Resolution and Texture Analysis

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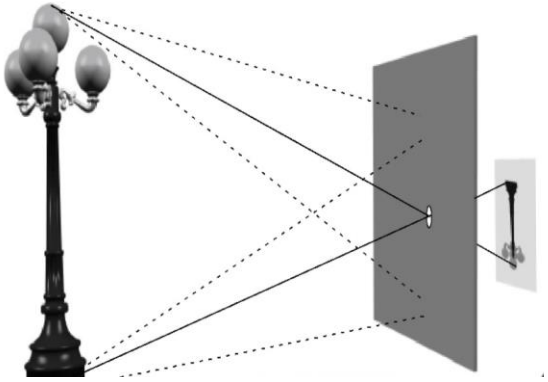
Physical Inspection and AttacKs on ElectronicS (PHIKS)

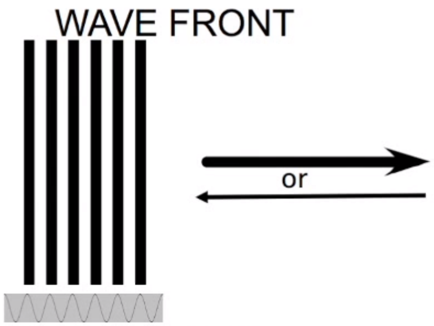
Resolution

- Why light does not provide infinite magnification
  - Light travels in straight line!
- Pin hole camera
  - If hole is bigger the image will be fuzzier
  - If hole is very small image gets blurry
  - Light is diffracted at the hole
- Light wave can travel in planar or spherical
  - Light is made of infinite small objects called Huygens wavelet

