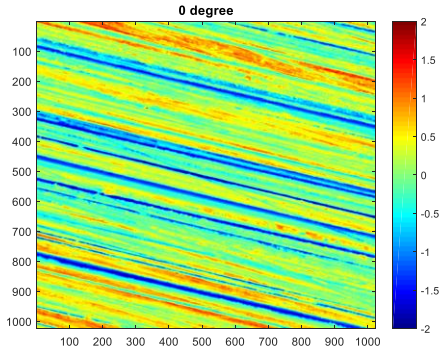
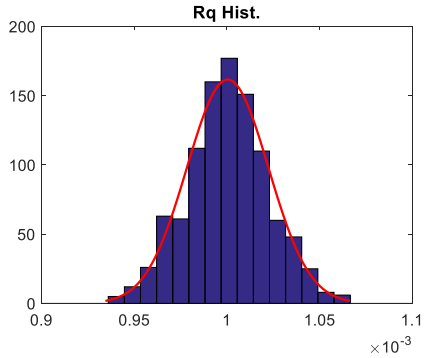
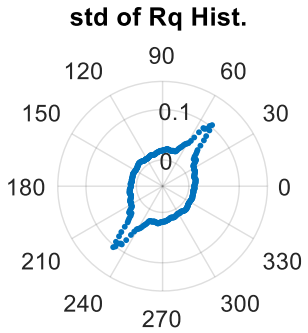
CHARACTERIZATION OF GEOMETRIC SURFACE FEATURES USING STATISTICALLY BASED ANALYTICAL TOOLS









Student: Farzad Azimi
Advisor: Dr. Mullany

UNC CHARLOTTE

The WILLIAM STATES LEE COLLEGE *of* ENGINEERING

Outline

- ❑ History
- ❑ Motivation
- ❑ Polar plots
  - With respect to surface texture
    - *Sq* roughness of a Gaussian surface
    - Isotropy
    - Directionality
    - Periodicity
  - With respect to surface feature
    - Single feature
      - Single dig
      - Single scratch
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      - Multiple scratches
      - Mixed features
  - ❑ Summary
  - ❑ Future directions

Surfaces topography

What is a surface?

- A continuous boundary dividing a three dimensional space into two regions. (*http://www.britannica.com*)
- Surface limiting the body and separating it from the surrounding medium. (*ISO 4287*)
- **Materials boundaries** (Thomas, T. R. "Rough surfaces")

Materials' properties [1]:

I. Mechanical

II. Geometrical

Surface topography: deviation of surface from a reference plane

Surface topography affects:

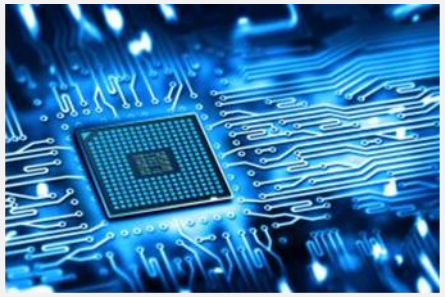
- Mechanical interaction **[2-7]**
- Dispersion and reflection of rays **[8-12]**
- Heat transfer **[13-16]**
- Fluid interaction with surface **[17-20]**
- Longevity and performance under fluctuating loads **[21-27]**
- Semiconductor parts functionality **[28-29]**

In general surface topography is one of the main factors that affects the final product functionality

https://www.quora.com/What-is-a-gearbox

http://ast.noao.edu/facilities/other/het

https://colombia.bioweb.co/products/binoculares-bushnell-powerview-super-high?variant=18514208837



https://bryantarchway.com/semiconductor-warfare/

Surfaces measurement

Lots of research to characterize surfaces and find metrics to link manufacturing to part functionality

Stylus measurement instrument (1927, [31])

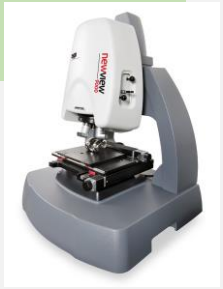
- Average roughness, R_a
- Extreme parameters, Pv

https://www.mahr.cn/zh/Services/Production-metrology/Products/MarSurf---Contour-Measuring-Units/MarSurf-XC-2/

Advance in technology and instruments

Areal measurement instrument (1970, [31-32])

S_a, S_q, S_{sk}, S_{ku}, S_{tr}, S_{al}, S_{dq},…



https://www.zygo.com/met/profilers/newview9000/newview9000_instrument_lg.jpg

Parameter rash

Standards

ISO 25187-2

Means of communication between manufacturer and customer

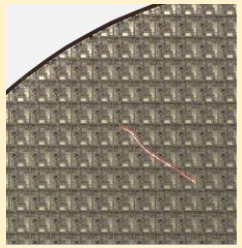
Need for:

- Precise and accurate measurements (sub-micron – sub-Nano)
- Flawless parts (electronics industry as driving force) [33]

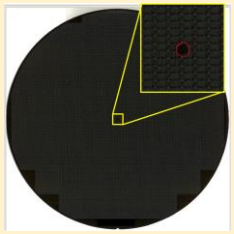
Features detection and characterization [33]

(Preferably in process inspection)

- Function
- cosmetics



http://www.microtronic.com/defect-library/scratches-by-human/

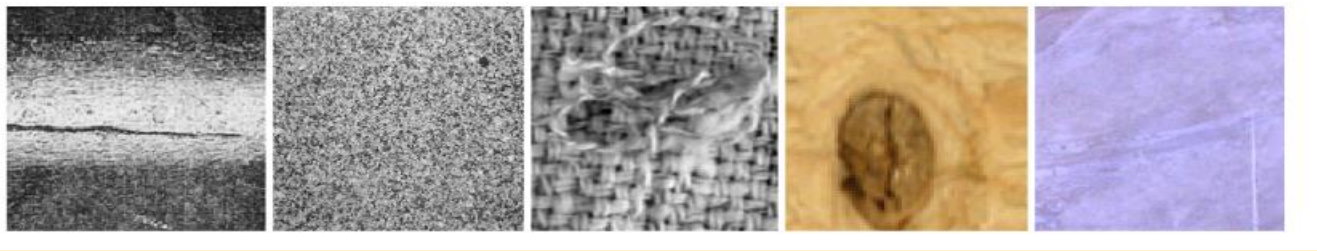


http://www.microtronic.com/defect-library/center-spin-macro-defect/

https://www.dpreview.com/forums/post/57784834

http://www.karimunjawaadventure.com/product-tag/window-concealed-hinges-heavy-duty.html

steel stone textile wood Ceramic tile



Xie, Xianghua. "A review of recent advances in surface defect detection using texture analysis techniques." ELCVIA Electronic Letters on Computer Vision and Image Analysis 7.3 (2008).

Manual feature detection and characterization

Characterization
ISO-25178-2: 2012

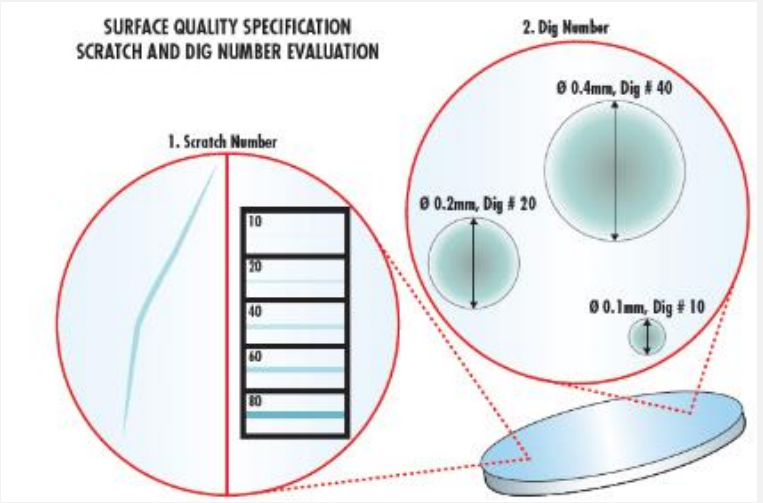
1. Selection of the type of texture
   - Hills and dales
   - Course and ridge lines
   - Peaks, pits, and saddle points
2. Segmentation
   - To determine regions of the surface that defines the features
3. Determining significant features
   - To determine features that are functionally significant
4. Selection of feature attributes
   - To determine suitable feature attributes for characterization
5. Quantification of feature attribute statistics
   - To calculate suitable statistics for the significant features

- S_{pd}
- S_{pc}
- S_{10z}
- S_{5p}
- S_{5v}
- $S_{da(c)}$
- $S_{ha(c)}$
- $S_{dv(c)}$
- $S_{hv(c)}$

Manual detection
MIL-PRF-13830B

1. Slow
2. Subjective (operator dependent)
3. Costly (time + labor)

https://www.edmundoptics.com/resources/application-notes/optics/understanding-surface-quality-specifications/



https://www.edmundoptics.com/resources/application-notes/optics/understanding-surface-quality-specifications/

Automatic feature detection

Detection: Image processing techniques [34-40]		
VISUAL INSPECTION SYSTEMS	APPROACH	METHOD
	STATISTICAL	1. Histogram properties 2. Co-occurrence matrix 3. Autocorrelation 4. Local binary pattern 5. Other gray level statistics 6. Registration based
	FILTER BASED	1. Primitive measurement 2. Edge feature 3. Skeleton representation 4. Morphological operations
	MODEL BASED	1. Spatial domain filtering 2. Frequency domain analysis 3. Joint spatial/spatial frequency
	STRUCTURAL	1. Fractal models 2. Random field model 3. Texem model

Automatic inspection

- Saving human labor cost
- Performing inspection in an unfavorable environment
- Reducing demand for highly skilled inspectors
- Analyzing statistics on test information and keeping records for management decision
- Matching high speed production with high speed inspection

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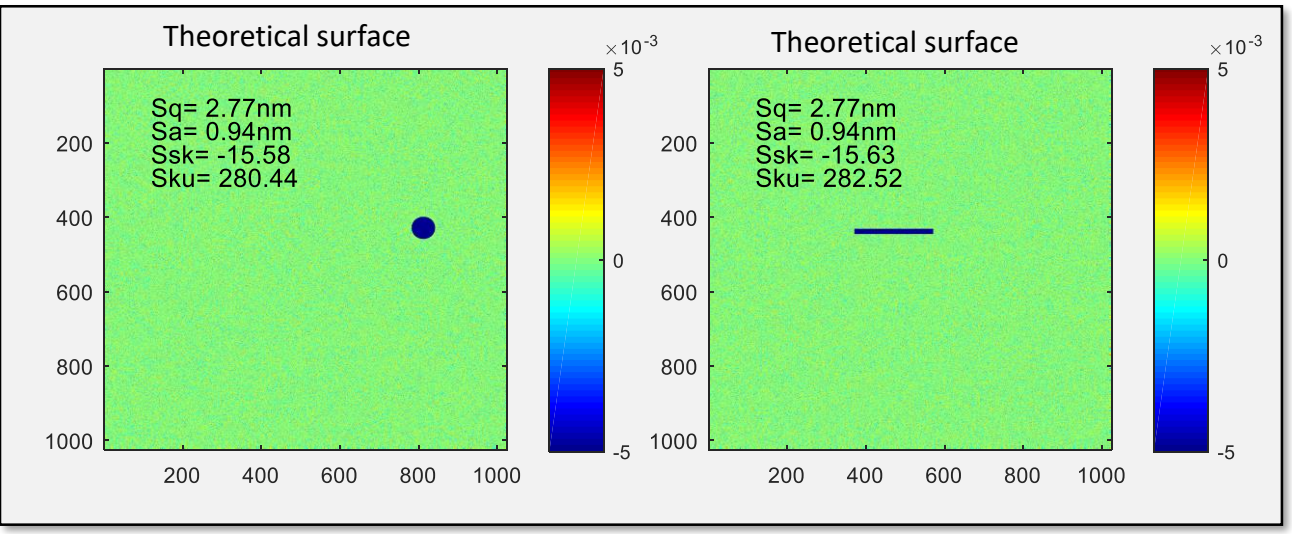
Motivation and goal

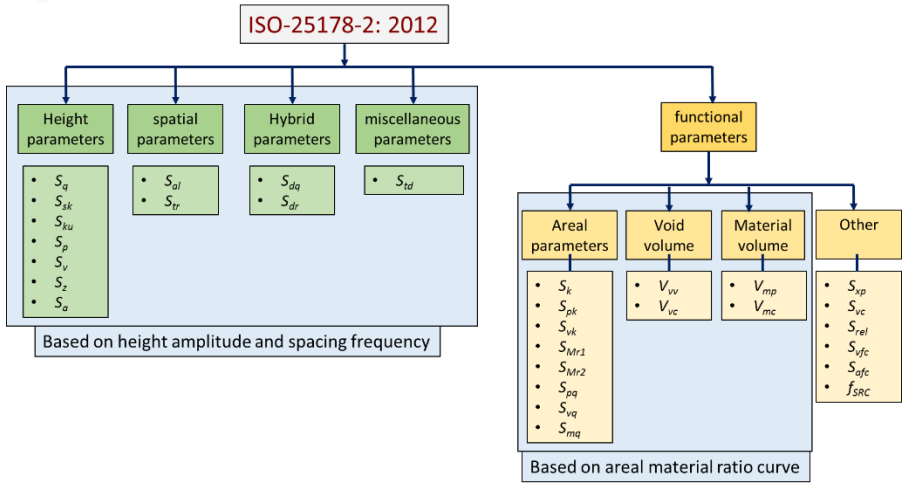


What else can be done?

Conventional approach
(ISO 25178-2)

More than 1,000,000 data points reduced to:

- Sa
- Sq
- Ssk
- …



Motivation:

Advance in technology

- Cheap memory
- Fast computing capacity

Goal:

- Automatic surface feature detection
- Surface feature characterization
- Process endpoint detection
- …

Tools:

Statistical tools

- Histogram

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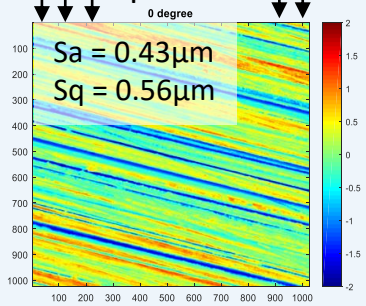
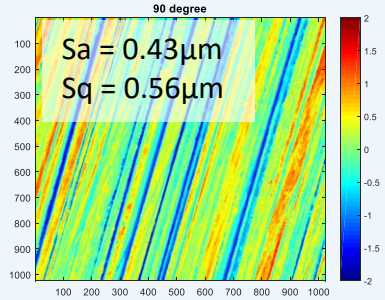
Polar plot evolution

Surf. Measured with ZeGage, 20x
(1024×1024 pixel, 417×417 µm FOV)