Pin hole camera

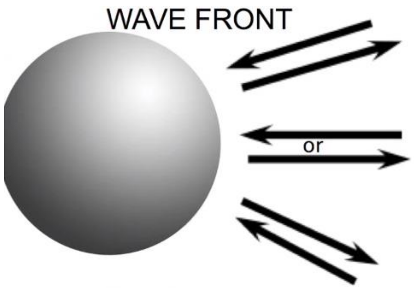


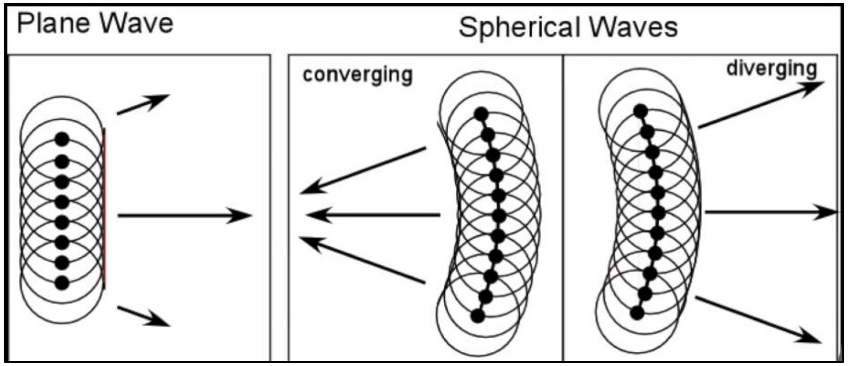
Planar wave



Peak and valley

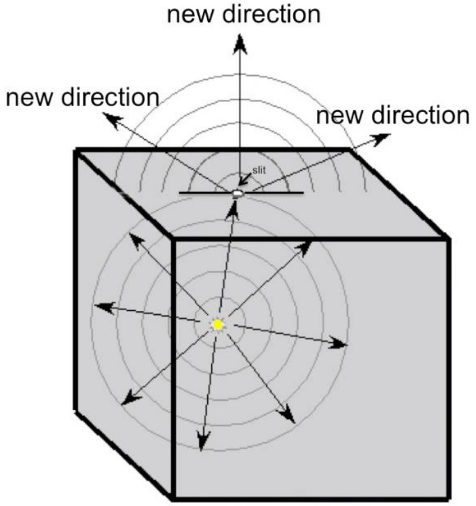
Spherical wave

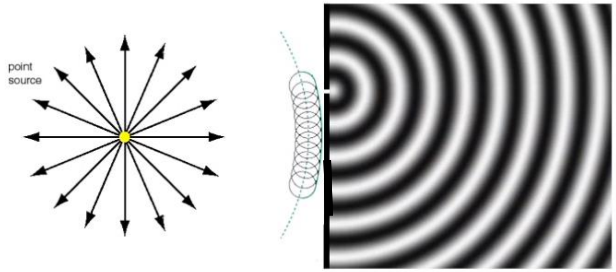


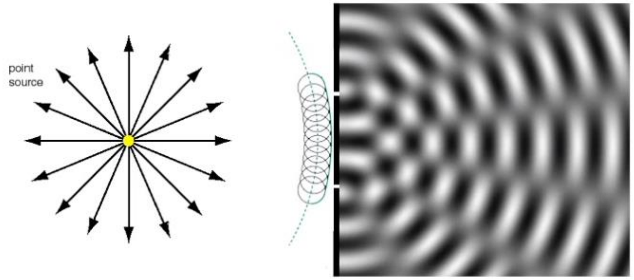


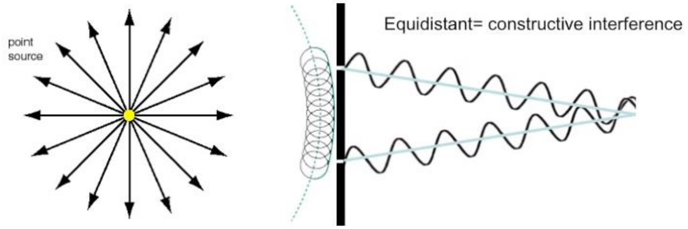
Light Diffraction

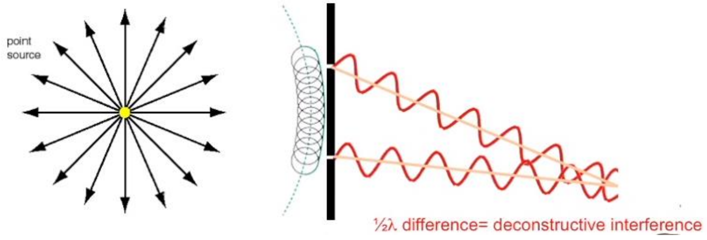
- **Light in Wave form**



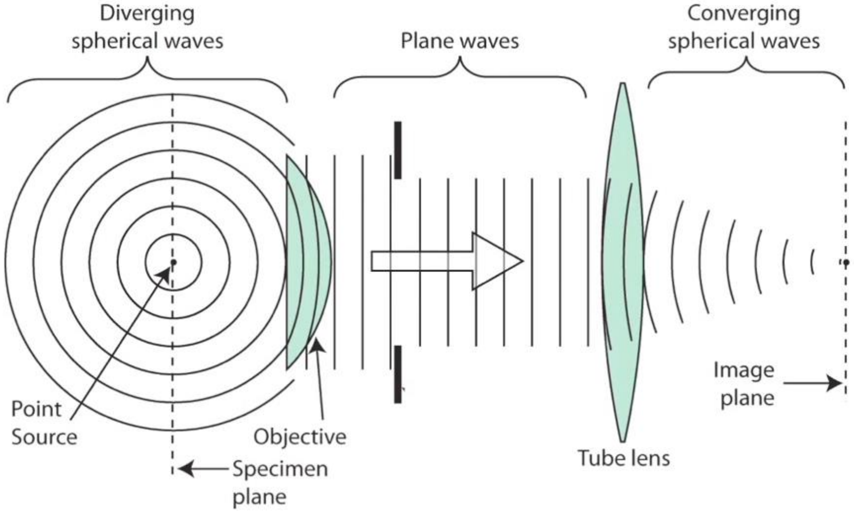






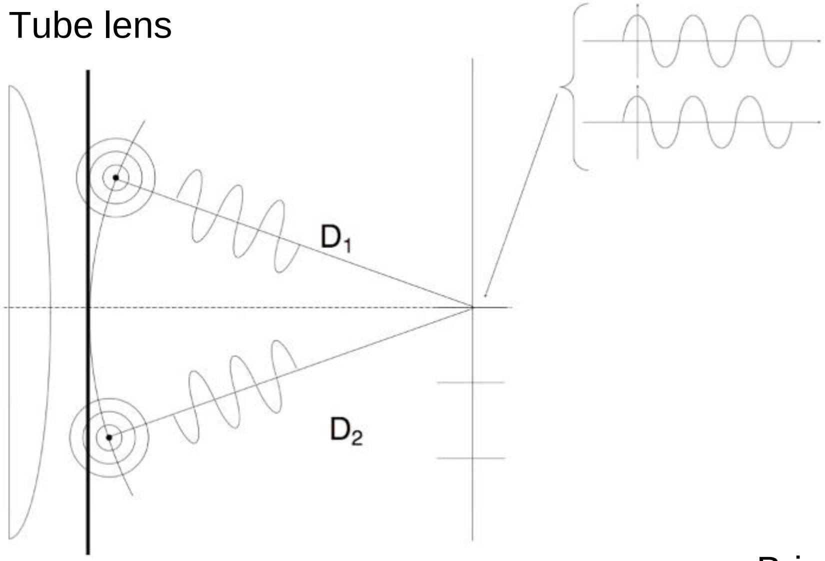


Optics of Microscope



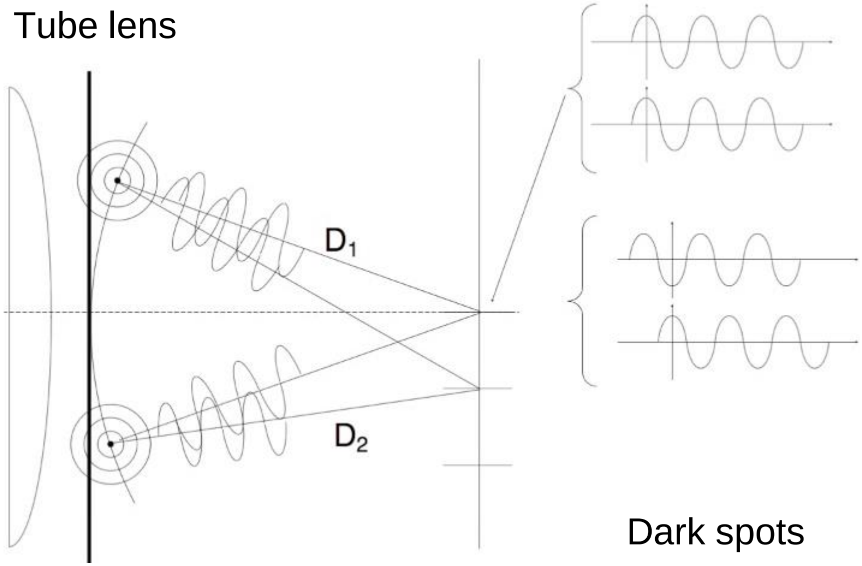
What is the distribution
of light in this point
Point Spread Function

Tube lens



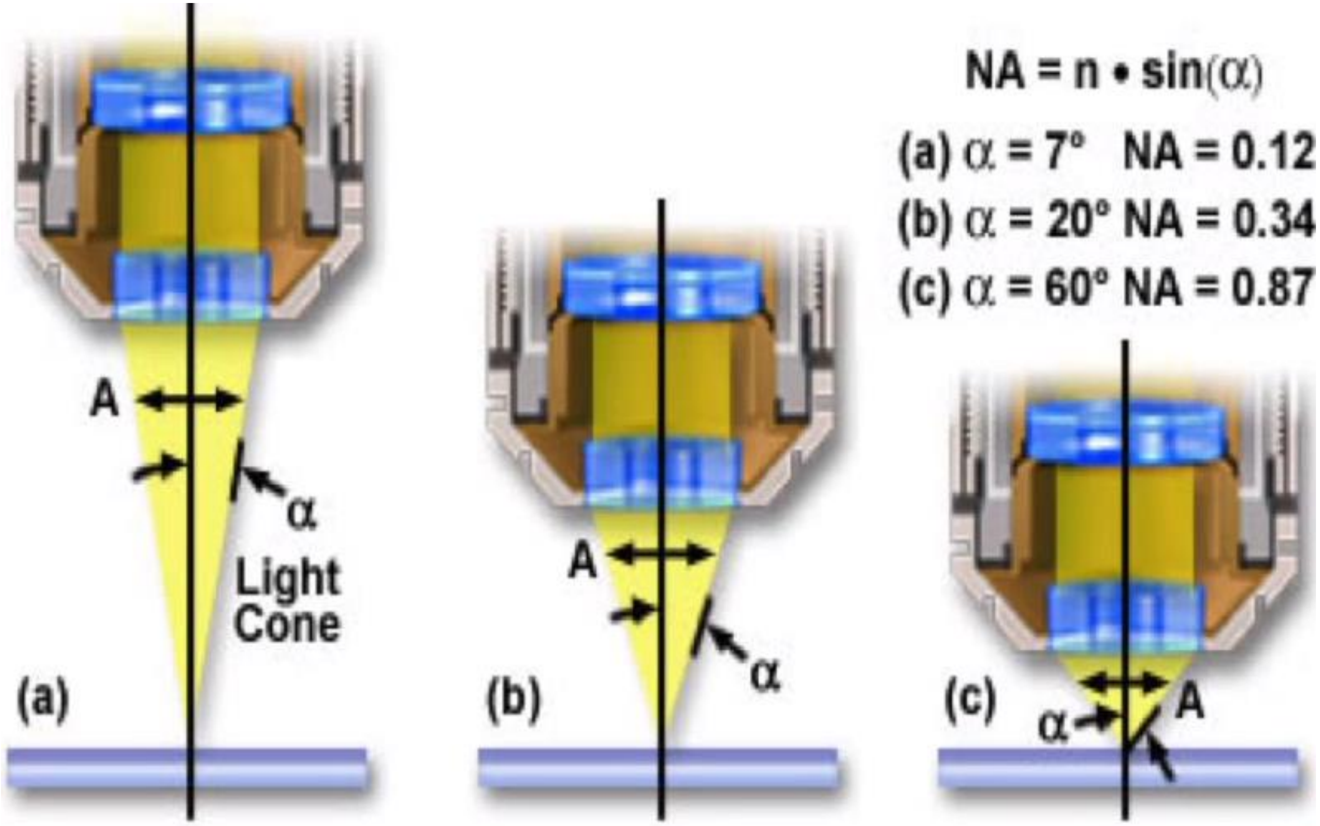
Bright spots

Tube lens



Dark spots

Numerical Aperture



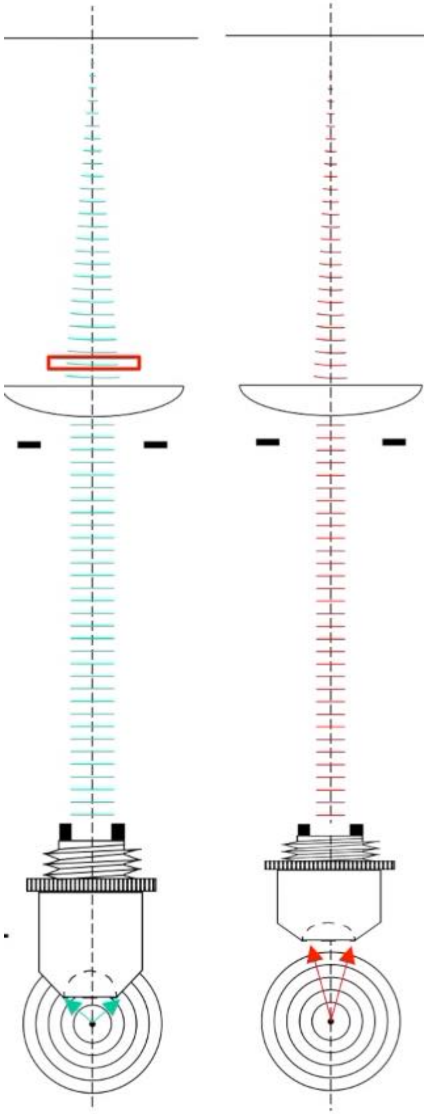
$\mathrm{NA} = n \bullet \sin(\alpha)$

(a) $\alpha = 7°$ NA = 0.12

(b) $\alpha = 20°$ NA = 0.34

(c) $\alpha = 60°$ NA = 0.87

Low NA Medium NA High NA

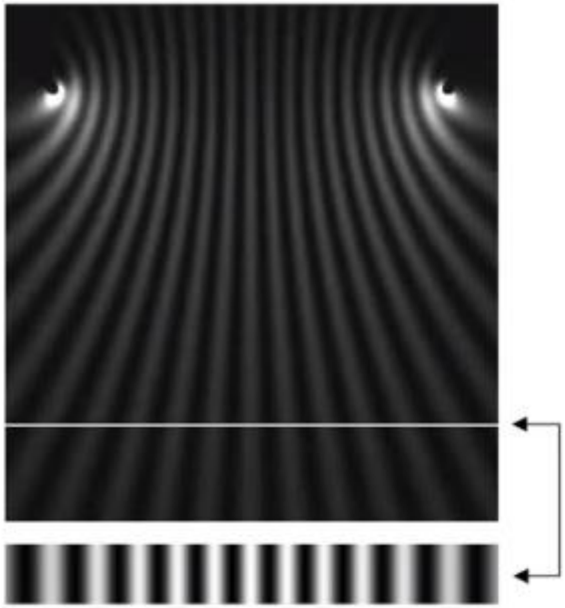


n: index of refraction

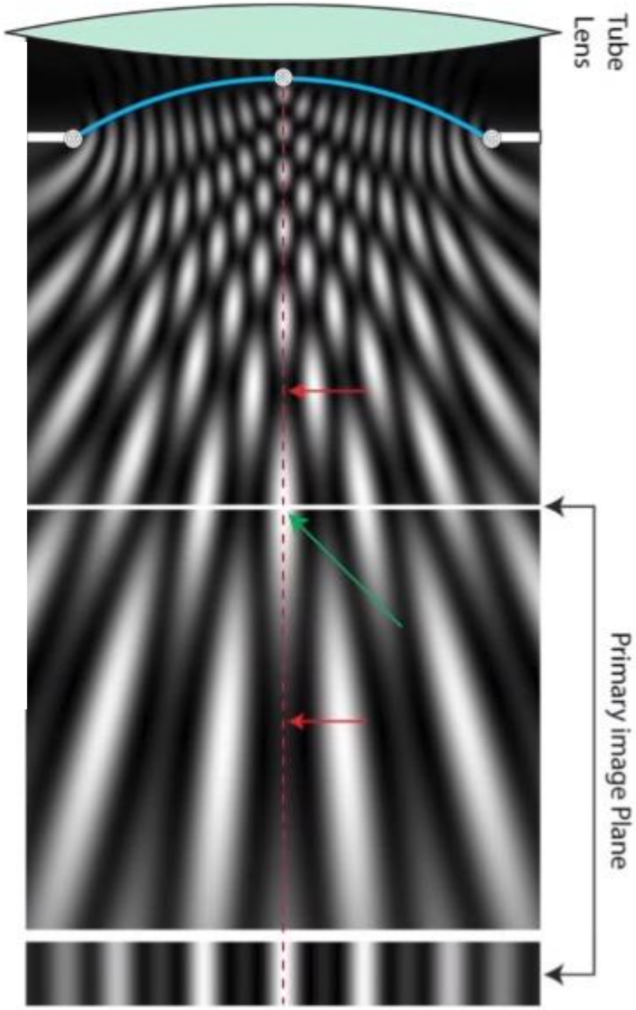
α:angle between vertical line and the most extreme light angle collected by lens