1024 Line profiles



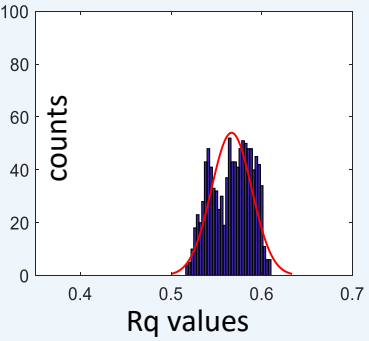
Same Surf. Rotated 90°



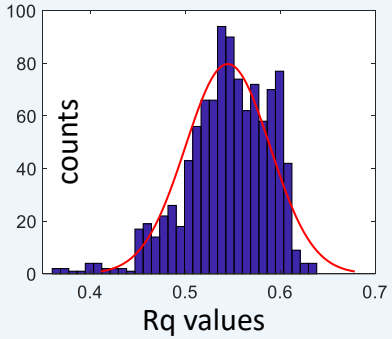
1024 *Rq* values

1024 *Rq* values

Hist. of *Rq* values

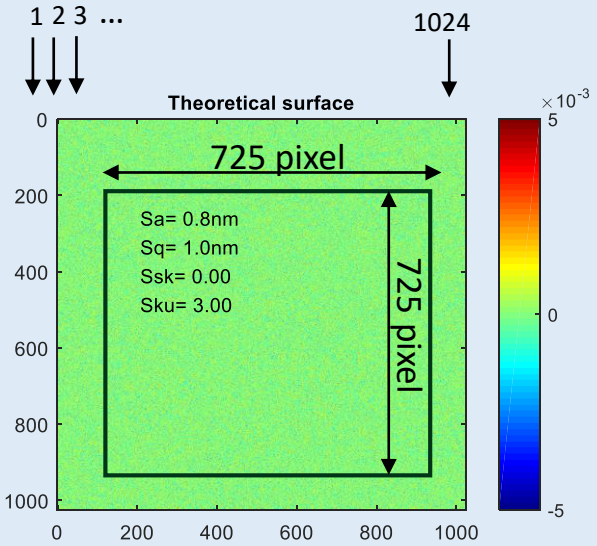


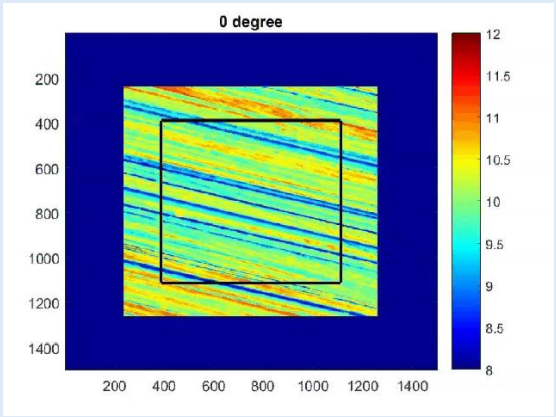
Hist. of *Rq* values



Rq shape changes for a sample

Quantify histogram
- Mean
- Standard deviation
- Skewness
- kurtosis





Rotation in MATLAB

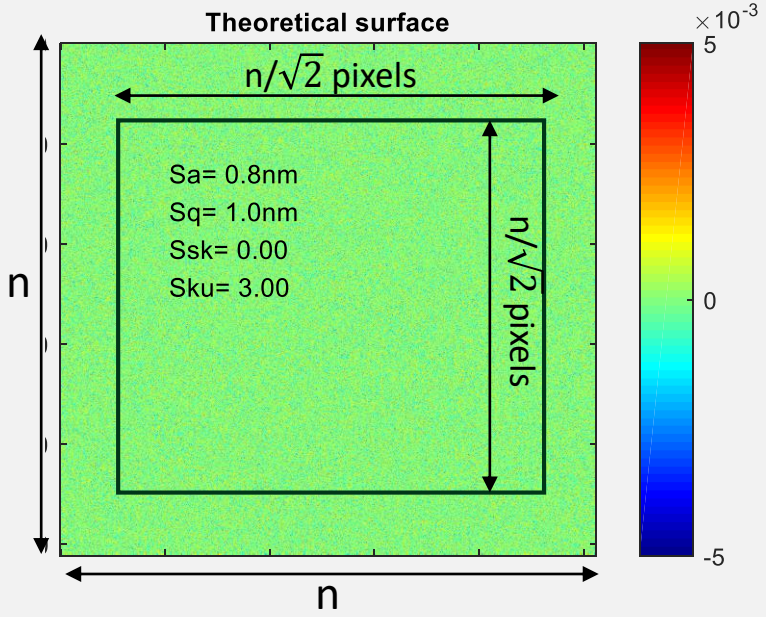
`Imrotate` command	○ Nearest neighbor interpolation ○ Bilinear interpolation ○ Bicubic interpolation

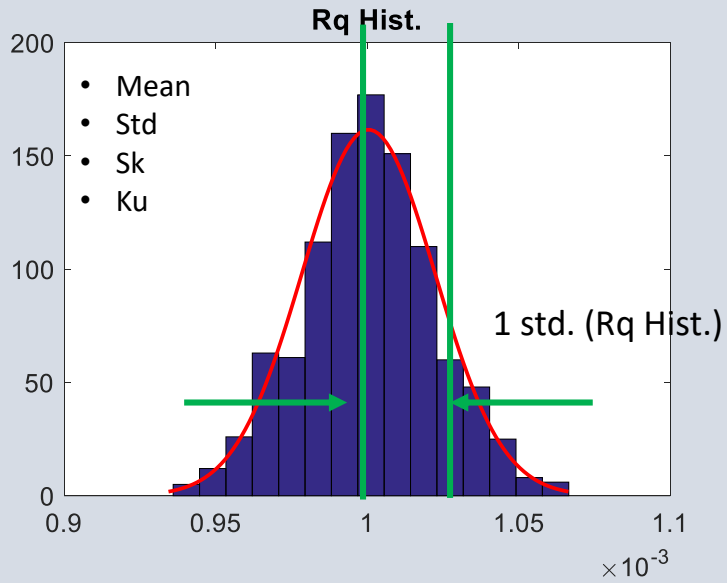
Nearest neighbor interpolation was used in order to avoid using new generated height values.

Resolution of rotation

Theory	no limit, could be any value
Computer system	Size of surface and rotation angle $\cos(\Delta\theta)+\sin(\Delta\theta)>\frac{1+n_{initial}}{n_{initial}}$

Polar plot evolution





Hist. of 725 **Rq** values at angle θ

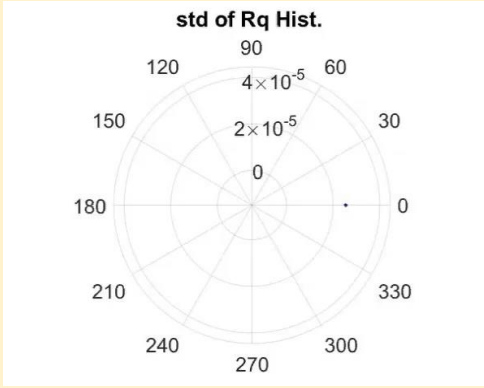
Cropping:

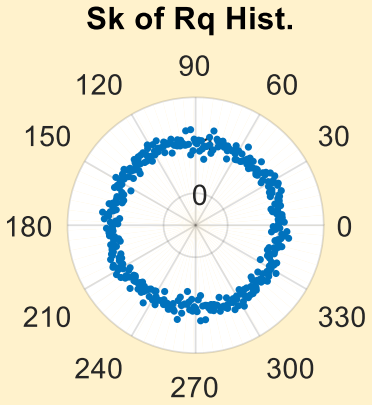
Causes data loss (50% area, 29.3% of lines)

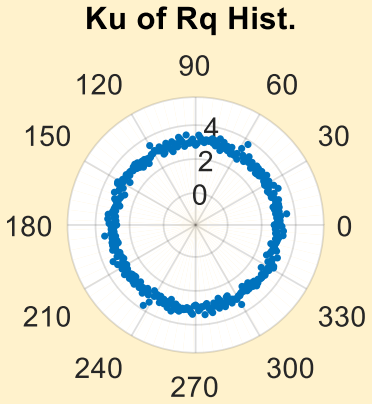
Ensures using real data

Histogram quantification

Sensitivity increase ↓	Square root of 2nd order moment of data (std.)	$\sigma_{Rq} = \sqrt{\frac{\sum_{i=1}^{N}(Rq_i - \overline{Rq})^2}{N}}$
	3rd order moment of data (skewness)	$Sk_{Rq} = \frac{\frac{1}{N}\sum_{i=1}^{N}(Rq_i - \overline{Rq})^3}{(\sigma_{Rq})^3}$
	4th order moment of data (kurtosis)	$Ku_{Rq} = \frac{\frac{1}{N}\sum_{i=1}^{N}(Rq_i - \overline{Rq})^4}{(\sigma_{Rq})^4}$







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Surface roughness of Gaussian surfaces

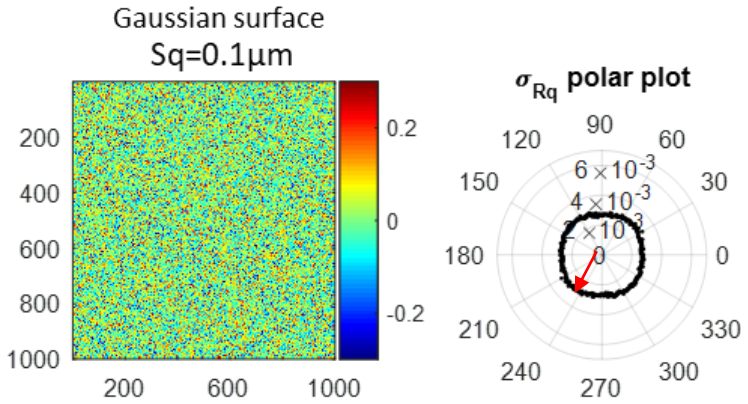
From polar plot:

Sq roughness of a Gaussian surface and radius of the σ_{Rq} polar plot.

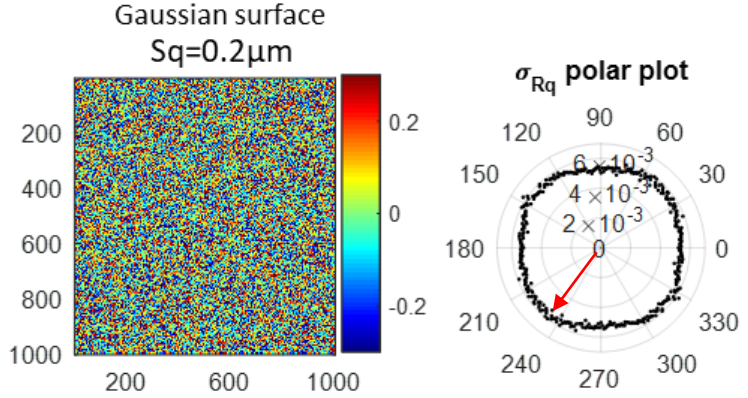
Skewness = 0

Kurtosis = 3

$$r_{\sigma_{Rq}} = \frac{Sq}{\sqrt{\sqrt{2}n}}$$



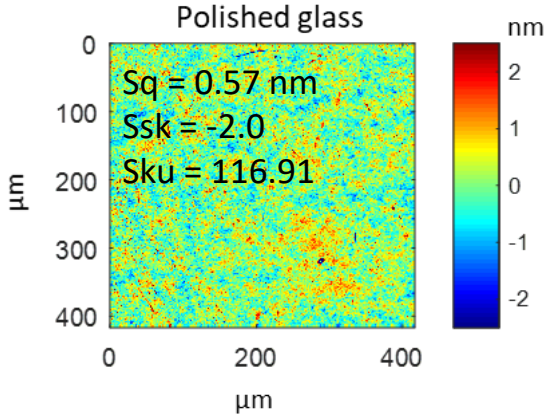
Sq increase

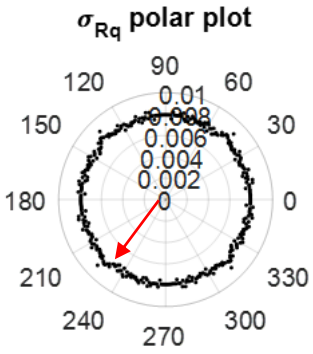


20× objective

FOV: 417 µm × 417 µm

Pixel resolution: 0.4 µm





$$r_{\sigma_{Rq}} = \frac{Sq}{\sqrt{\sqrt{2}n}} \rightarrow 0.0084 = \frac{Sq}{\sqrt{\sqrt{2}(1024)}} \rightarrow Sq = 0.56nm$$

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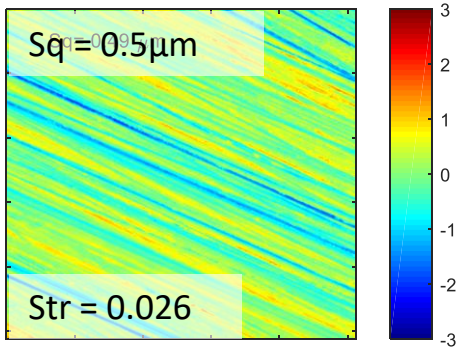
Isotropy

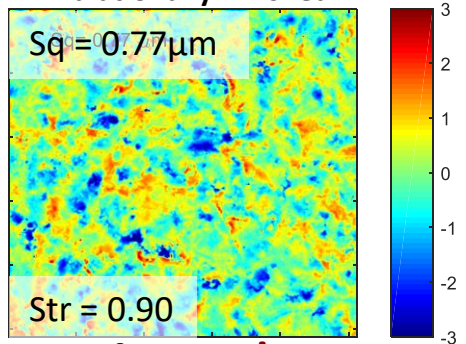
From polar plot:
Nominally circular shape shows isotropy

Ground

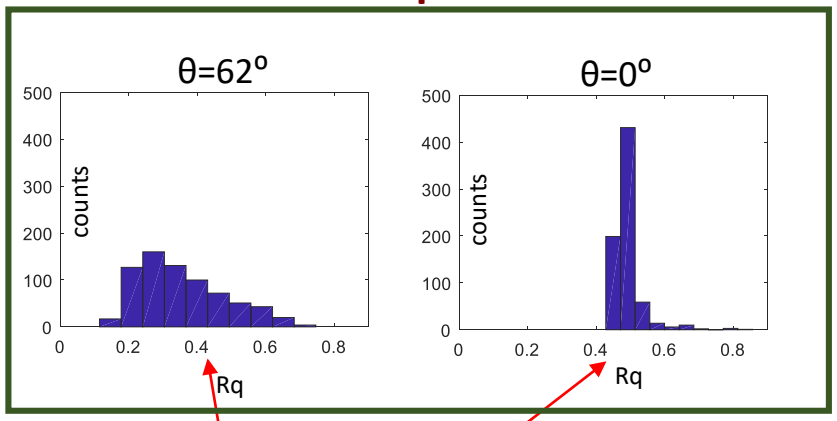


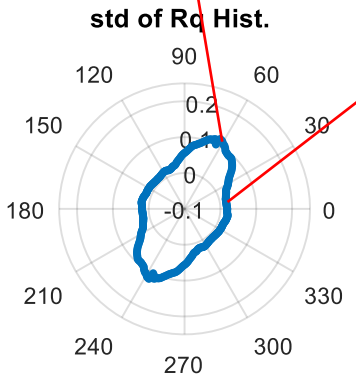
Vibrational finishing

Vibrationally Finished



anisotropic

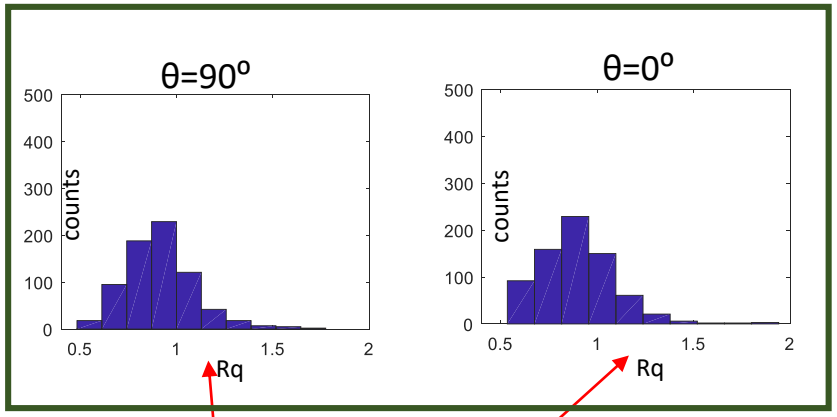


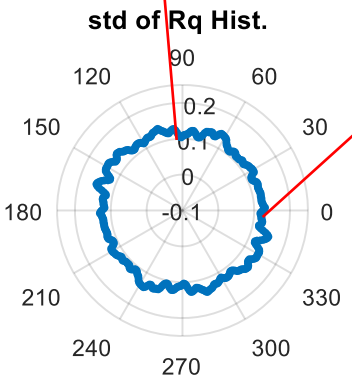


Wide dist. (When vertical lay) → large std., large radius

narrow dist. → smaller std., smaller radius

Isotropic





No significant change in hist. during rotation → no significant change in the radius

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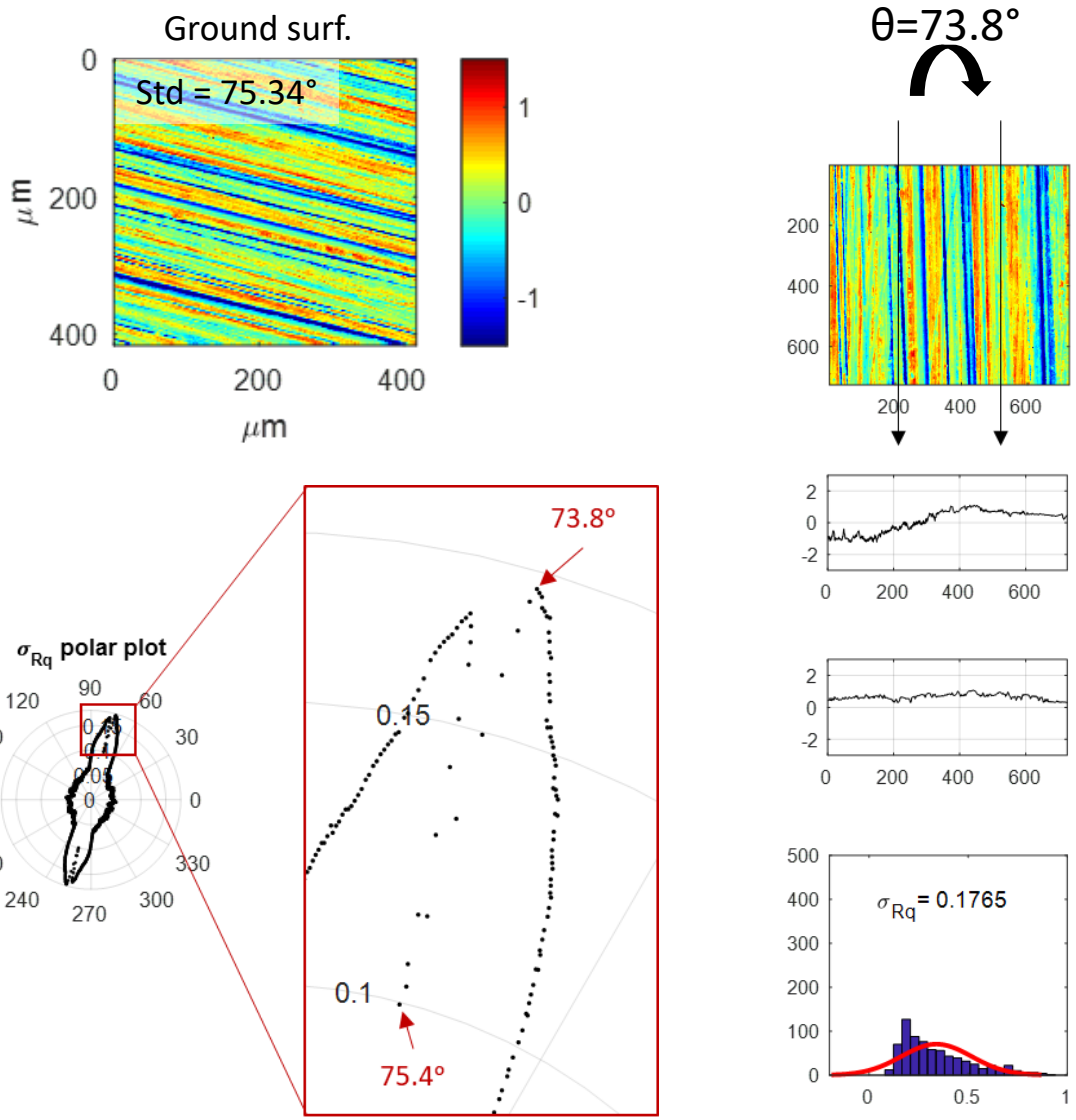
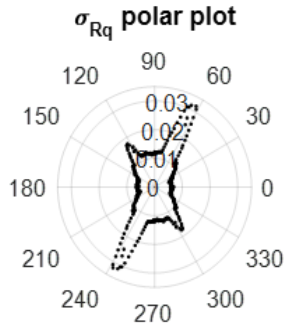
Directionality

From polar plot:
Angular location of lobe or local minimum shows the directionality wrt vertical axis



Multidirectional surfaces



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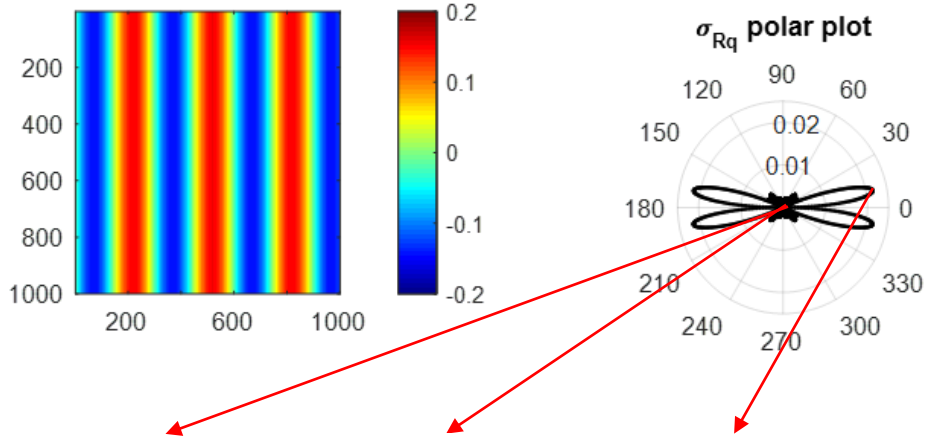
Periodic feature

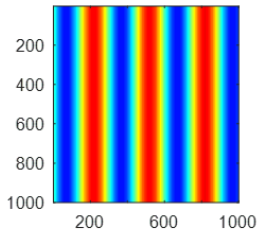
From polar plot:

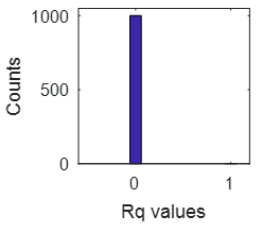
Wavelength of the periodic structure

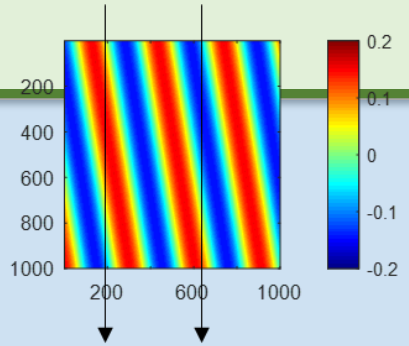
Sinewave structure

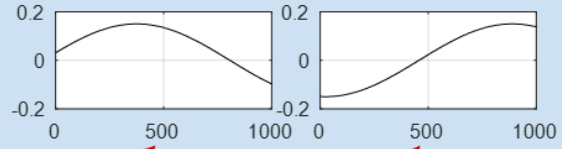


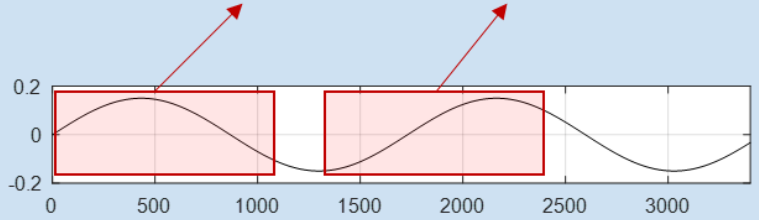
θ=0°

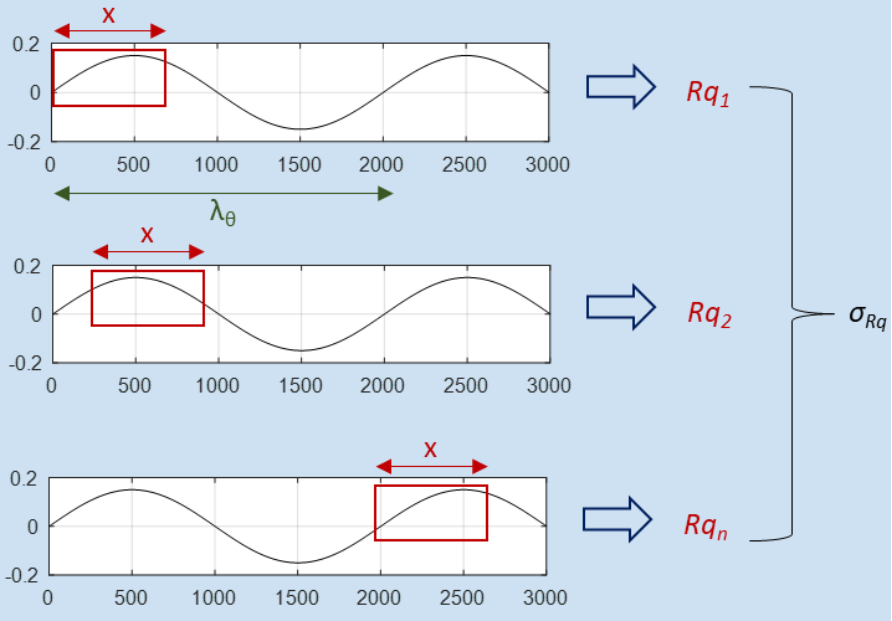






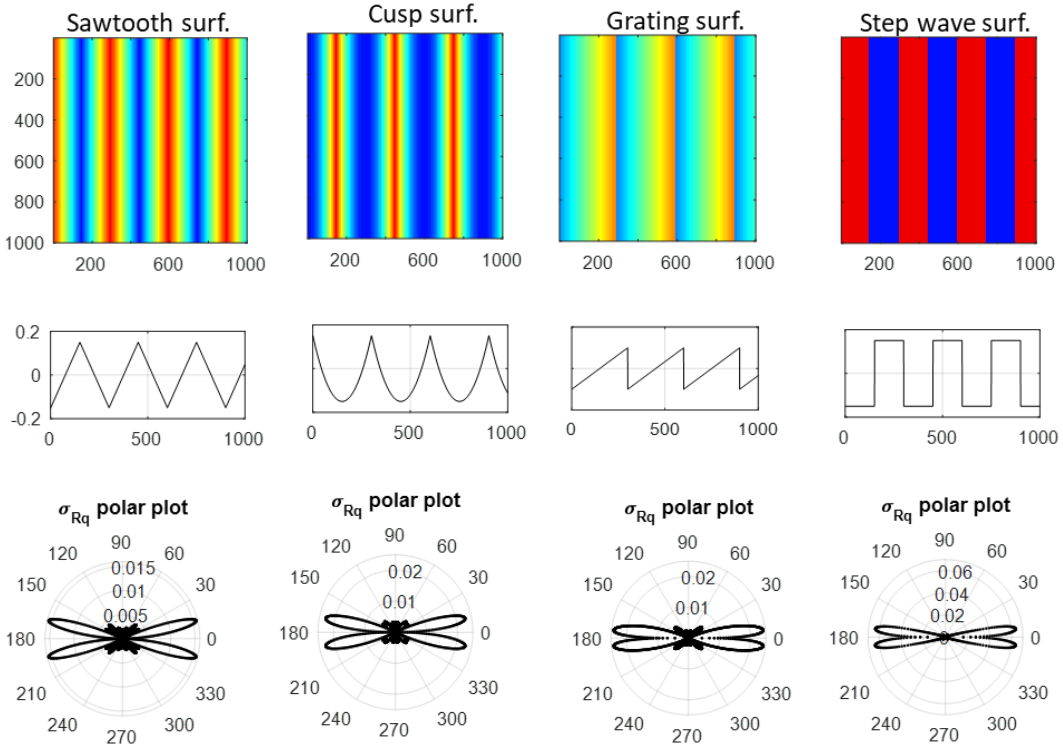






Periodic feature

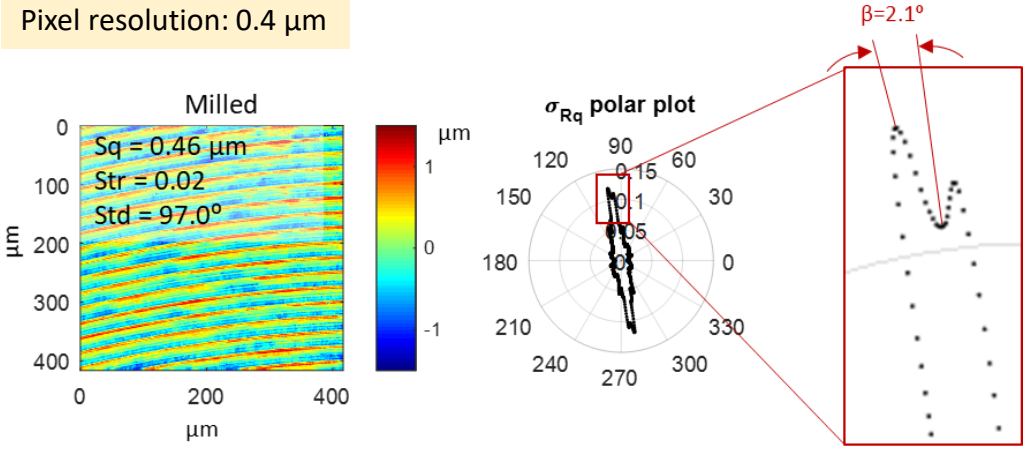
Other periodic structures



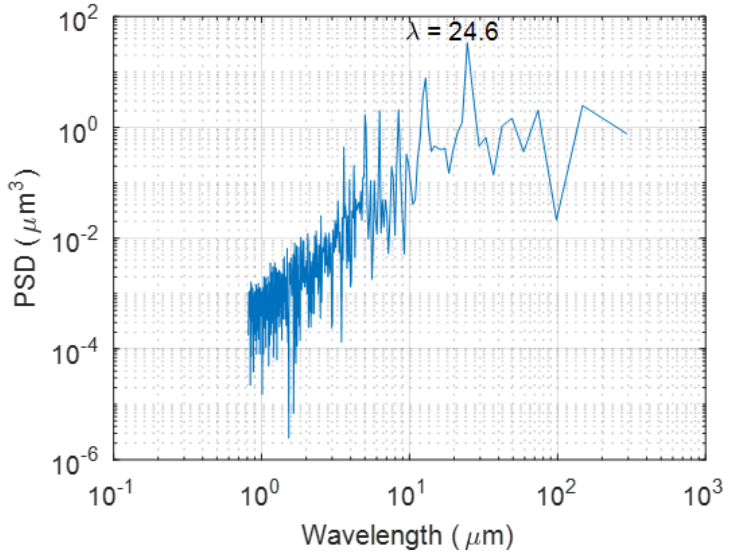
$$\lambda = round\left[\frac{n}{c\sqrt{2}}\sin\beta\right]$$

Saw tooth	Cusp	Grating	Step wave
0.565	0.546	0.278	0.269

20× objective
FOV: 417 μm × 417 μm
Pixel resolution: 0.4 μm



$$\lambda_{\sin ewave} = round\left[\frac{1024}{0.435\sqrt{2}}\sin 2.1\right] = 61 pixels \quad 24.4\ \mu m$$



- History
- Motivation
- Polar plots
  - With respect to surface texture
    - *Sq* roughness of a Gaussian surface
    - Isotropy
    - Directionality
    - Periodicity
  - With respect to surface feature
    - Single feature
      - Single dig
      - Single scratch
    - Multiple features
      - Multiple digs
      - Multiple scratches
      - Mixed features
  - Summary
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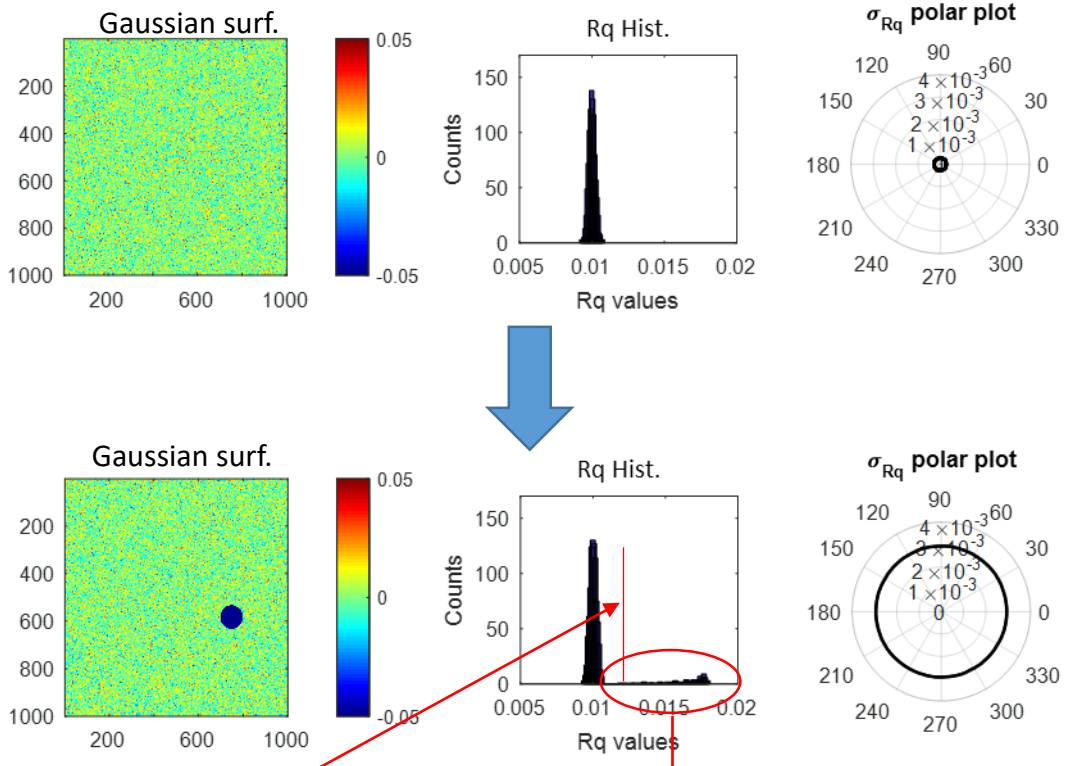
Gaussian surf. with single circular feature