Effect of Wavelets

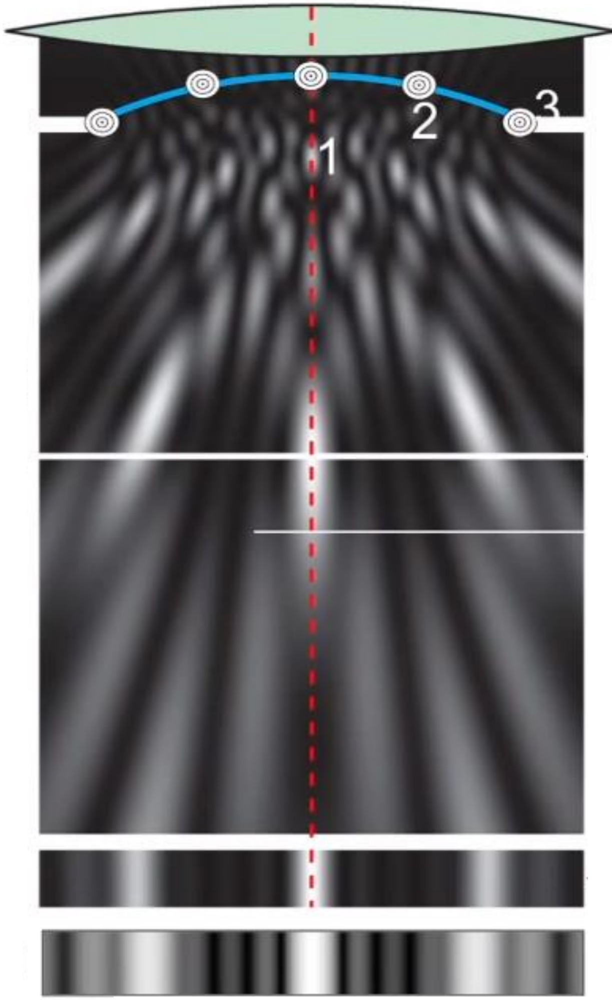
Two wavelets



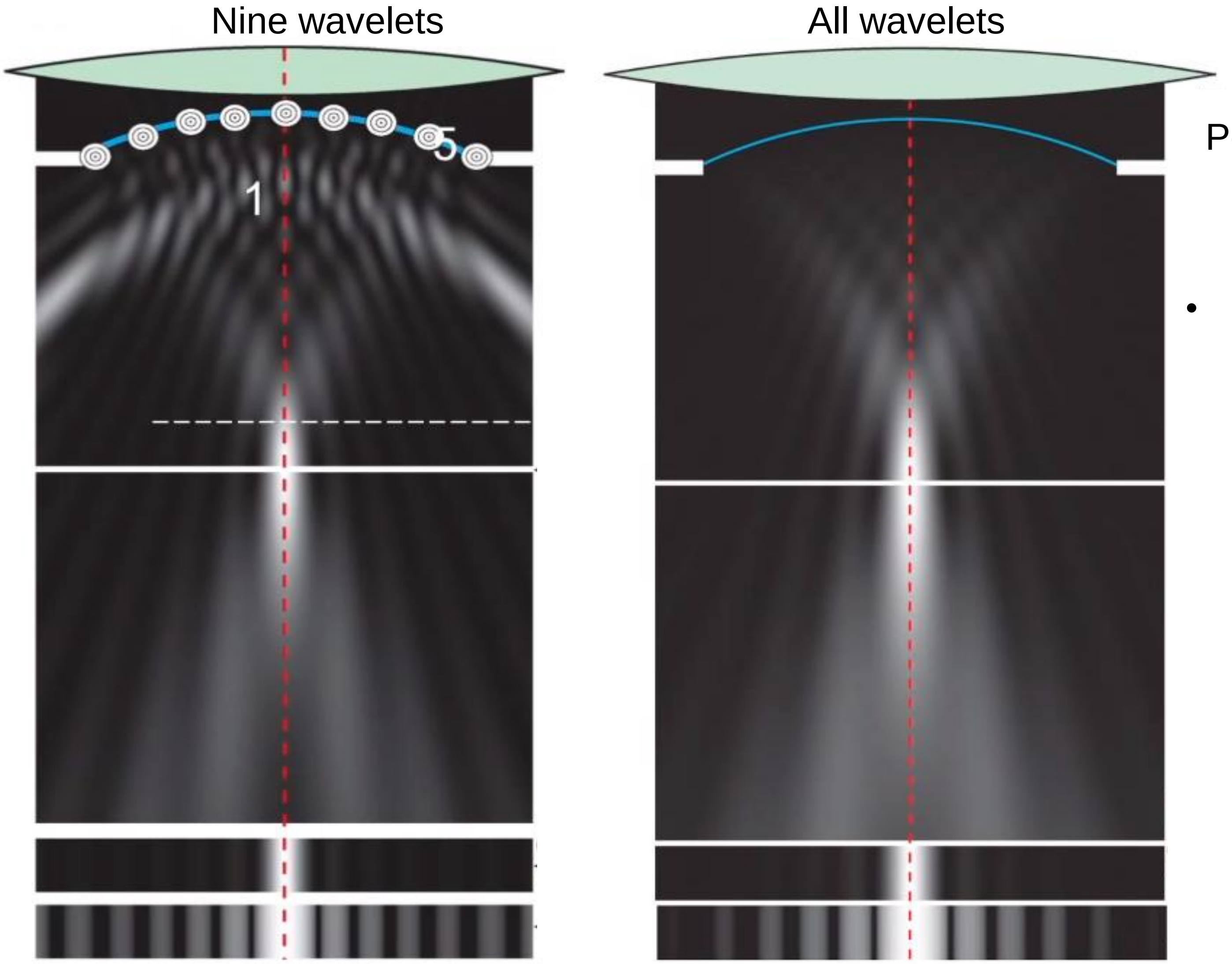
Three wavelets



Five wavelets



Effect of Wavelets

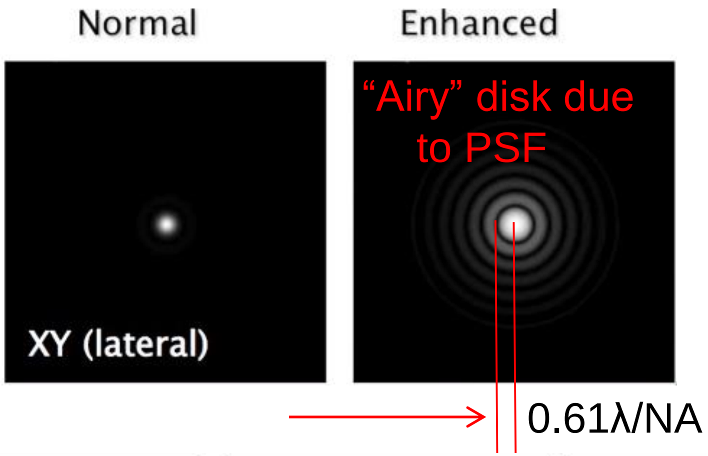


Point Spread Function (PSF)

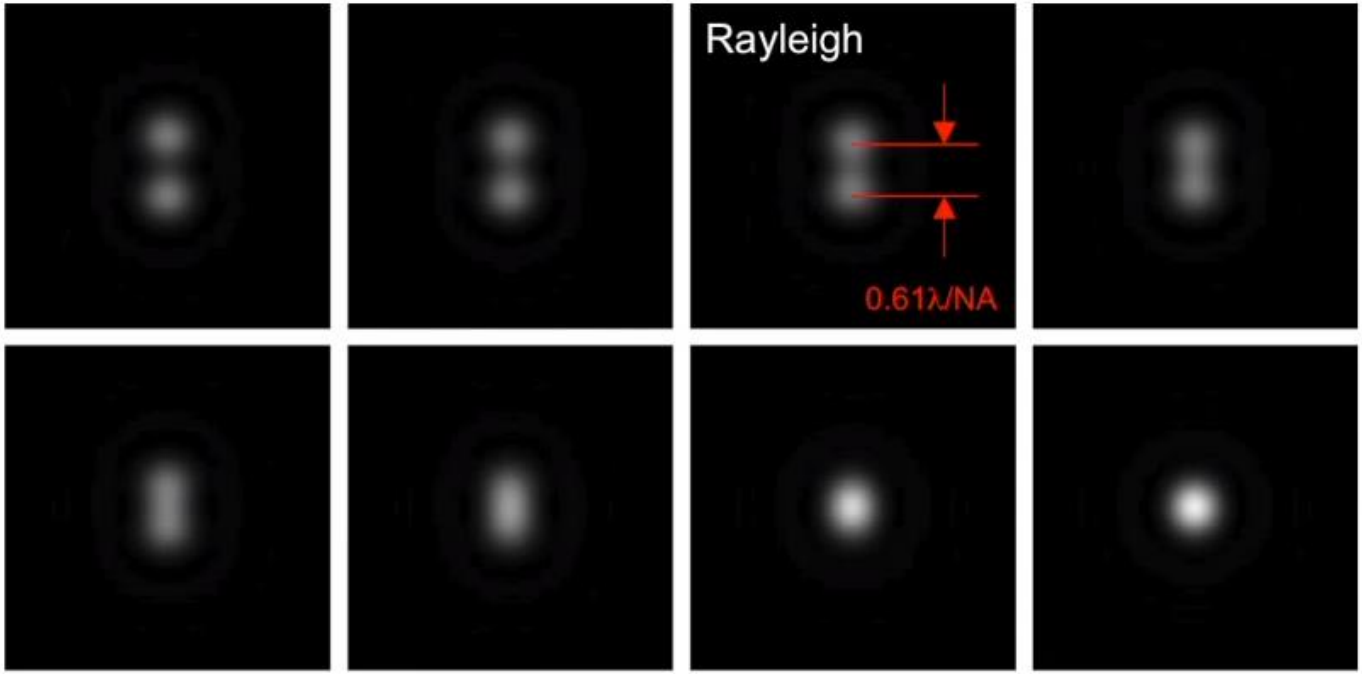
- Size of the image is related to the side wavelets and that is why NA is important