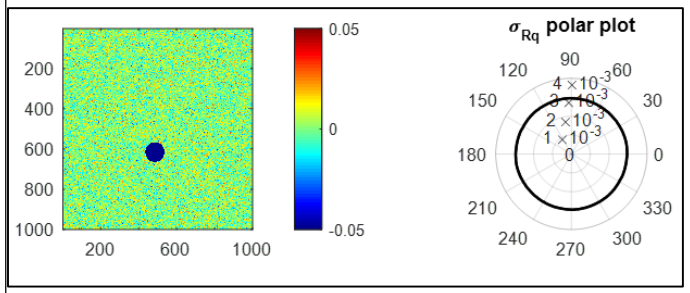
From polar plot:

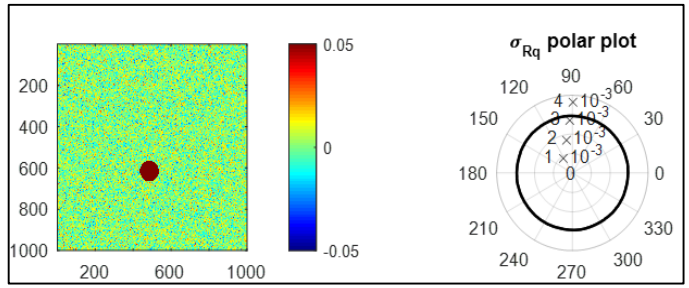
- Min. feature detectable properties graph based on surface *Sq*
- Dig diameter
- Dig depth



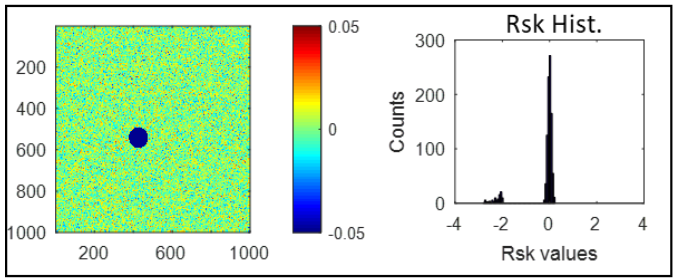
$$Rq_{defect} > Rq_{mean} + 3.2 \times \sigma_{Rq\_hist}$$

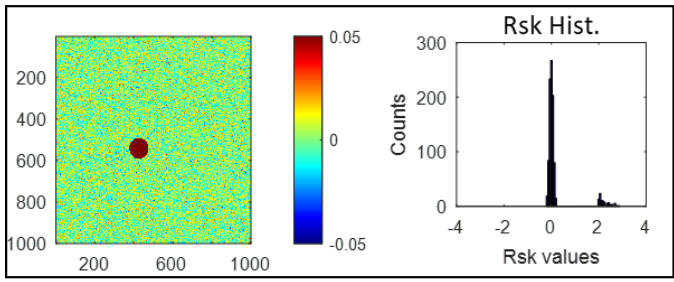
On or below the surface





$$\sigma_{Rq} = \sqrt{\frac{\sum_{i=1}^{N}(Rq_i - \overline{Rq})^2}{N}}$$



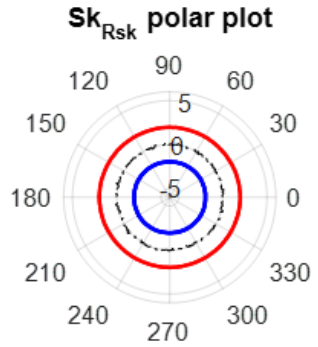


$$Sk_{Rsk} = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(Rsk_i - \overline{Rsk}\right)^3}{(\sigma_{Rsk})^3}$$

- - - polar plot of defect free sample

— polar plot of surface with dig

— polar plot of surface with dirt



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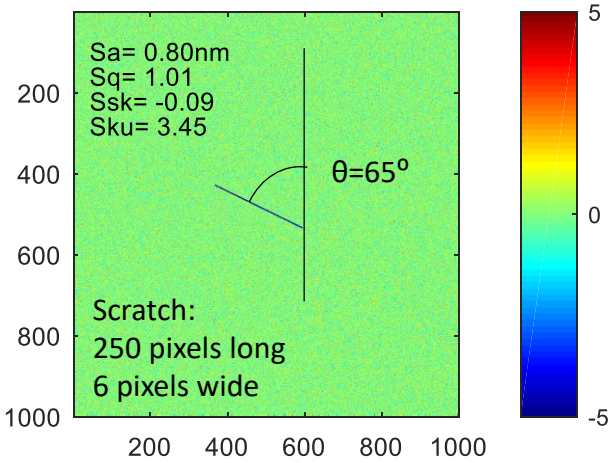
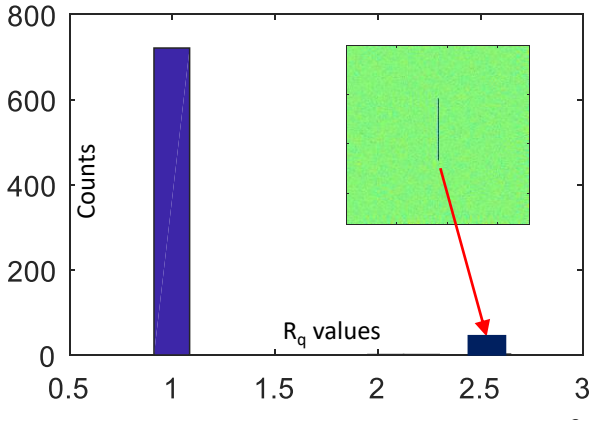
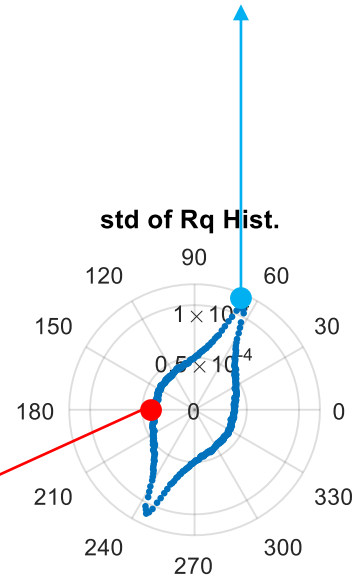
Gaussian surf. with single linear feature

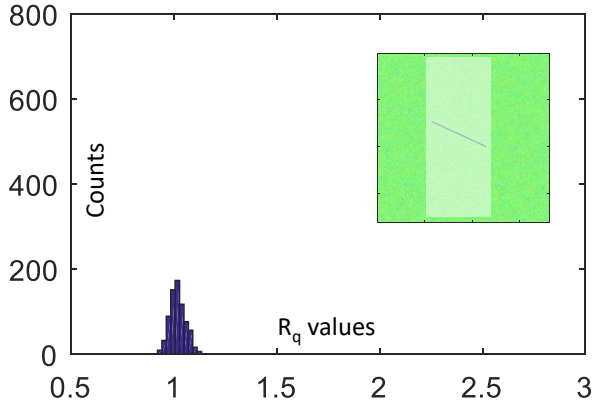
From polar plot:

- Detects scratch
- Orientation of scratch
- Length
- Width
- Min. detectable scratch curve

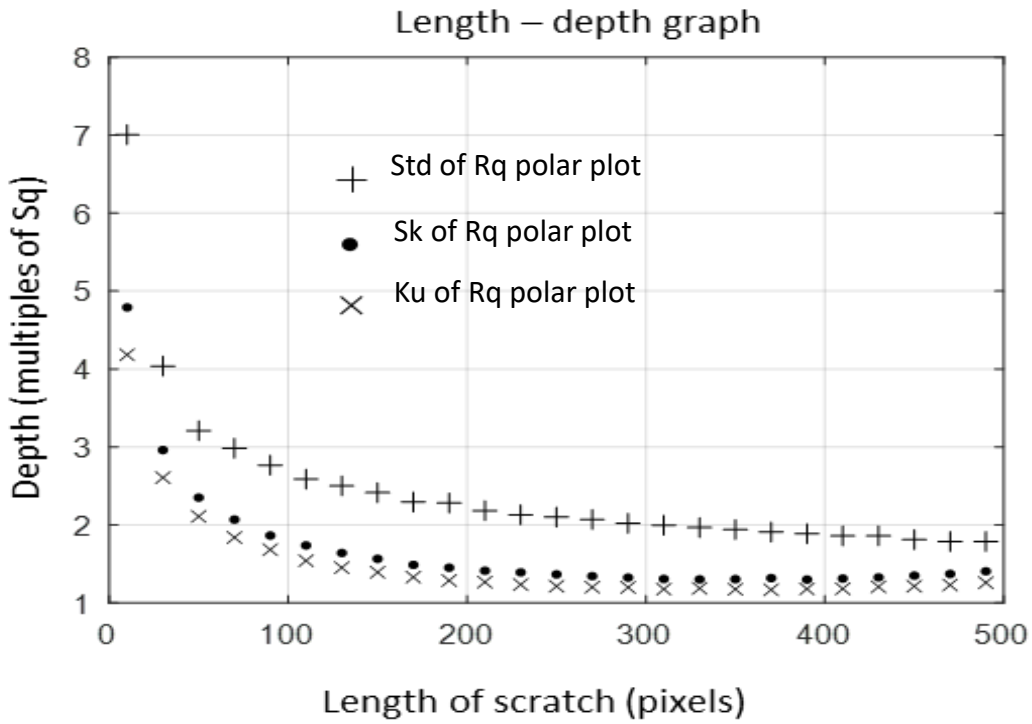








Resolution of rotation affects	
number of columns that go through scratch: #column = $ls \sin\theta$	Projected length of scratch on each column: Projected length= $ls \cos\theta$



- ❑ History
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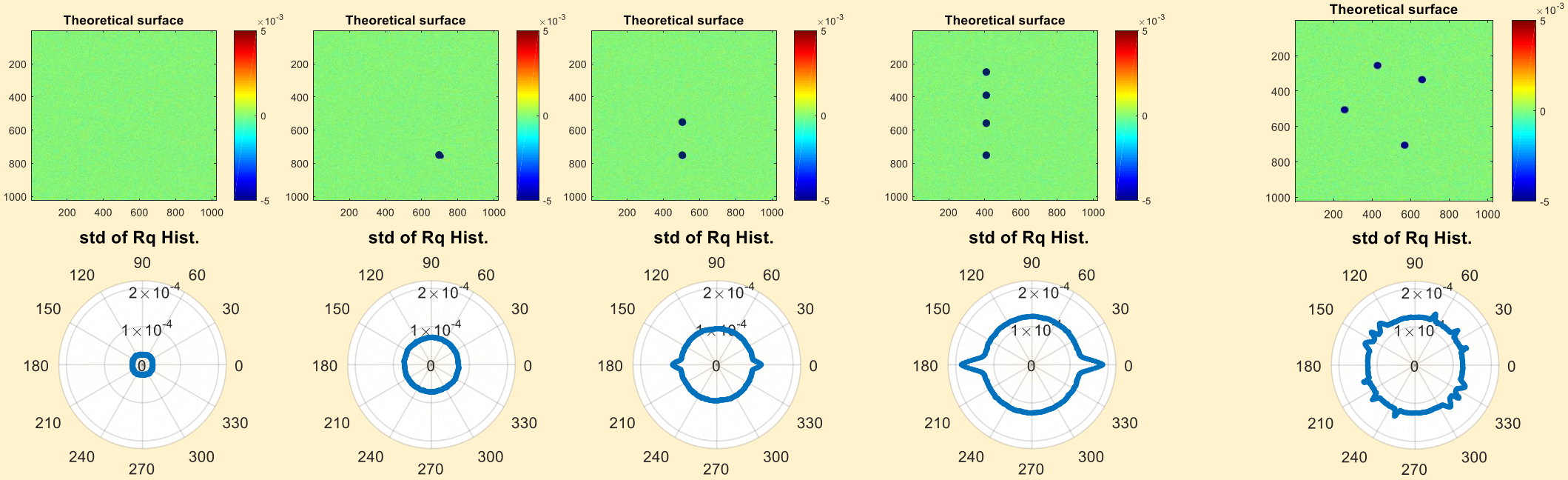
  - ❑ Future directions

Gaussian surf. with multiple dig



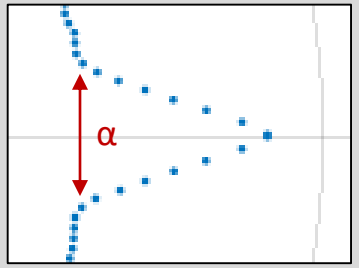
f is the number of digs

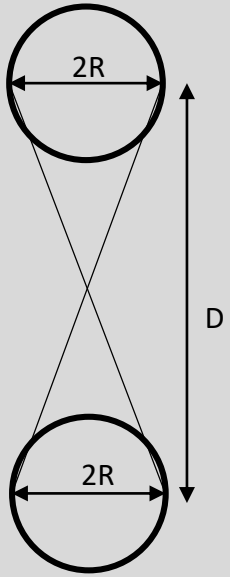
Lb is the number of lobes

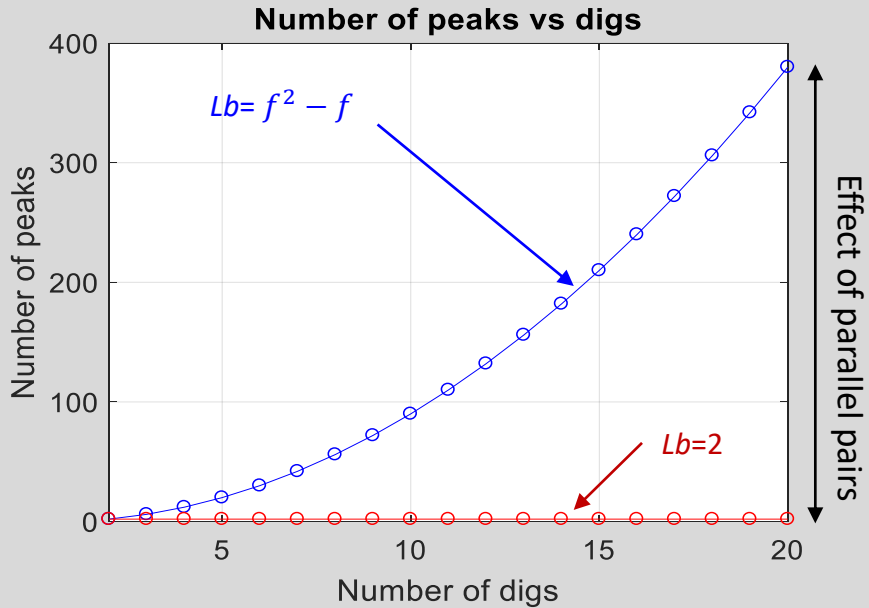
$$Lb = \frac{f!}{(f-2)!}$$

Note: Shape of Peak – function of distance between digs

$\alpha = 2\,[\tan^{-1}(2R/D) - 1]$







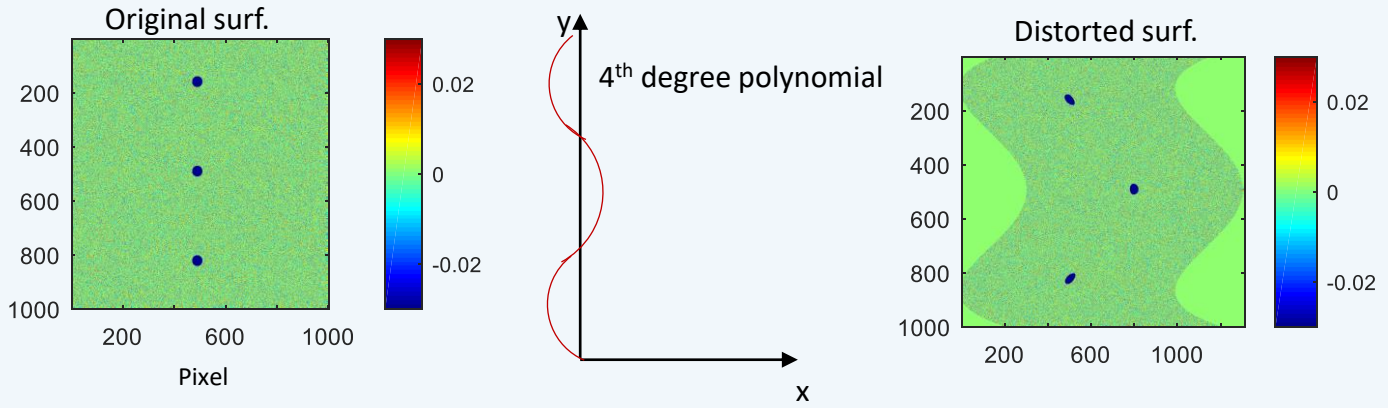
Min of estimation, $Lb = 2$

Max of estimation, $f^2 - f = Lb$

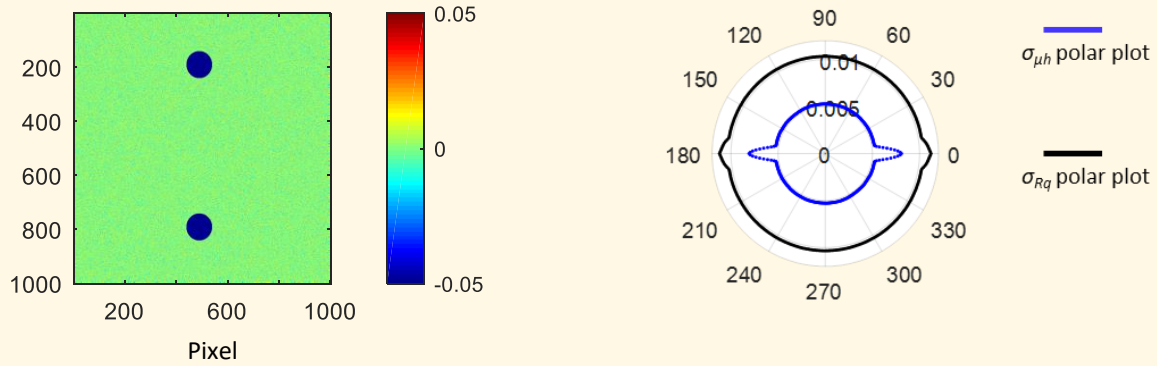
Gaussian surf. with multiple dig

Accuracy of estimation

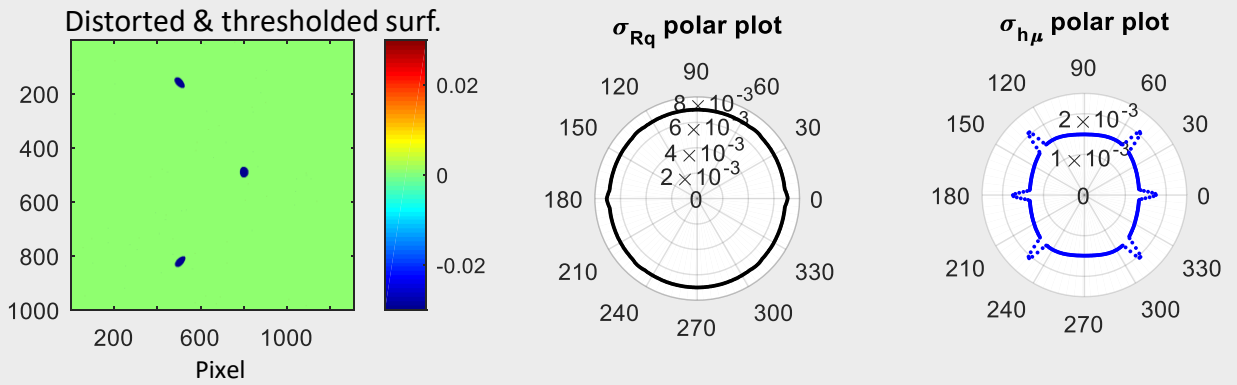
- Distortion
- Std. of mean
- thresholding



Rectifies collinearity



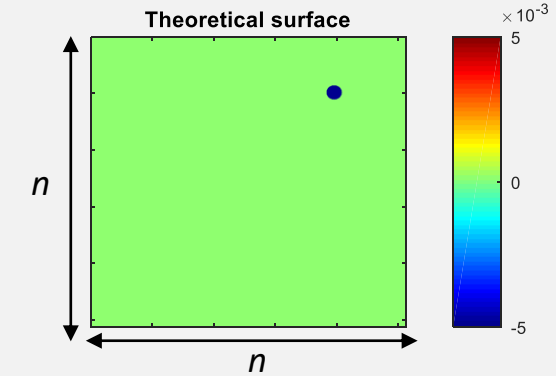
Enhances peaks magnitude

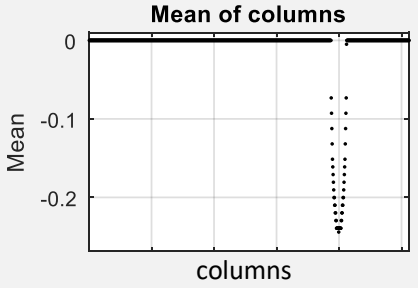


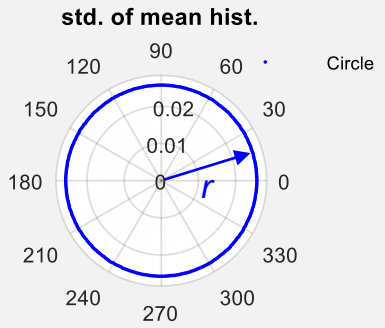
Applicable to different type surfaces

Whole FOV coverage possible

Gaussian surf. With multiple dig – another approach





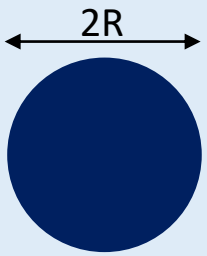


$$r = \sqrt{\frac{(n-2R)\left(\frac{-2d}{n^2}\sum_{i=1}^{R} Y_i\right)^2 + 2\sum_{i=1}^{R}\left(\frac{Y_i d}{n} - \frac{2d}{n^2}\sum_{j=1}^{R} Y_j\right)^2}{n}}$$

n: size of matrix
R: radius of the dig
d: depth of the dig
Y_i: length of the dig in one column

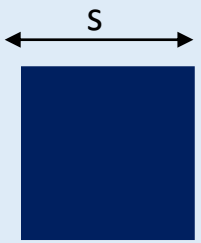
Assumption:

- convert the dig to a square with same area.
- Identical digs

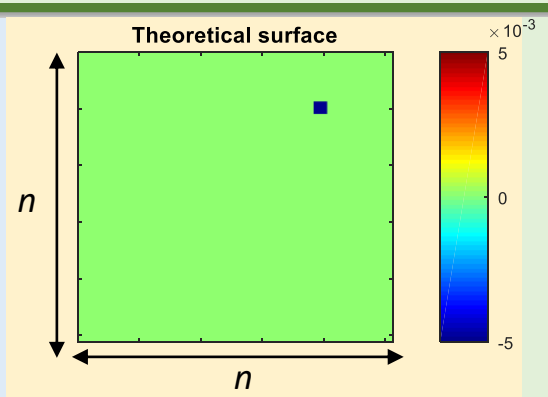


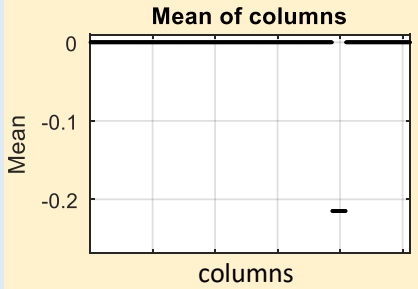
$$area = \pi R^2$$

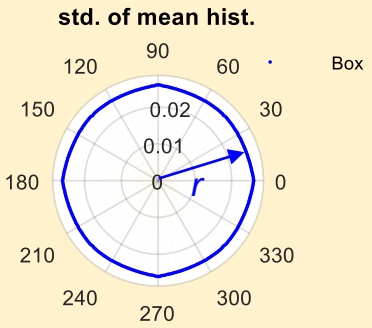
Equal areas



$$s = R\sqrt{\pi}$$



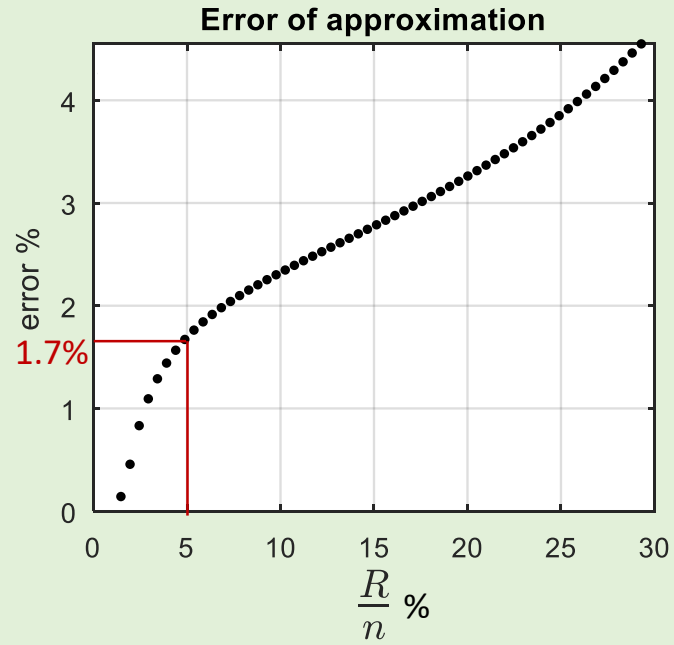




$$r_{\min} = \sqrt{\frac{\sqrt{2}nd^2s^3 - d^2s^4}{4n^4}}$$

s: length of box
n: size of matrix
d: depth of box

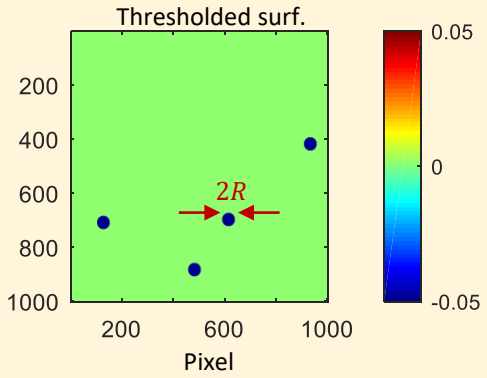
Error is independent of the depth

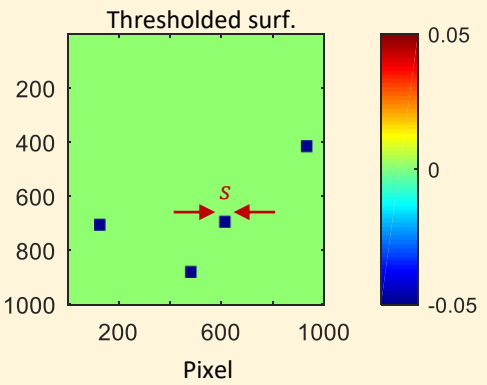


20× objective
FOV= 417 × 417 µm

Radius of dig =21 µm

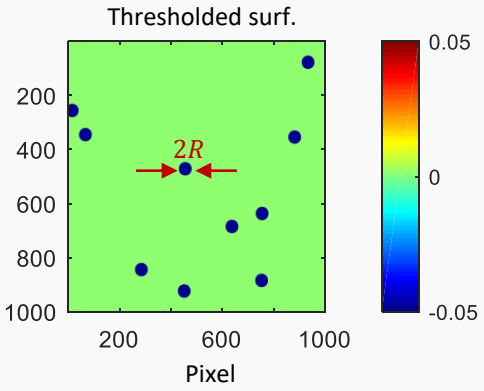
Gaussian surf. With multiple dig – another approach

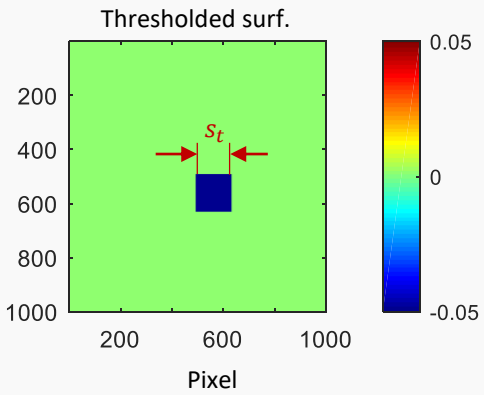


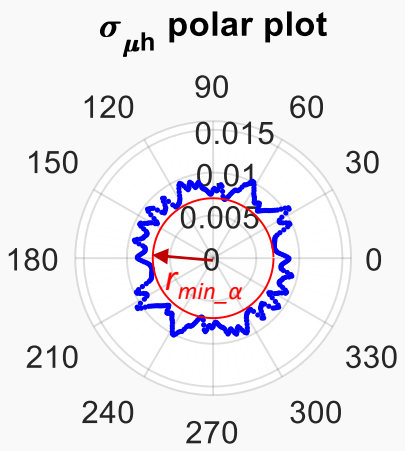


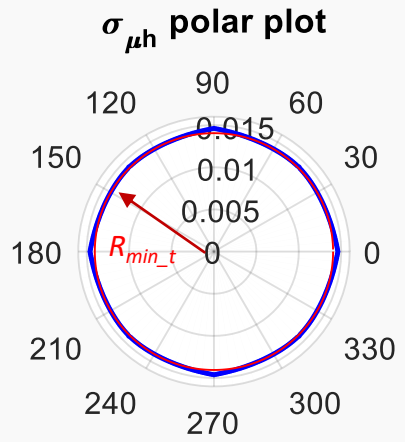
$$r_{\min\_\alpha} = \sqrt{\frac{\sqrt{2}\alpha n s^3 d^2 - (\alpha d)^2 s^4}{4n^4}}$$

Surfaces with equal area of feature(s)









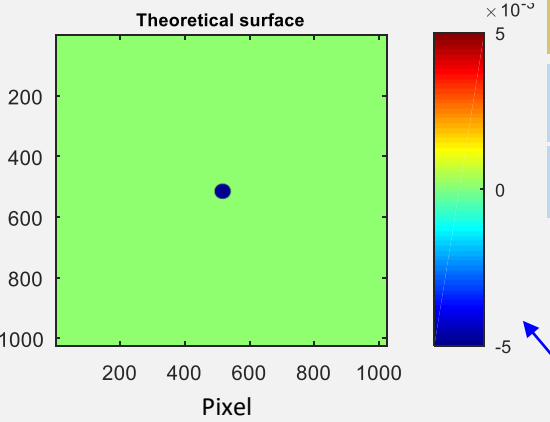
$$r_{\min\_t} = \sqrt{\frac{\sqrt{2}n\alpha\sqrt{\alpha}d^2 s^3 - d^2\alpha^2 s^4}{4n^4}}$$

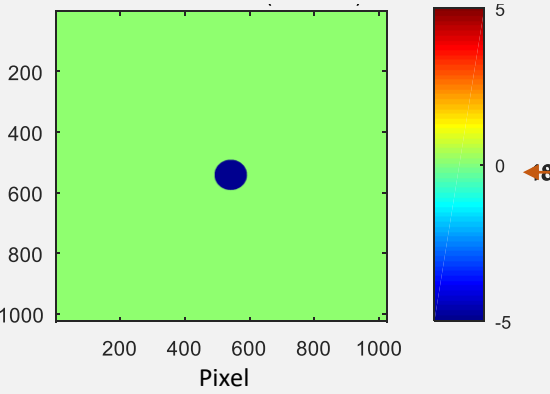
Gaussian surf. With multiple dig – another approach