Resolving

- Looking down on the xy plane
- PSF has center Airy disks
- PSF has a series of concentric rings

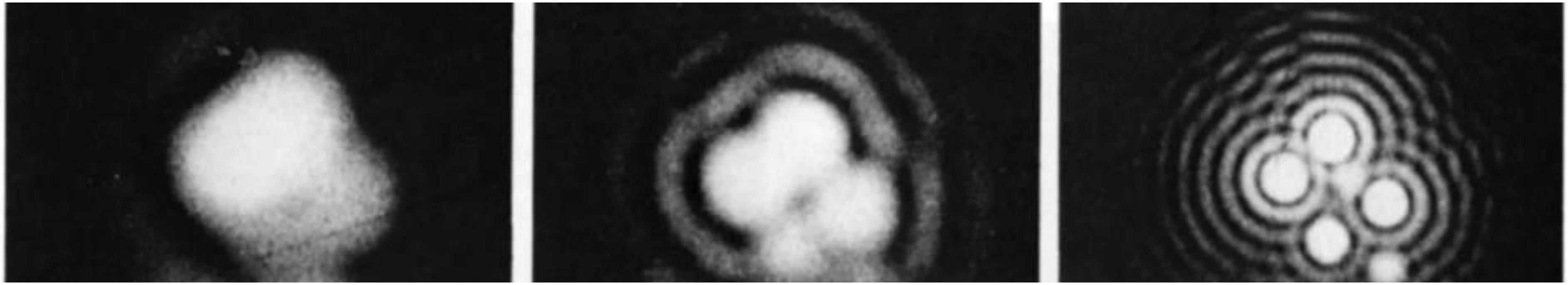


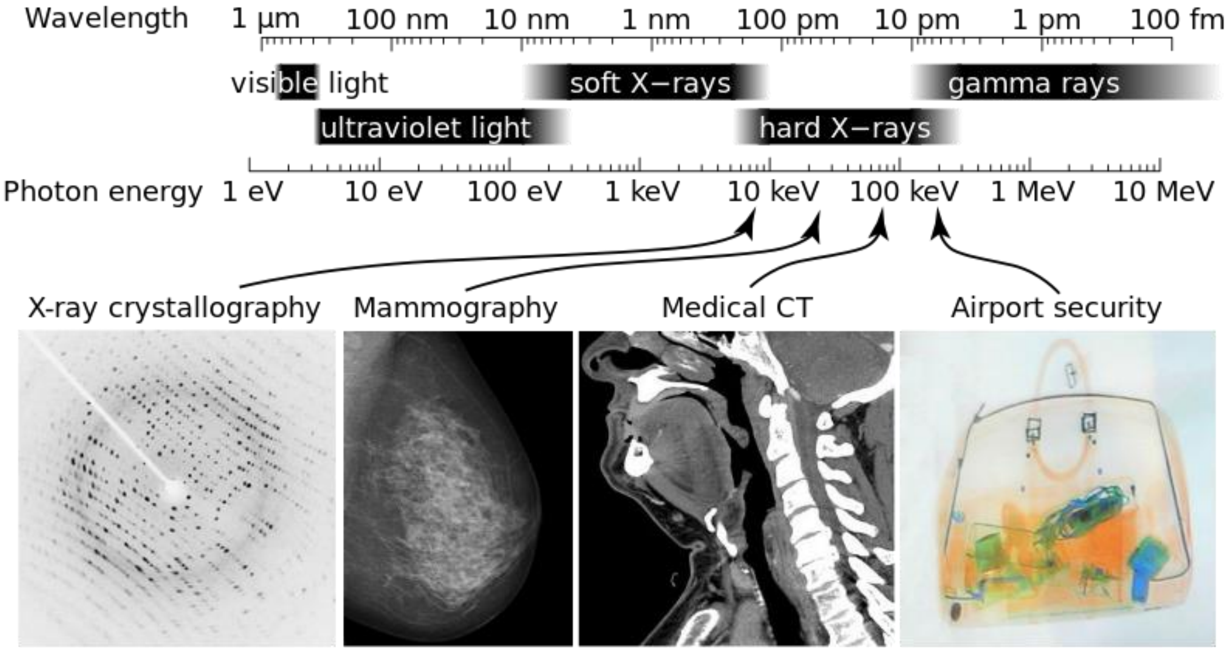
- There is no rule to define resolution but a generally accepted criterion of Rayleigh mostly used by microscopists.
- The center of an object is right at the first dark circle of other object



NA and Wavelength

- Same magnification and different NA

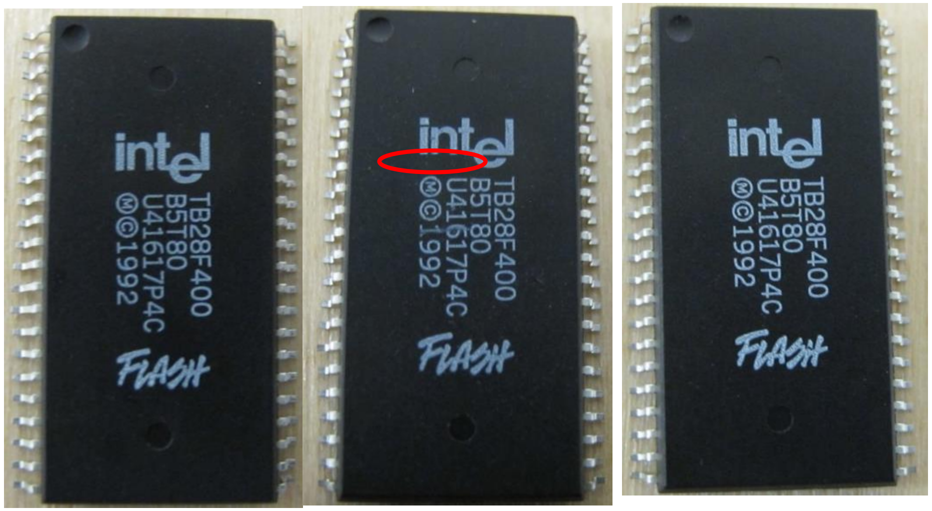


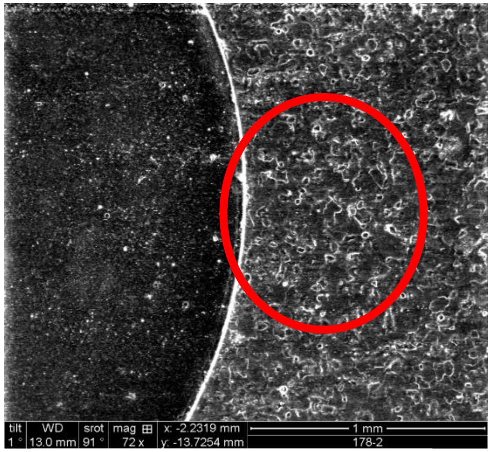


Taxonomy of Defects

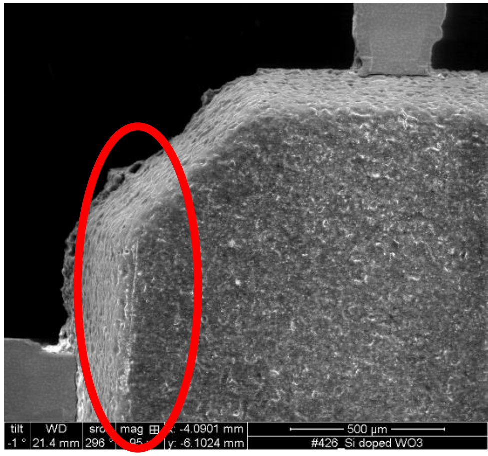
- **Defects**
  - **Physical**
    - **Exterior**
      - Packaging/ Shipping
        - D1: Invalid Lot Code
        - D2: Invalid OEM Shipping Labels
        - D3: Invalid OEM Packaging
        - D4: No ESD Bags for ESD Sensitive Devices
        - D5: Missing/ Forged Paperwork
        - D6: Multiple Date Codes within a Lot
        - D7: Part Orientation within Packaging
        - D8: Missing/ incorrect MSD Indicators
      - Leads/Balls/ Columns
        - D9: Dents
        - D10: Re-tinned
        - D11: Incorrect Dimensions
        - D12: Wrong Materials
        - D13: Contamination
        - D14: Oxidation/ Corrosion
        - D15: Color Variations
        - D16: Tooling Marks
        - D17: Misaligned/ missing Balls/ Columns
        - D18: Distorted/ Non-uniform Balls/Columns
      - Package
        - D19: Invalid Lot/Date/ Country Code
        - D20: Sanding / Grinding Marks
        - D21: Markings
        - D22: Burned Markings
        - D23:Ghost Markings
        - D24: Color Variations/Fade
        - D25: Improper Textures
        - D26: Extraneous Markings
        - D27: Dirty Cavities
        - D28: Incorrect Dimensions/ Weight
        - D29: High Fine/Gross Leak (Hermetic)
        - D30: Package Mold Variations
        - D31: Corrosion
        - D32: Contamination
        - D33: Package Damage
    - **Interior**
      - Bond Wires
        - D34: Missing Wires
        - D35: Poor Connection
        - D36: Broken Wires
        - D37: Poor/ Inconsistent Lead Dress
        - D38: Double Wire Bonds
      - Die
        - D39: Missing Die
        - D40: Wrong Die
        - D41: Delamination
        - D42: Gross Cracks
        - D43: Improper Die Markings
        - D44: Die Damage/ Extraneous Markings
  - **Electrical**
    - **Parametric**
      - D45: Transistor V_{th} Variation
      - D46: TDDB
      - D47: Resistive Open / Short
      - D48: Out-of-spec Leakage Current
      - D49: Out-of-spec. Transient Current
      - D50: Incorrect Temp. Profile
      - D51: Delay Defects
    - **Manufacturing**
      - Process
        - D52: Missing Contact Windows
        - D53: Misaligned Window
        - D54: Oxide Break-down
        - D55: Parasitic Transistors
      - Material
        - D56: Fine Cracks
        - D57: Crystal Imperfection
        - D58: Surface Impurities
        - D59: Improper Materials (Seals, Epoxies, Dielectrics, etc)
      - Package
        - D60: Surface Passivation and Corrosion
        - D61: Contact Degradation
        - D62: Seal Leaks
        - D63: Electromigration
        - D64: Mechanical Interfaces: Intermetallic Growth
        - D65: Mechanical Interfaces: Fatigue