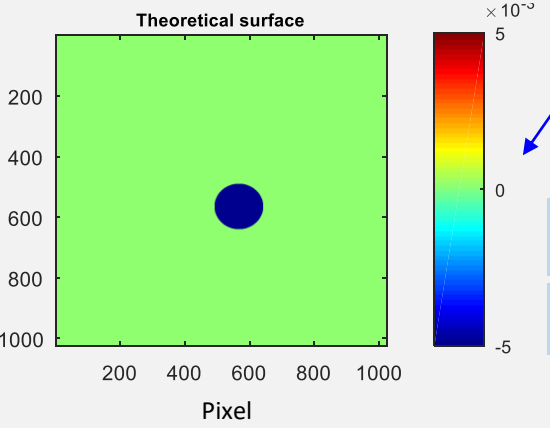
r_t : radius of **accepted feature's** polar plot

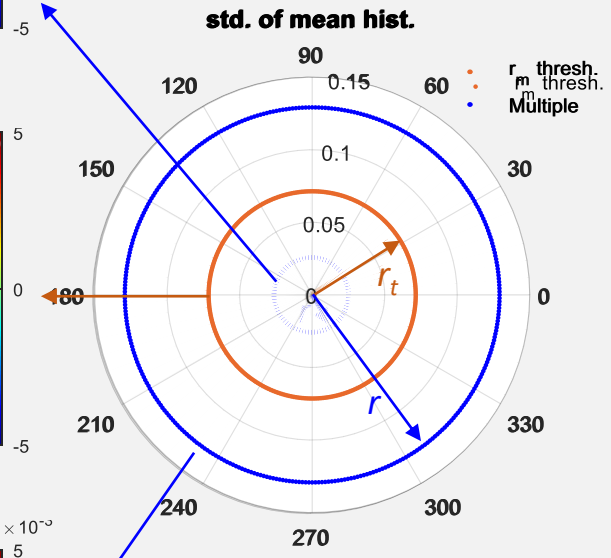
$r < r_t$

r : radius of **feature** polar plot



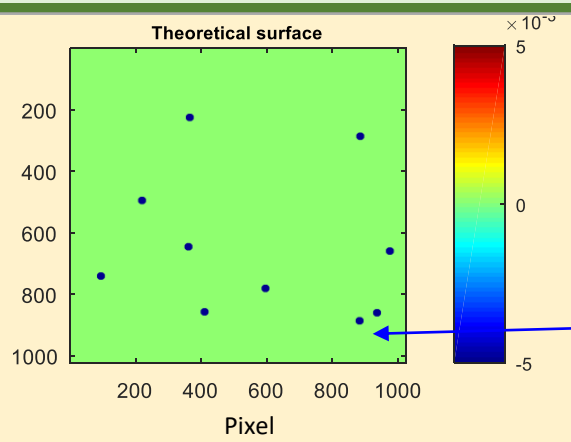


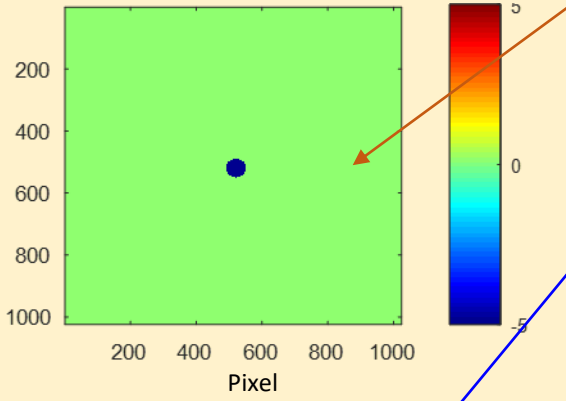


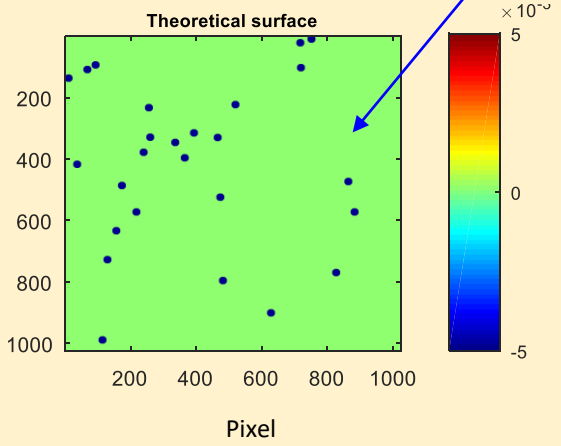


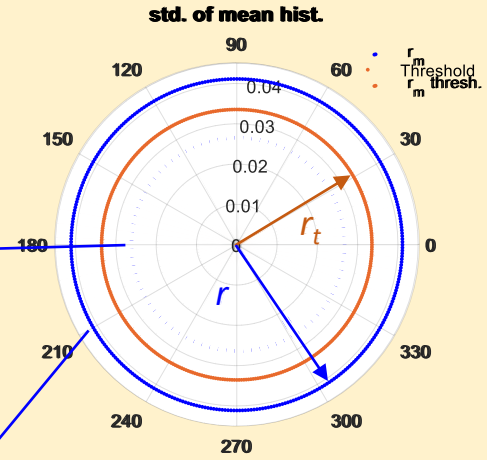
$r > r_t$

r : radius of **feature** polar plot









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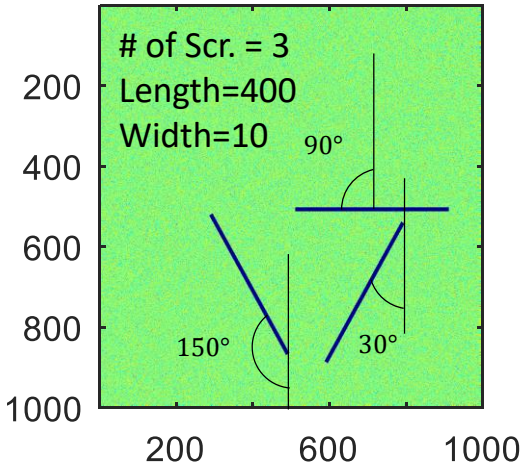
Gaussian surf. with scratches – non parallel

Each scratch creates two peaks on the polar plot, so # of scratches = $\frac{\#\ peaks}{2}$

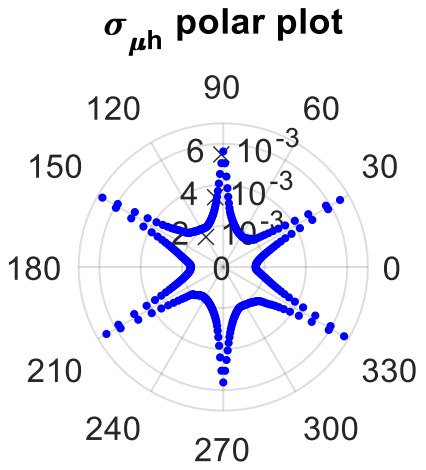


Assumptions: All scratches are identical and straight. Non parallel to the others.

Limitation: based on the # points required for peak detection, pd

$$\alpha_{scr\_\max} = \frac{180}{\Delta\theta \times pd}$$

Peak detection: based on a defined # of points window

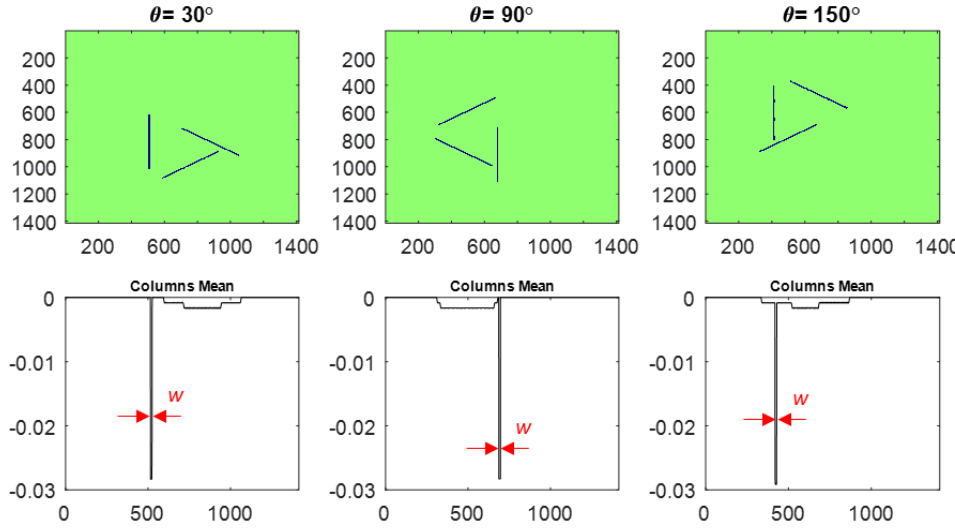


# of peaks = 6

How to calculate length, width

1. Number of scratches from polar plot, *m*
2. Angle of each peak, *r*
3. Rotate the surface to make each scratch vertical
4. Create the mean of columns plot
5. Finding the width of scratch from 4
6. Based on $A=mlw$, the only unknown, length, can be found

Rotate the surface based on each peak angle



Get the width, *w*

$$A = mlw$$

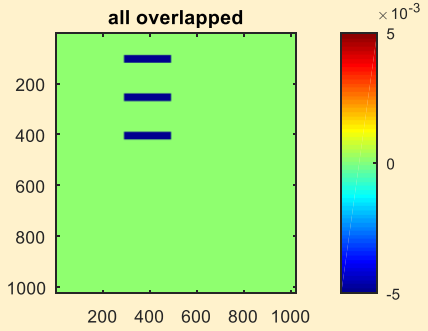
Calculate length, *l*

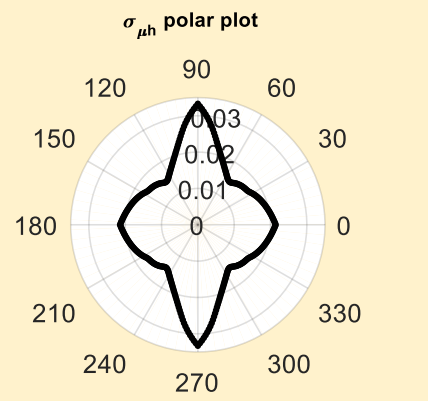
Gaussian surf. with scratches – parallel

The method in previous slide doesn't work on these cases (parallel scratches)

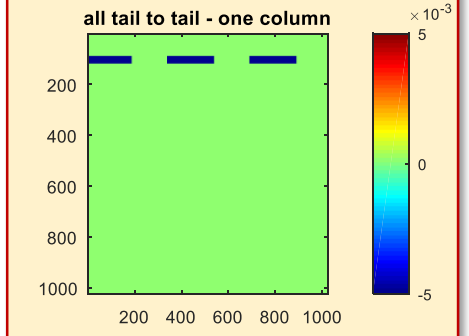
Equal overall area of features

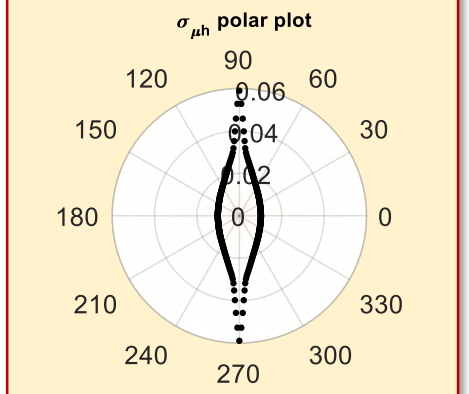
All below each other



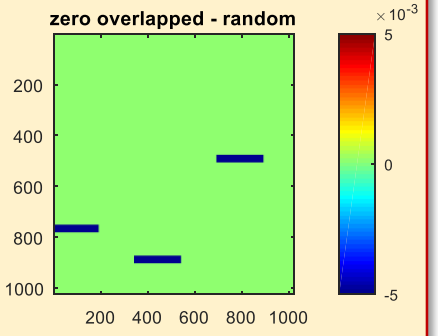


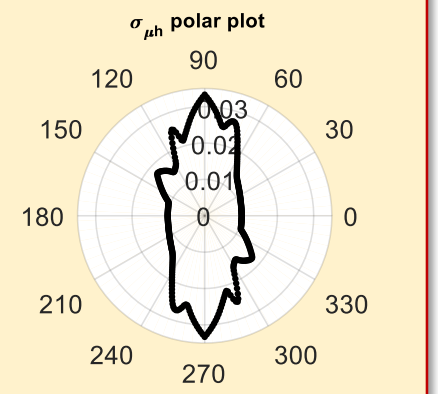
All aligned



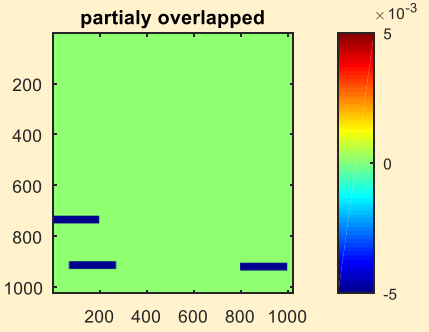


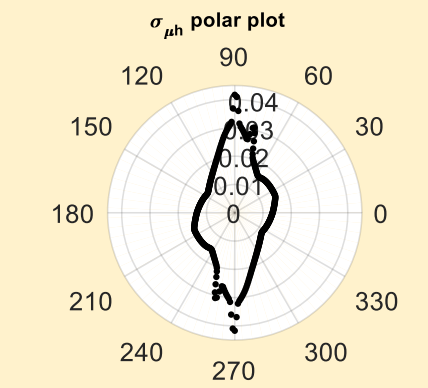
Non-overlapping





Random locations

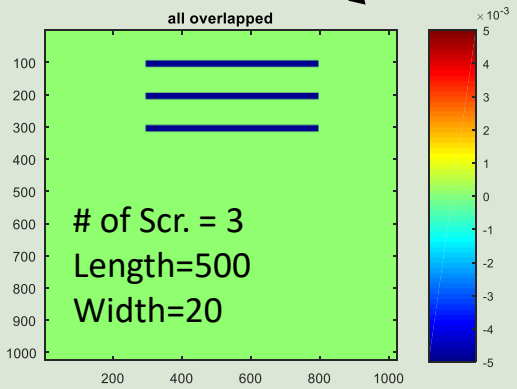


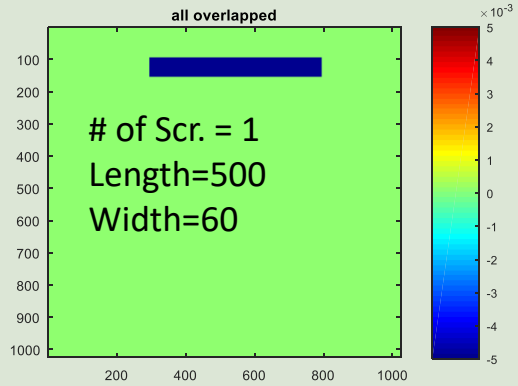


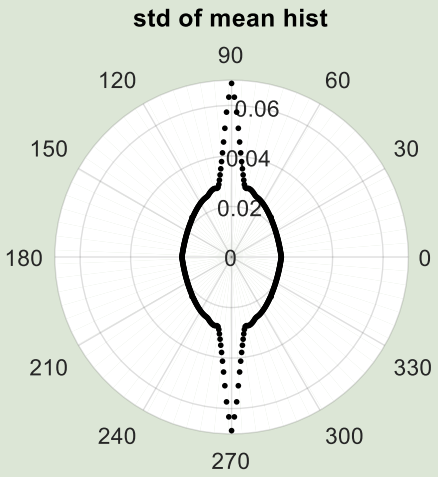
# of scratches can't be found only from peaks