SEM Imaging



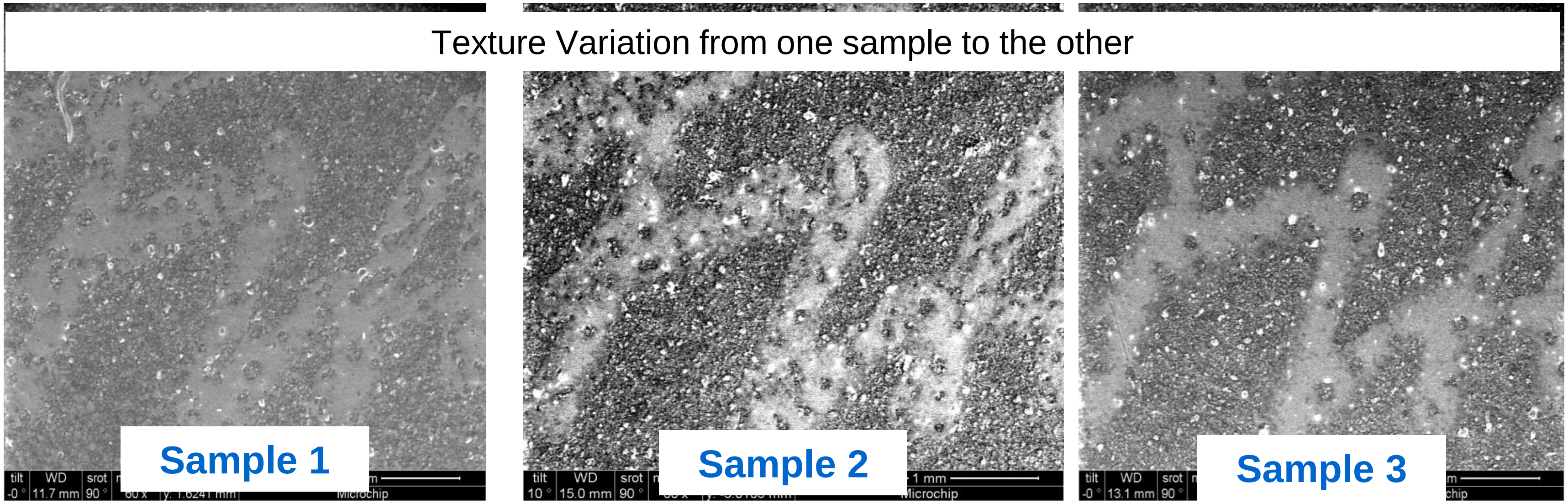


Polishing marks on smoothed top surface



Improper Texture

Texture Variation from one sample to the other



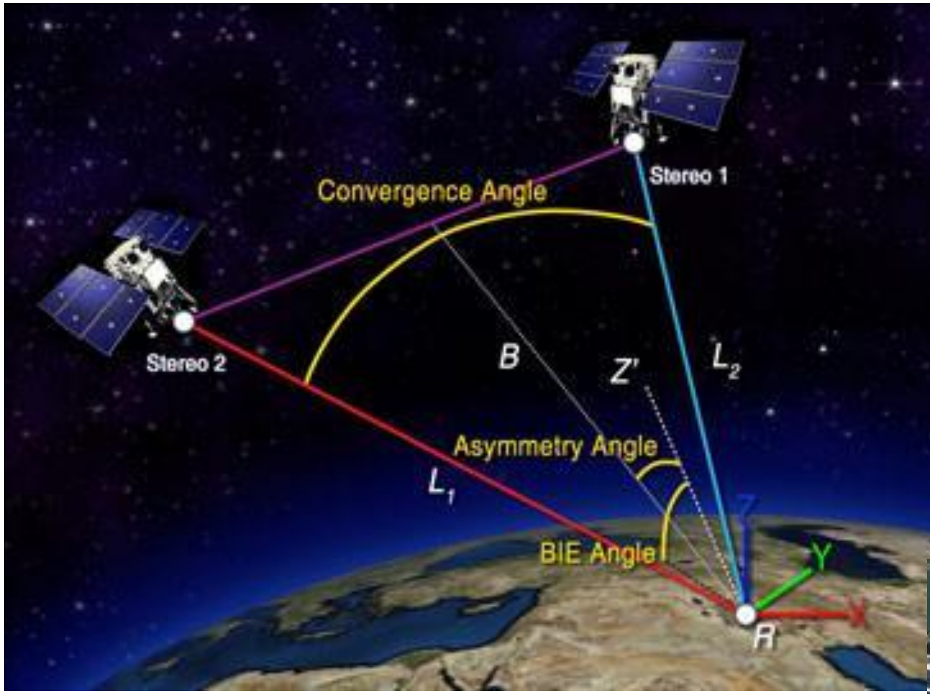
Sample 1

Sample 2

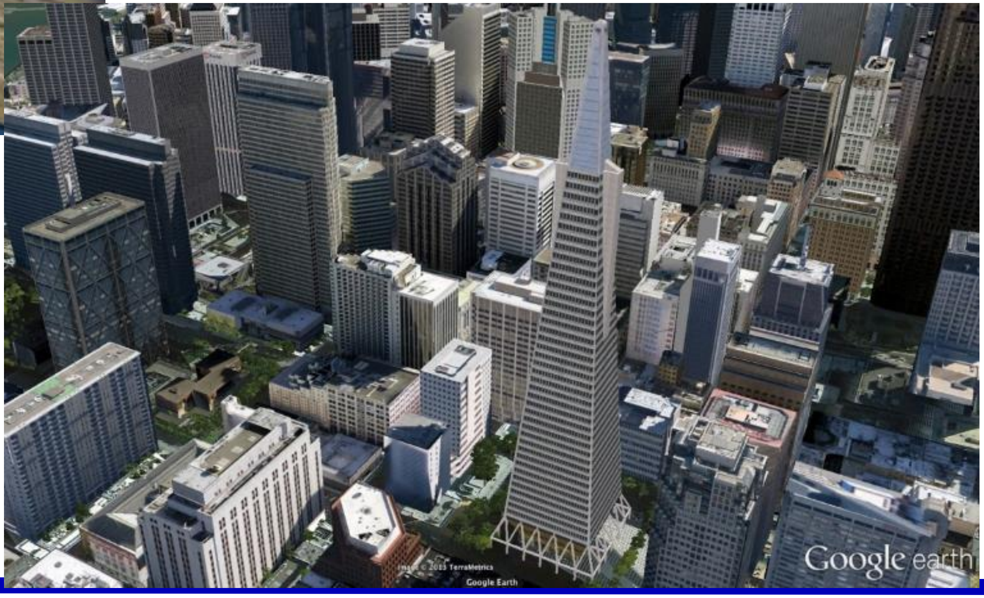
Sample 3

3D SEM Based Stereo-photogrammetry

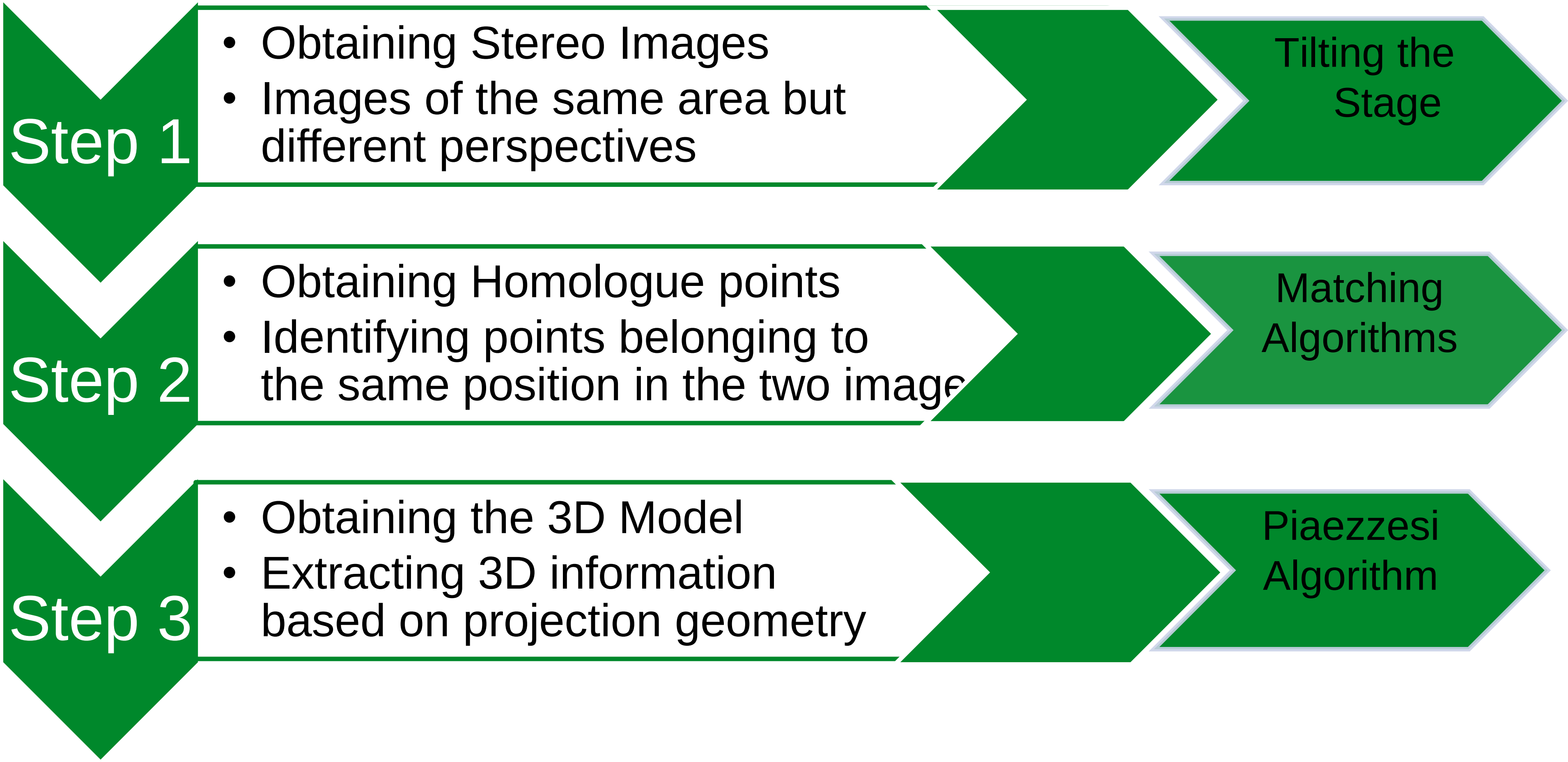
What is Stereo-photogrammetry?



By Taking 2D images of the same Location at different perspective one can reconstruct the 3D image



3D SEM Based Stereo-photogrammetry



Step 1

- Obtaining Stereo Images
- Images of the same area but different perspectives

Tilting the Stage

Step 2

- Obtaining Homologue points
- Identifying points belonging to the same position in the two image

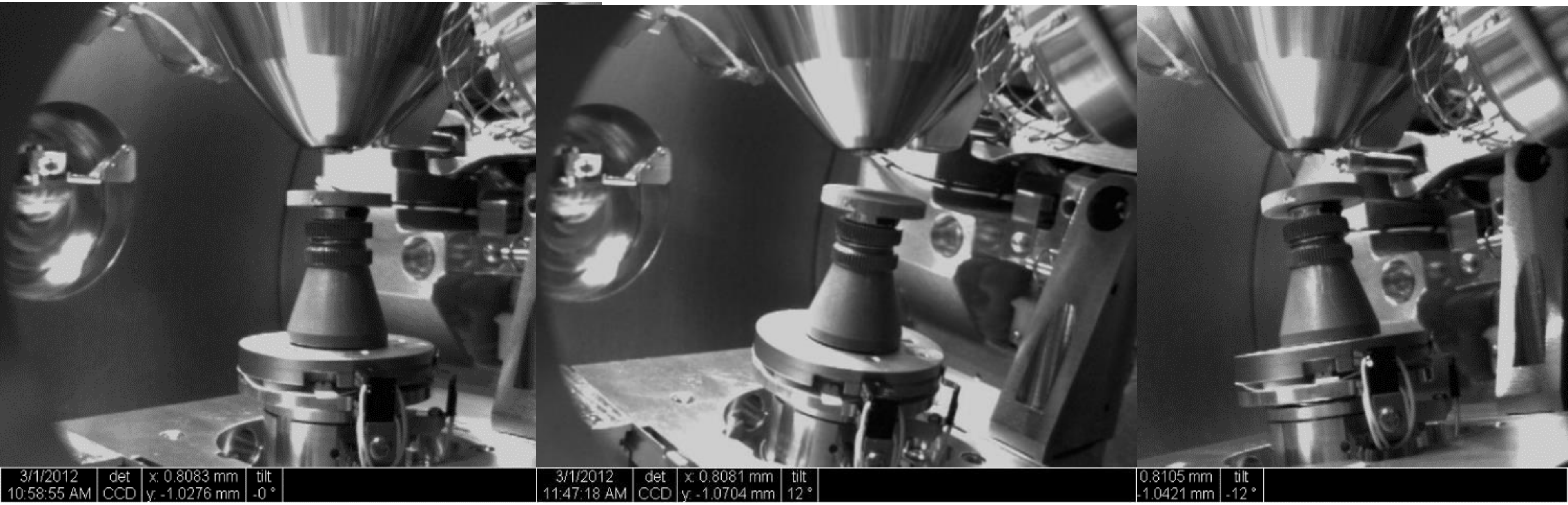
Matching Algorithms

Step 3

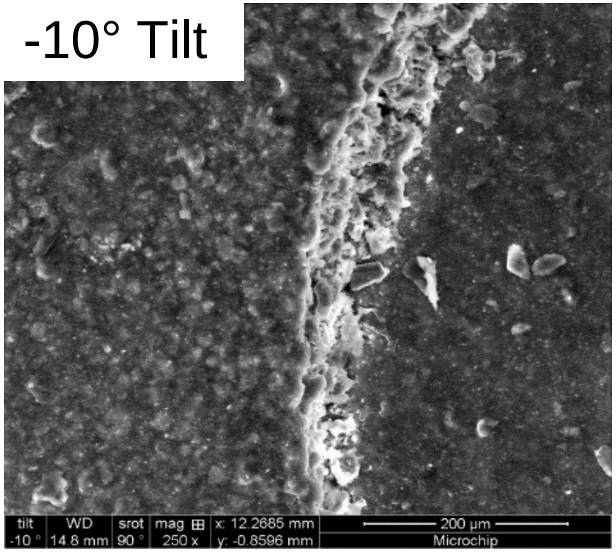
- Obtaining the 3D Model
- Extracting 3D information based on projection geometry