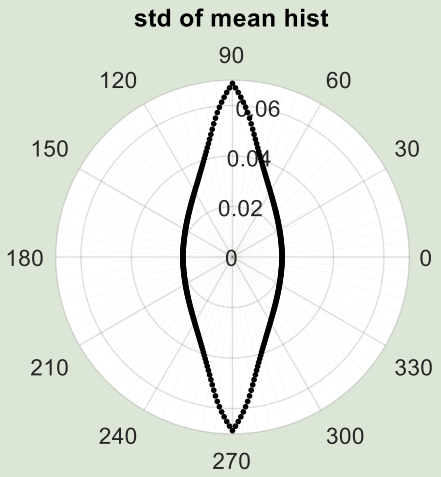
Identification of polar plots metrics

Equal overall area of features







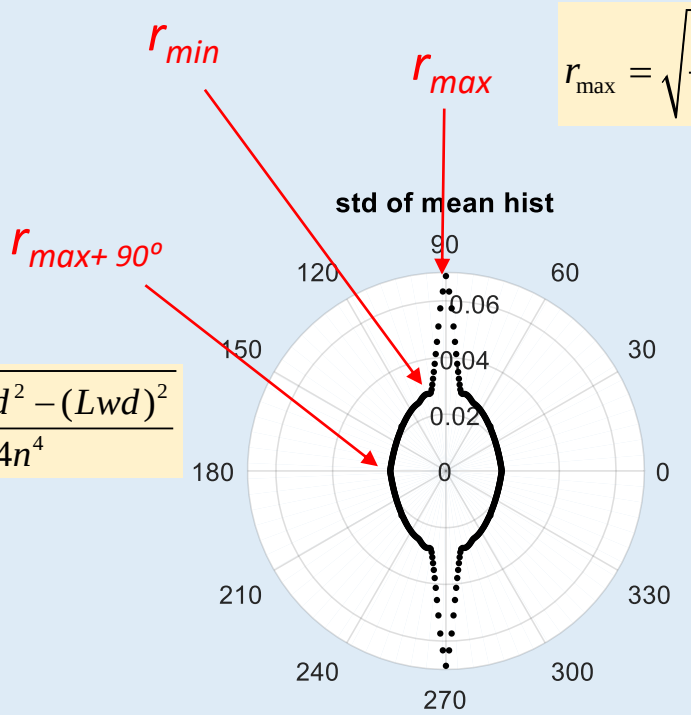


2 peaks → 1 scratches

2 peaks → 1 scratches

Key factors form the polar plot:

- r_{max}
- $r_{max\pm 90^o}$ (r value 90 degrees after/before r_{max})
- r_{min}



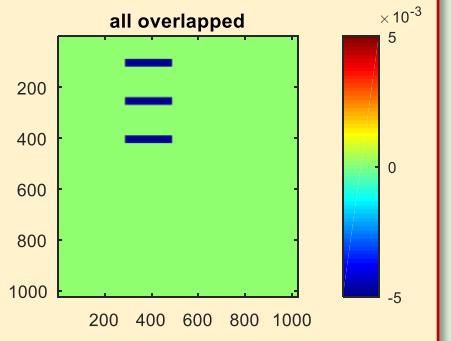
$$r_{max} = \sqrt{\frac{\sqrt{2}nwL^2d^2 - (Lwd)^2}{4n^4}}$$

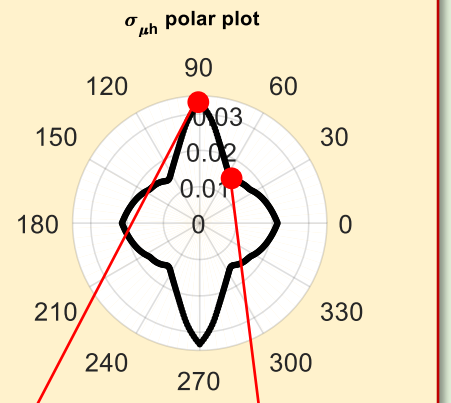
$$r_{max+90} = \sqrt{\frac{\sqrt{2}nLw^2d^2 - (Lwd)^2}{4n^4}}$$

L: length
w: width
n: size of surface
d: depth
r: radius of the polar plot

Gaussian surf. with scratches – parallel

All below each other





r_{max} r_{min}

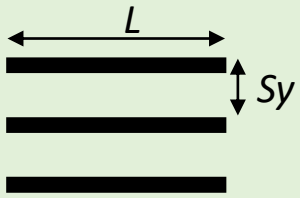
- Only four lobes exist on the polar plot.
- R_{max} occur at the angles where the features are vertical.
- $r_{min} \neq r_{max\pm 90^o}$

$$L = \frac{4n^4 r_{\max}^2 + A_{total\_scr}^2 d^2}{\sqrt{2} n A_{total\_scr} d^2} = 200.42$$

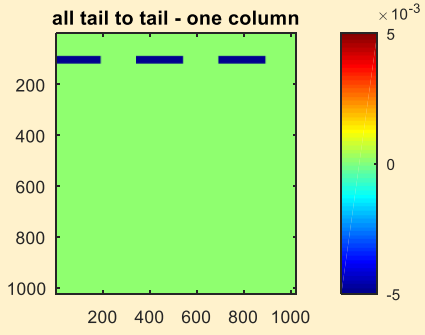
$$w_{total} = \frac{A_{total\_scr}}{L} = 60.08$$

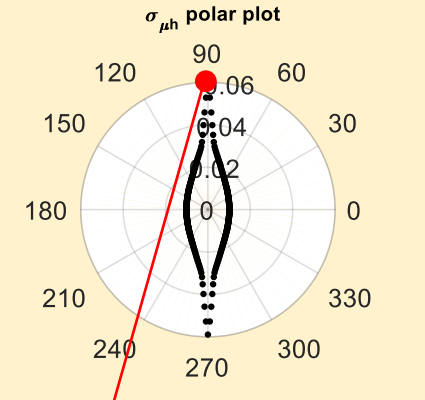
The spacing between scratches sets a limit to max number of them, so the number of scratches can be calculated.

$$\omega = \tan^{-1}\left(\frac{L}{Sy}\right)$$



All aligned





r_{max}

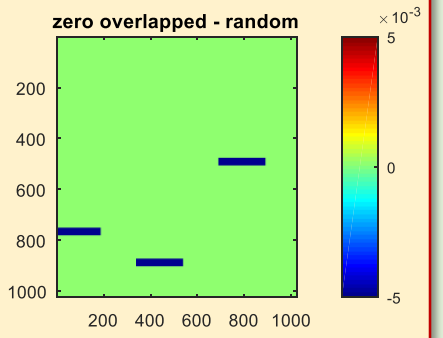
- Only two lobes exist on the polar plot.
- R_{max} occur at the angles where the features are vertical.
- $r_{min} = r_{max\pm 90^o}$

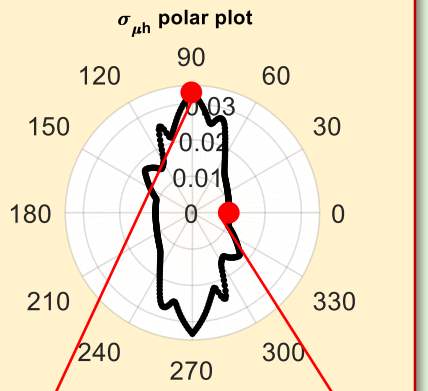
$$L_{total} = \frac{4n^4 r_{\max}^2 + A_{total\_scr}^2 d^2}{\sqrt{2} n A_{total\_scr} d^2} = 601.68$$

$$w = \frac{A}{L_{total}} = 20.01$$

Gaussian surf. with scratches – parallel

Non-overlapping

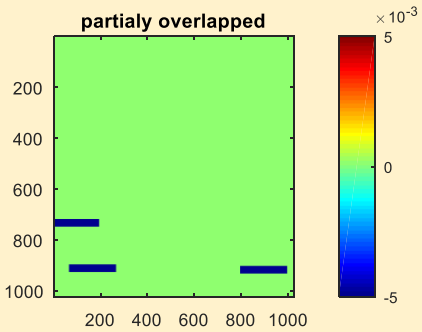


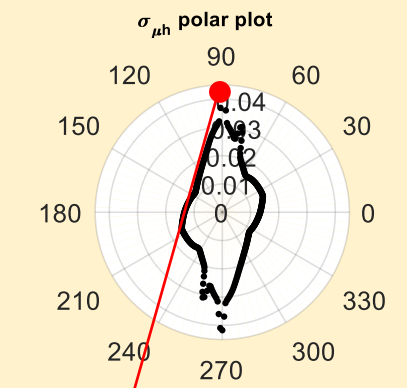


r_{max} $r_{max \pm 90^o}$

- More than two lobes are present on the polar plot.
- R_{max} occur at the angles where the features are vertical.
- $r_{min} = r_{max \pm 90^o}$

Random locations

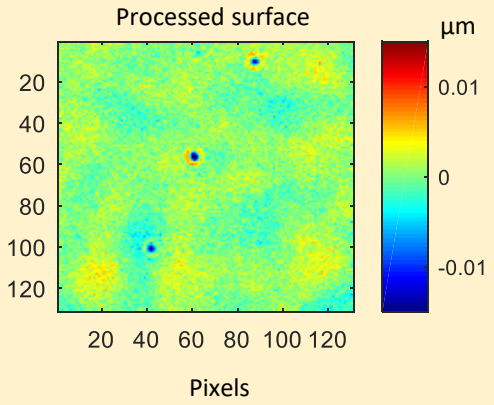


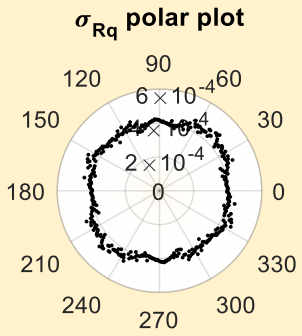


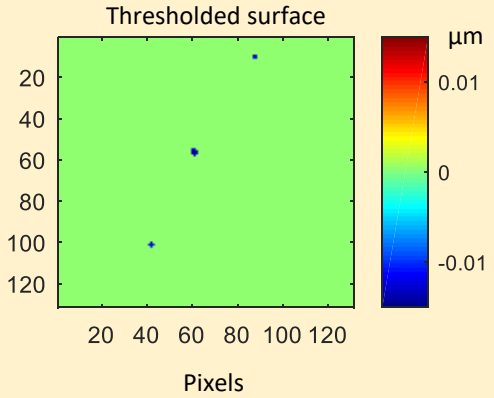
r_{max}

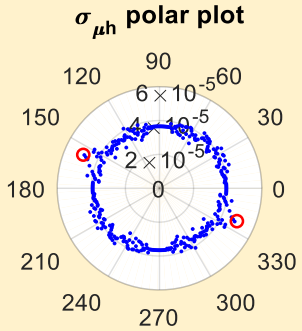
- More than two lobes exist on the polar plot.
- R_{max} occur at the angles where the features are vertical.
- $r_{min} \neq r_{max \pm 90^o}$