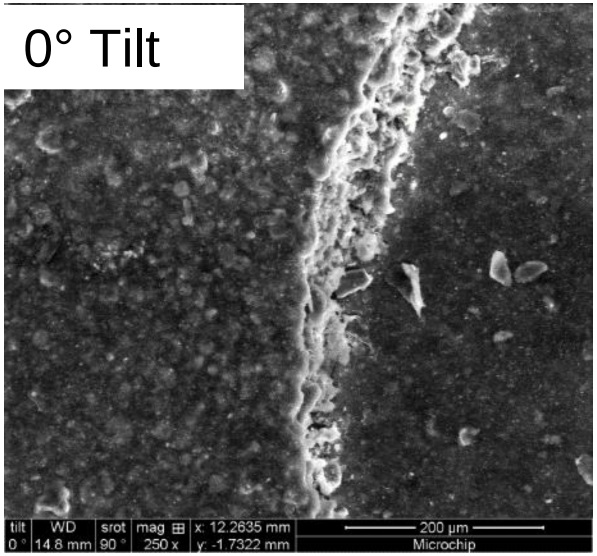
Piaezzesi Algorithm

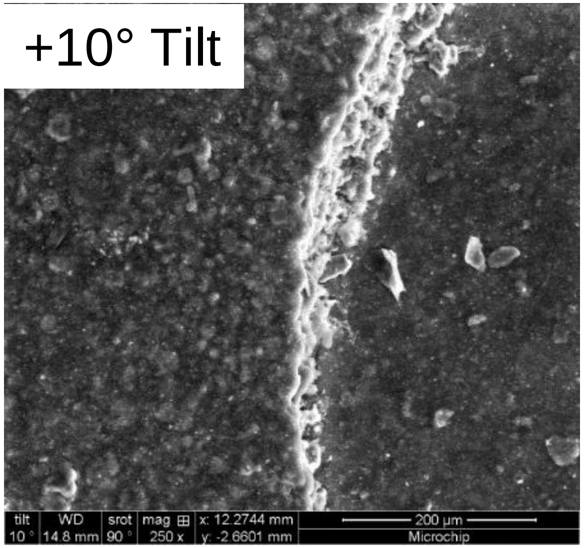
3D SEM Based Stereo-photogrammetry

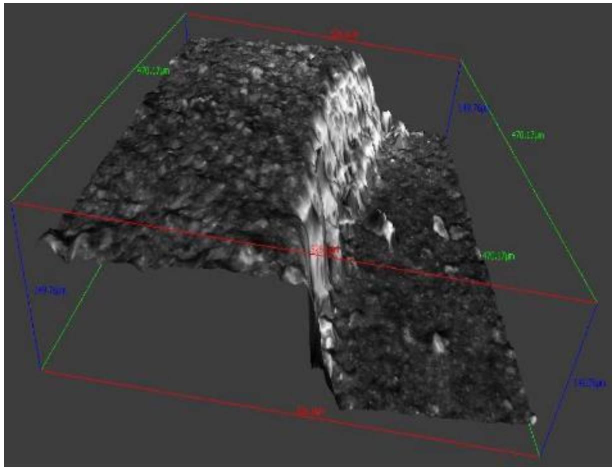


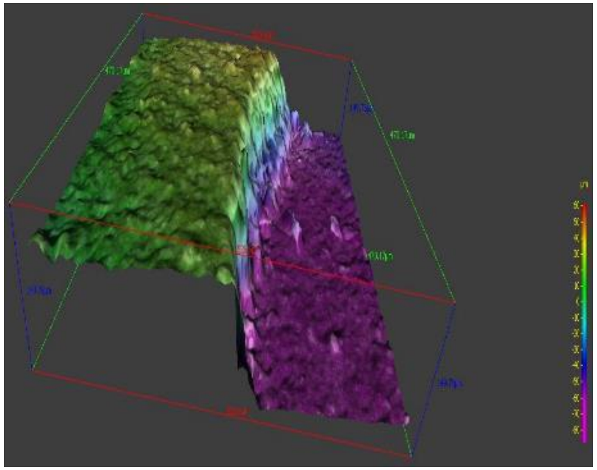
SEM- Stereo photogrammetry on a Dimple


-10° Tilt


0° Tilt


+10° Tilt

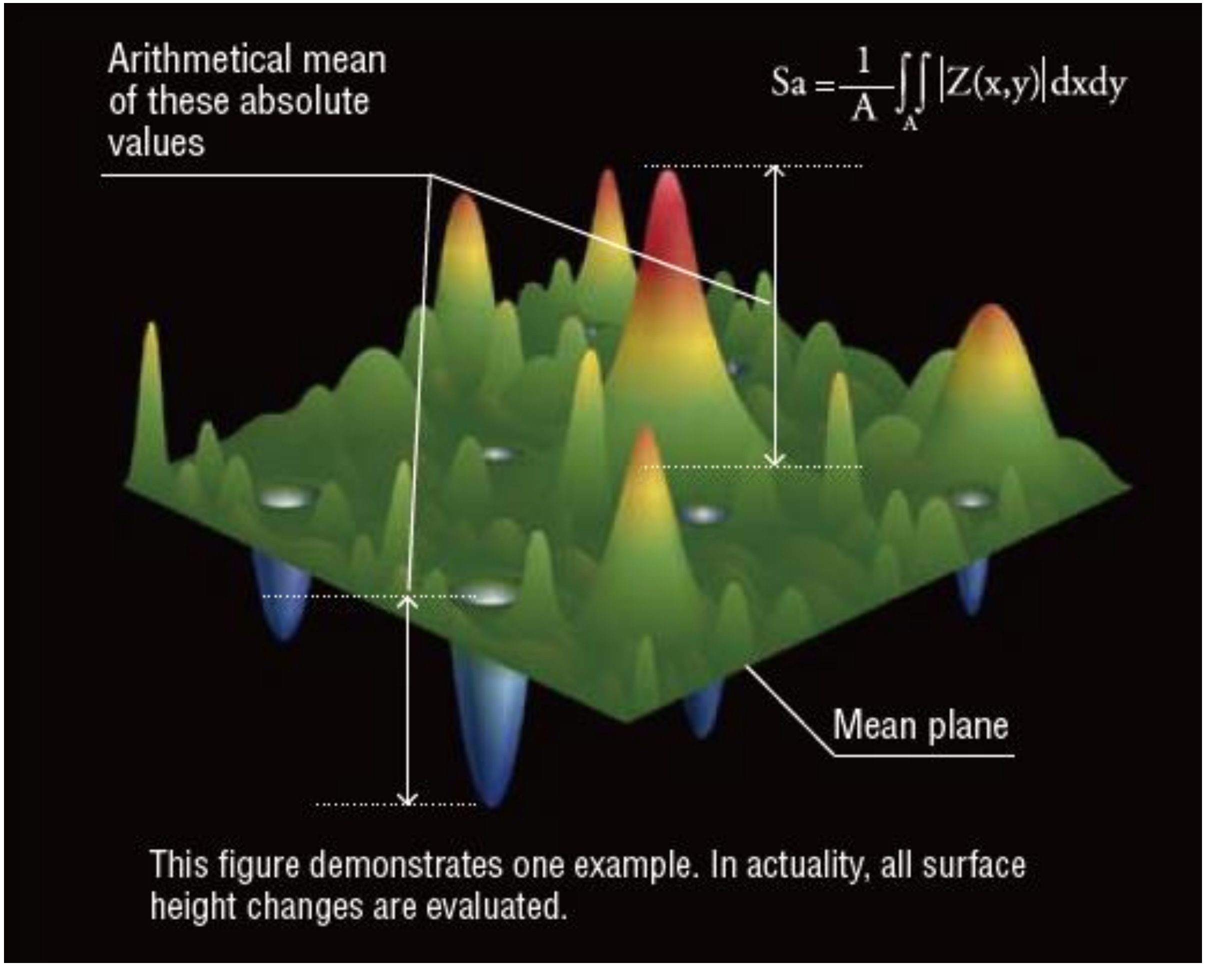




3D surface reconstruction from only 3 images while maintaining the actual texture of the dimples

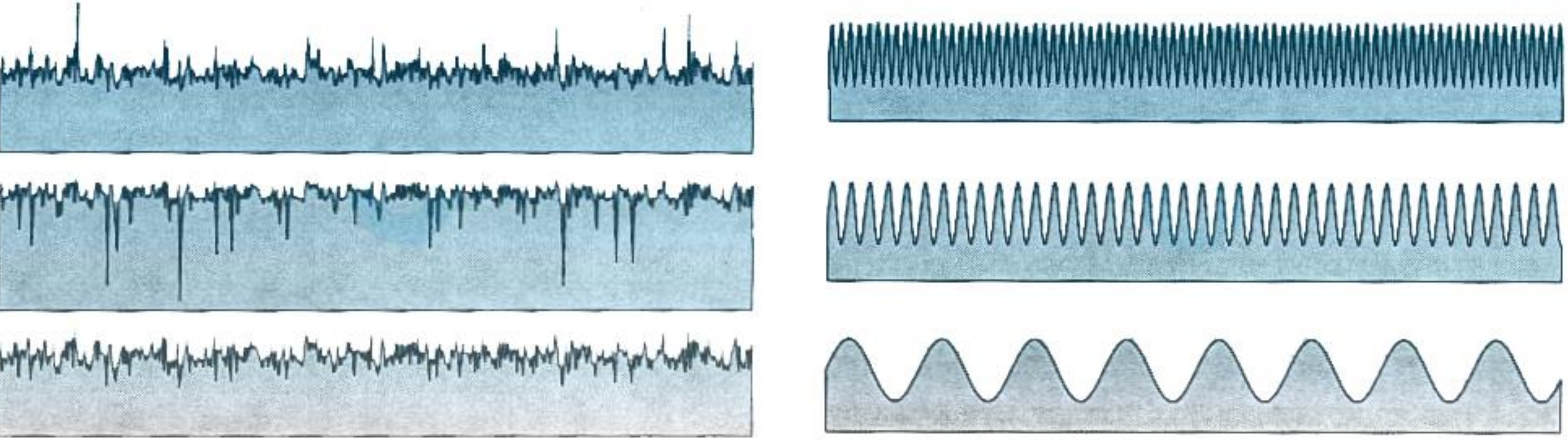
Surface Parameters for quantification

Height Sa (arithmetical mean height)

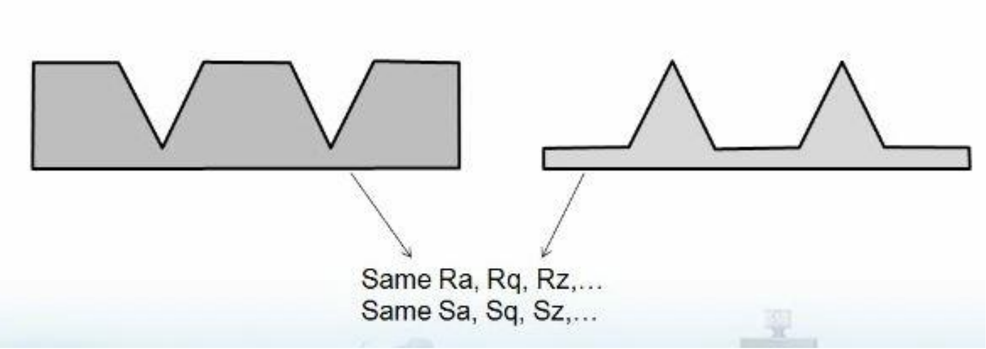


This figure demonstrates one example. In actuality, all surface height changes are evaluated.