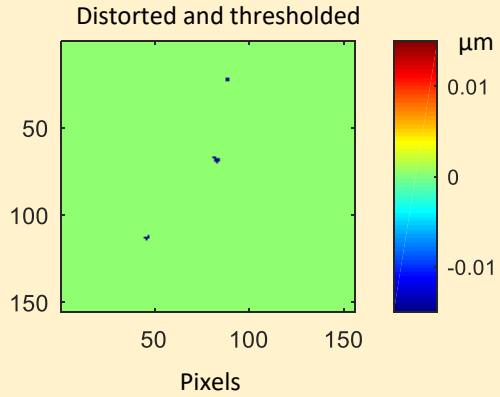
Case studies

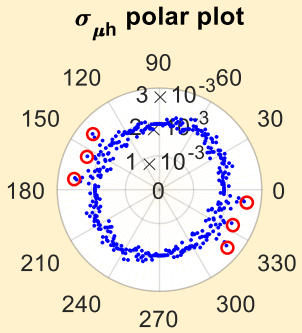


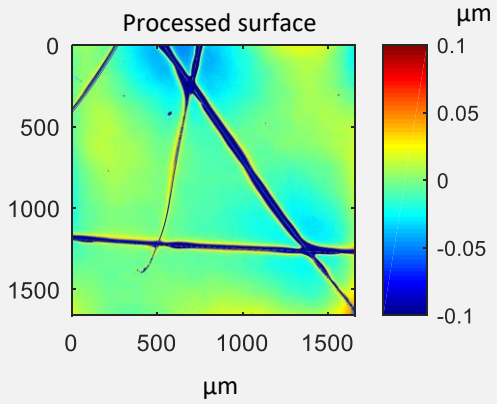


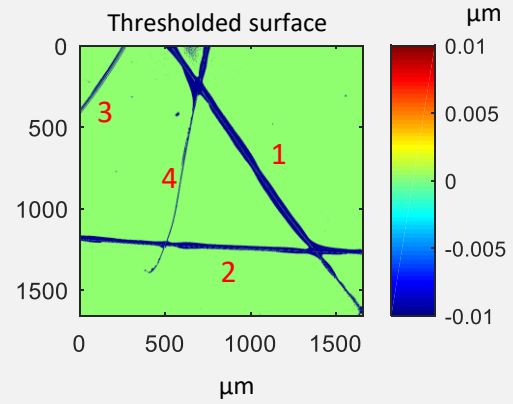


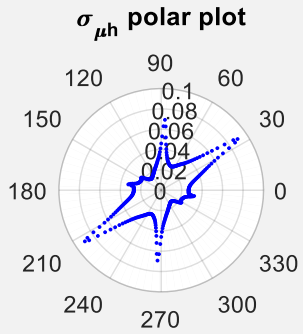








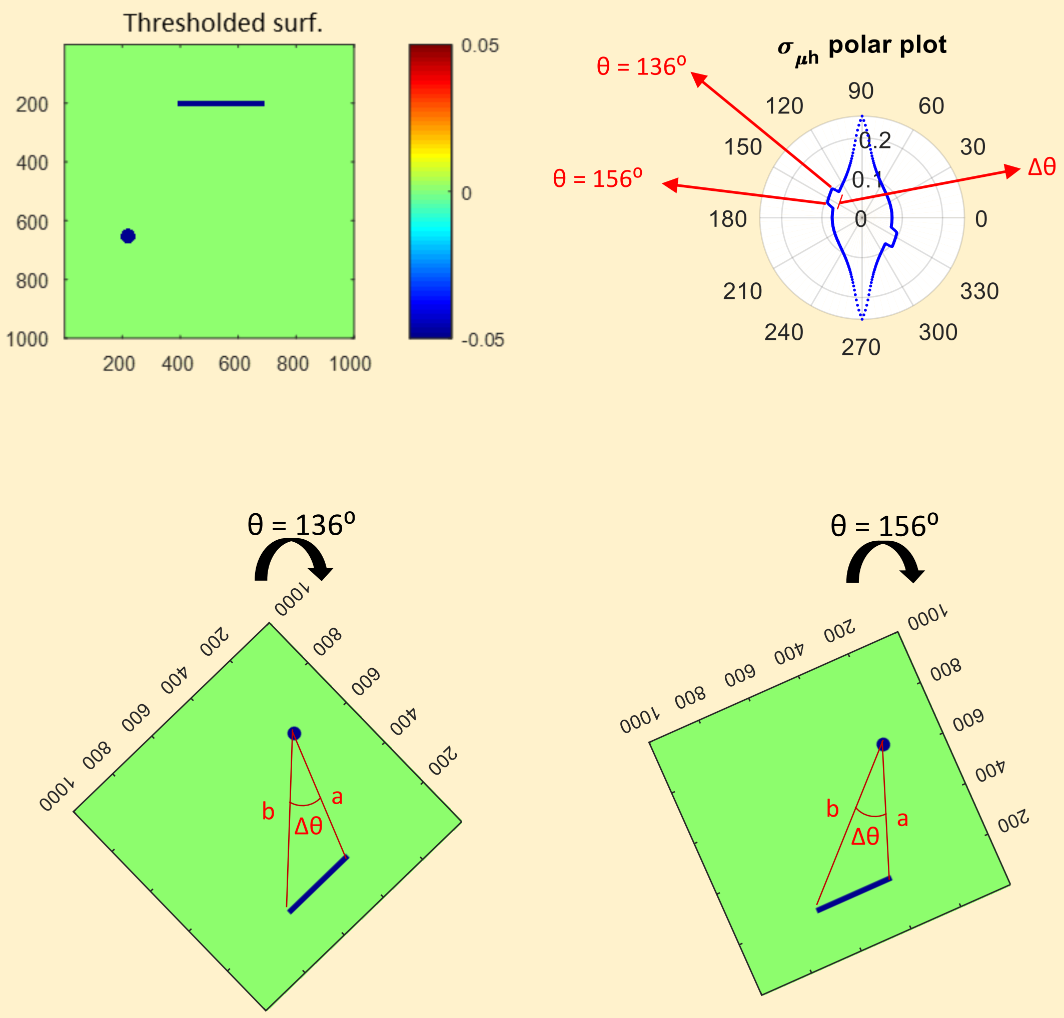




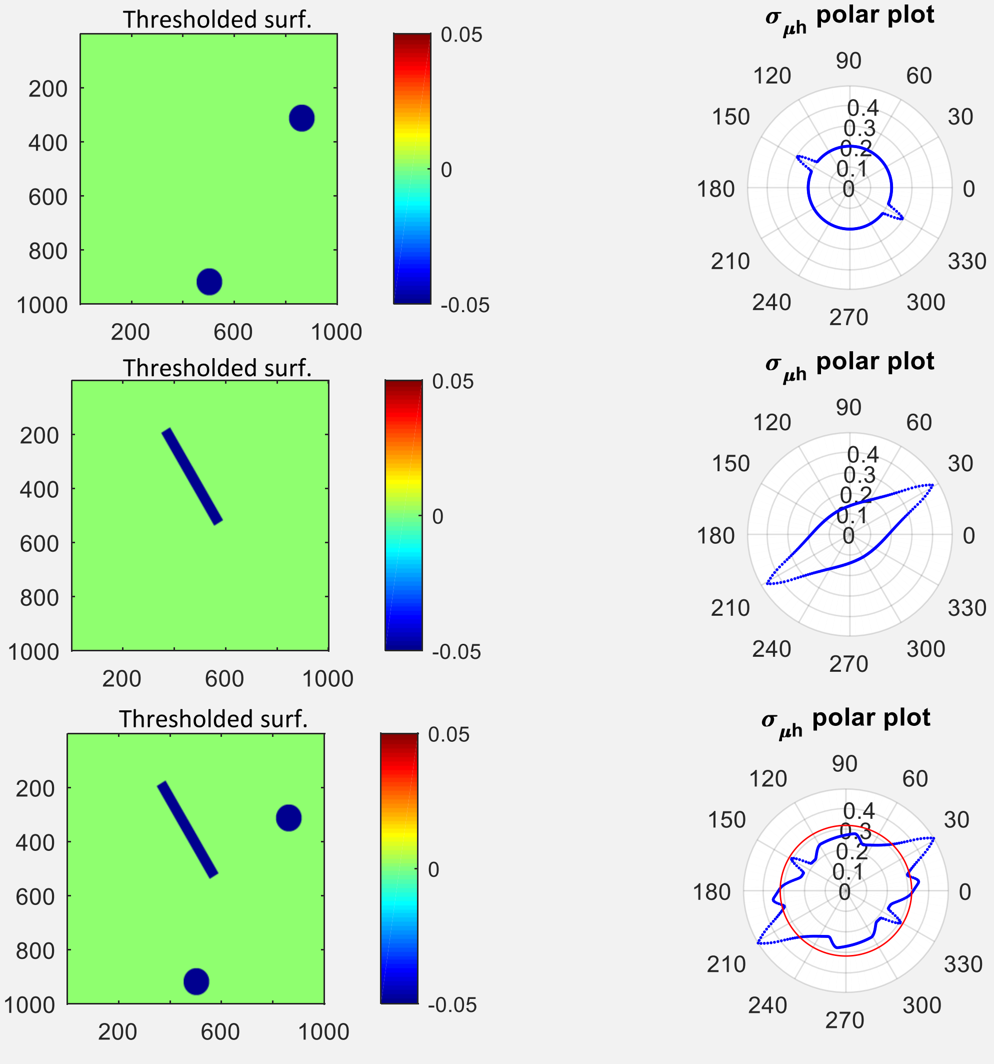
Scratch #	l × w × d (pixel × pixel × µm) from CSI	l × w × d (pixel × pixel × µm) from polar plot
1	1177 × 35 × 0.15	1143 × 30 × 0.12
2	1018 × 22 × 0.15	1023 × 20 × 0.14
3	313 × 4 × 0.14	291 × 3 × 0.12
4	780 × 9 × 0.11	670 × 5 × 0.08

- History
- Motivation
- Polar plots
  - With respect to surface texture
    - *Sq* roughness of a Gaussian surface
    - Isotropy
    - Directionality
    - Periodicity
  - With respect to surface feature
    - Single feature
      - Single dig
      - Single scratch
    - Multiple features
      - Multiple digs
      - Multiple scratches
      - Mixed features
  - Summary
  - Future directions

Mixed features



Each dig+scratch → step-like peak



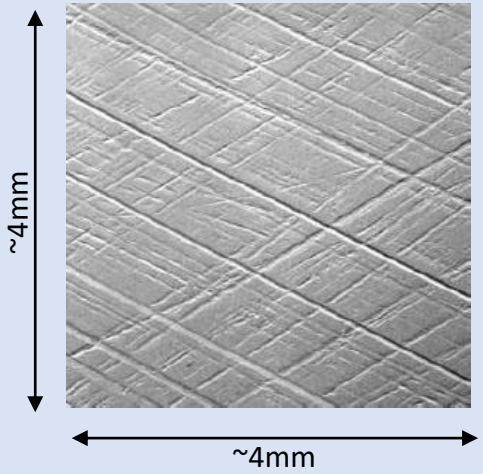
$$\frac{r_{peak}}{r_{\min}} > 1.5 \rightarrow scratch-related$$

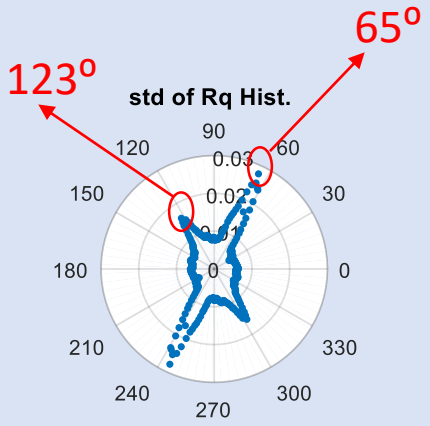
$$\frac{r_{peak}}{r_{\min}} \leq 1.5 \rightarrow dig-related$$

Grayscale images

Directionality

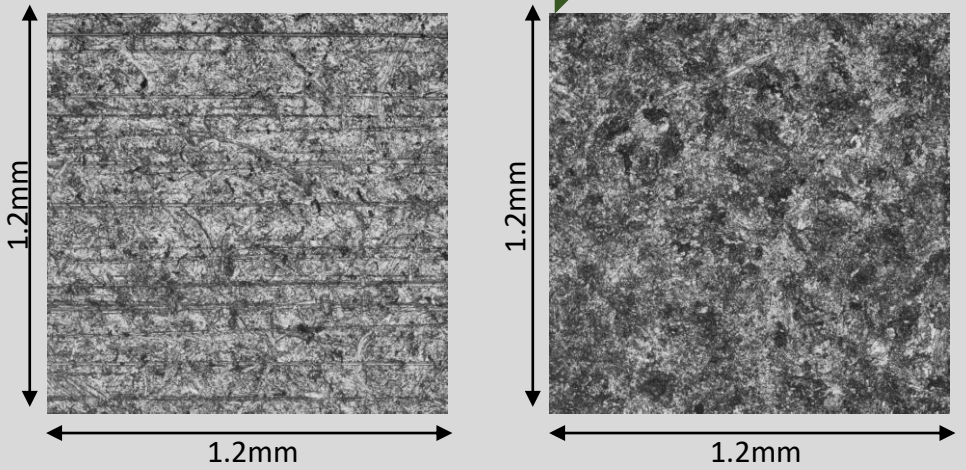
Plateau honed surf.

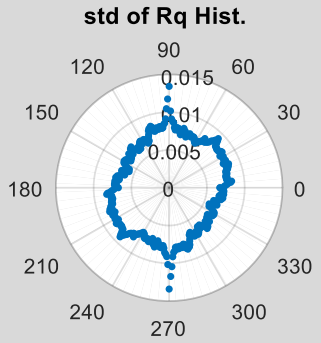


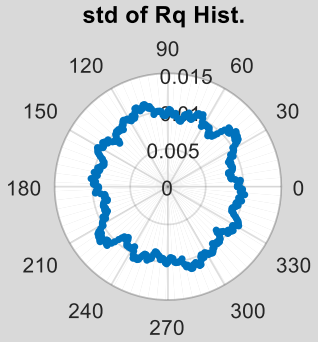


Isotropy

Vibratory finished

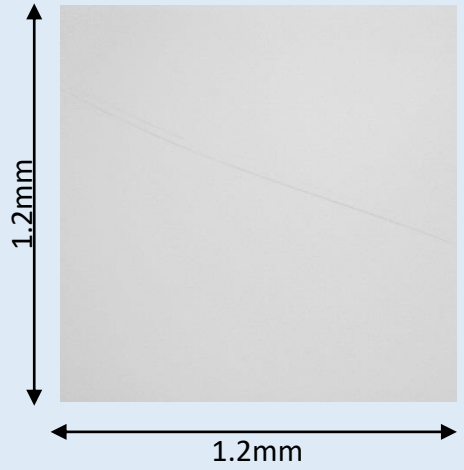


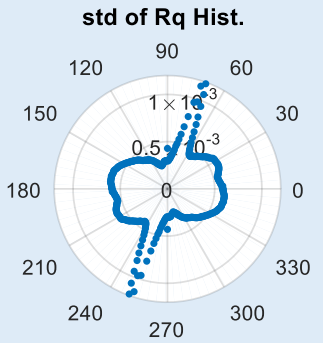




scratch

Glass





- ❑ History
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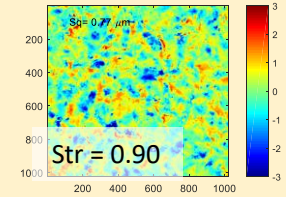
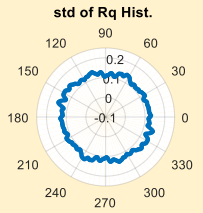
      - Single dig
      - Single scratch
    - Multiple features
      - Multiple digs
      - Multiple scratches
      - Mixed features
- ❑ Summary
- ❑ Future directions

Summary

Isotropic vs anisotropic

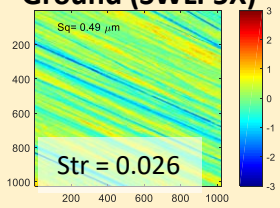
Vibrationally Finished (SWLI 5X)

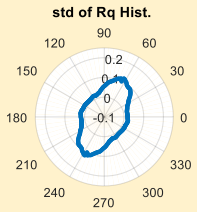




directionality

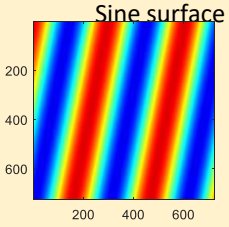
Ground (SWLI 5X)

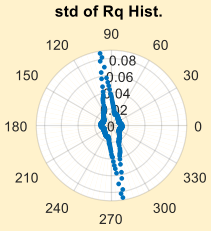




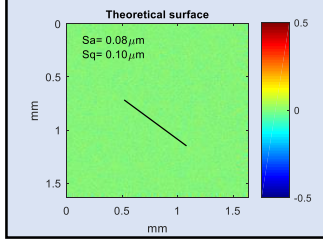
Periodic features

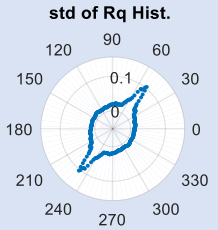
Sine surface



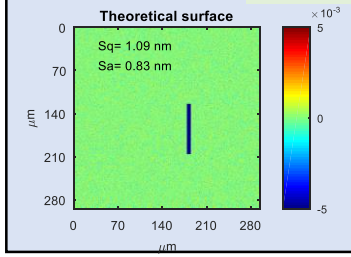


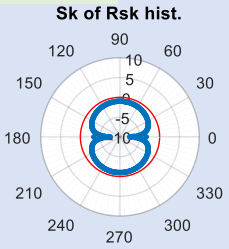
Single scratch



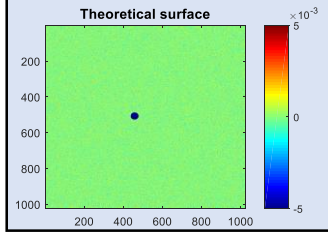


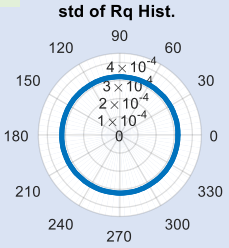
In or on the surface



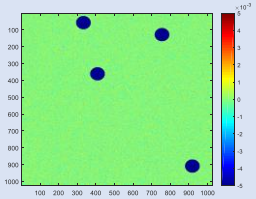


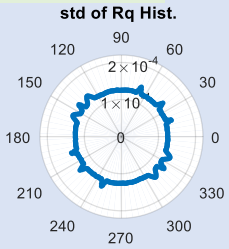
Single dig



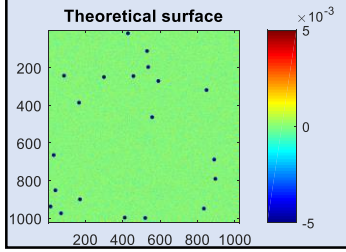


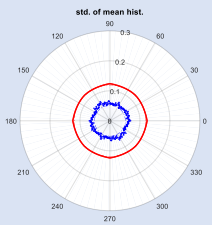
Multiple digs, (base on # peaks)



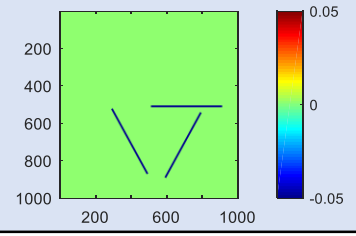


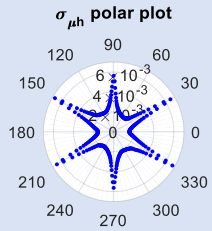
Multiple digs, (identical digs)



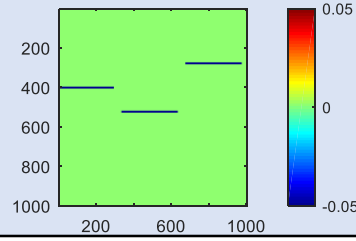


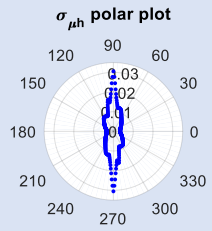
Multiple non parallel scratches



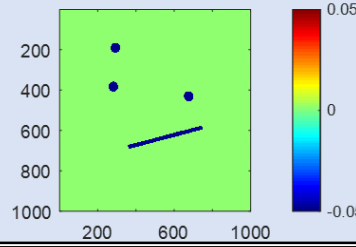


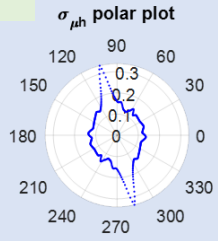
Multiple parallel scratches





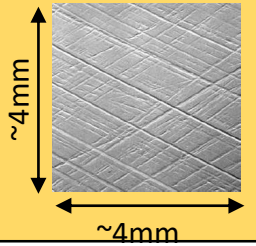
Mixed features

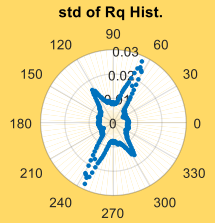




Gray scale images

Plateau honed surf.





Publications

Journals

- F. Azimi, B. Mullany, “Geometric surface feature detection using statistical based metrics” submitted to journal of Precision Engineering. Accepted on July 2019.

Conference proceedings

- F. Azimi, Benjamin Young, Brigid Mullany, “Statistical Analysis of Surface Measurements and Images”, ASPE conference, Charlotte, NC. November 2017.

- F Azimi, E Fleischhauer, P Tkacik, R Keanini, B Mullany, “Correlations Between Media-Workpiece Contact Modes Occurring During Vibrational Finishing and the Resulting Workpiece Topography”. 15th International Conference on Metrology and Properties of Engineering Surfaces, Charlotte, NC. March 2015

Under preparation

- Detection of multiple geometric surface features using polar plots. To be submitted to journal of Precision Engineering.

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