Surface Parameters for quantification



Some parameters have to be used that concerns heights and peaks/ volume analysis

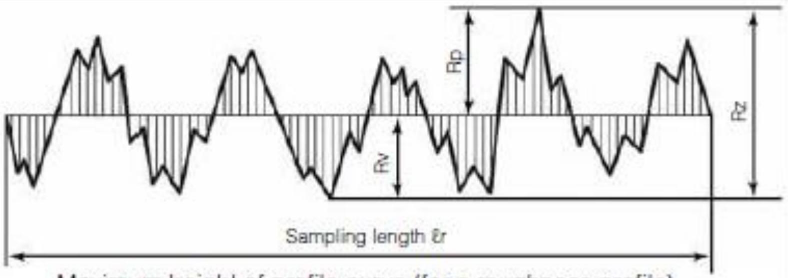


Surface Parameters for quantification

Height Sz (Maximum height)

sum of the largest peak height value and the largest pit depth value within the defined area

$$Sz = Sp + Sv$$



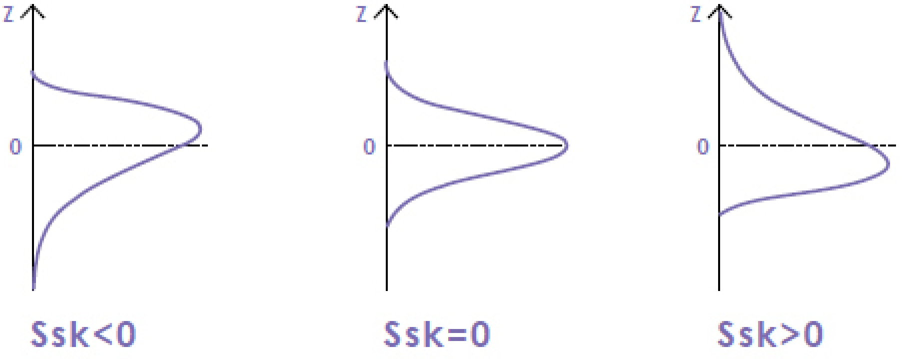
Maximum height of profile curve (for a roughness profile)

The figure is an example of Rz (maximum profile height of a line).
Sz is an areal extension of Rz.

Ssk (Skewness)

represent the degree of bias of the roughness shape (asperity)

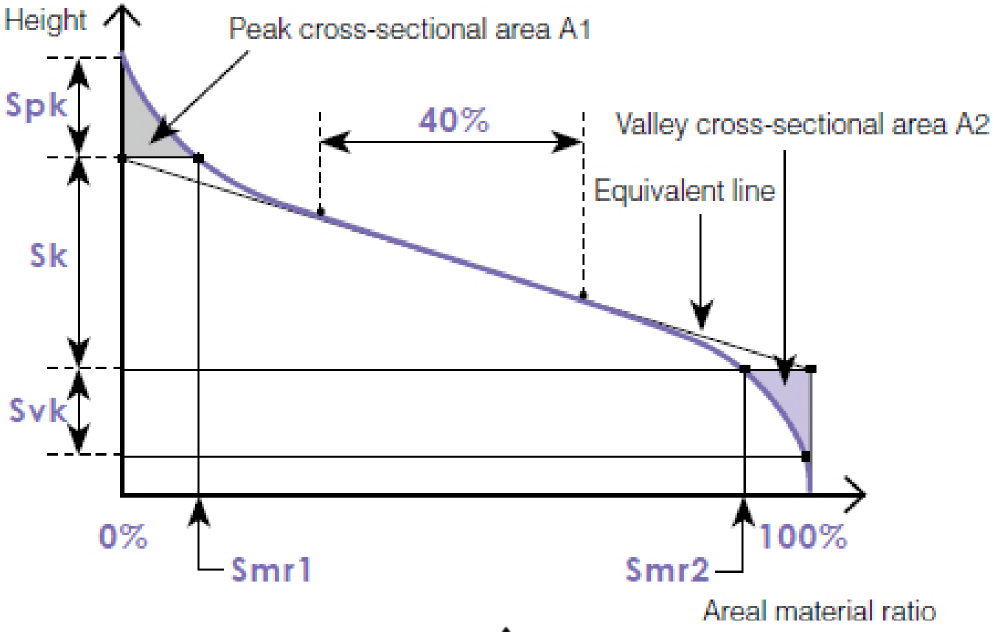
$$Ssk = \frac{1}{Sq^3}\left[\frac{1}{A}\iint_A Z^3(x,y)\,dx\,dy\right]$$



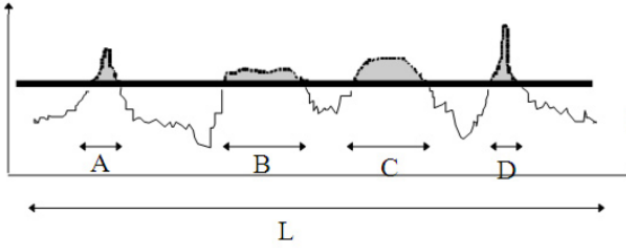
Ssk<0: Height distribution is skewed above the mean plane.
Ssk=0: Height distribution (peaks and pits) is symmetrical around the mean plane.
Ssk>0: Height distribution is skewed below the mean plane.

Surface Parameters for quantification

The **areal material ratio curve** of an area is a curve representing heights at which the areal material ratio changes from 0% to 100%



Aerial material ratio = (A+B+C+D)/L



Functional

Sk (Core roughness depth)
Spk (Reduced peak height)
Svk (reduced dale height (reduced valley depth))

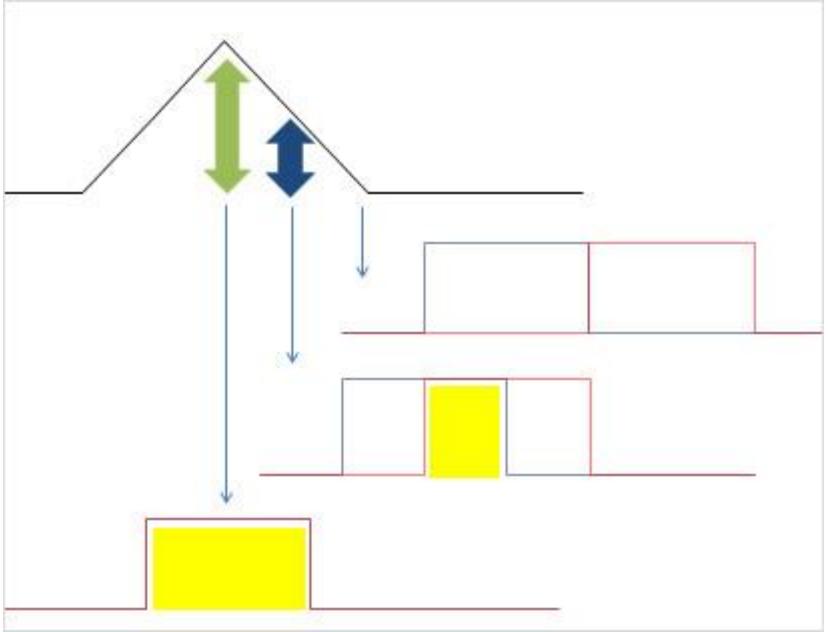
Surface Parameters for quantification

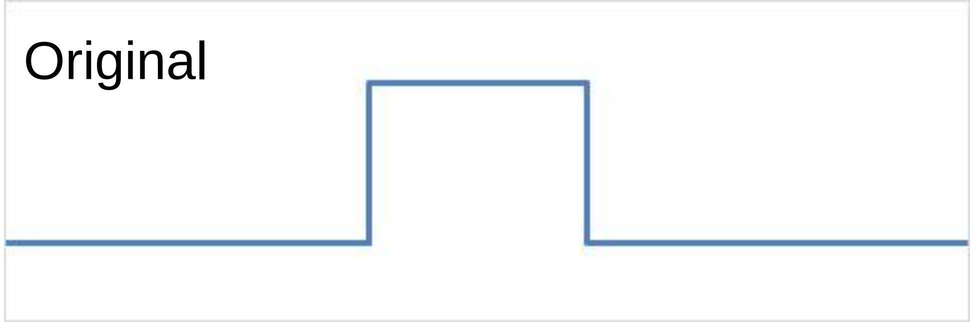
Spatial Sal (Auto-correlation length)

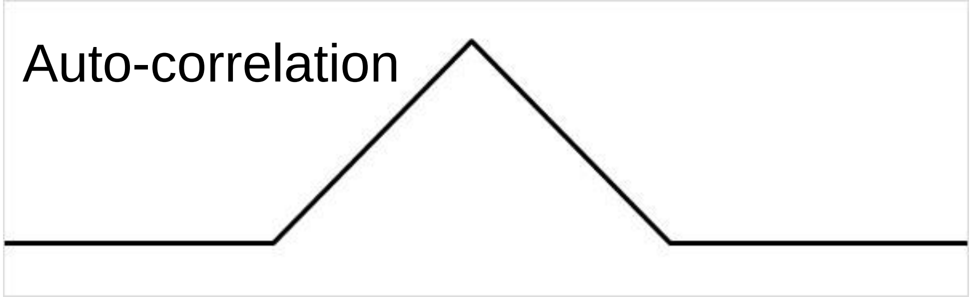
Represents horizontal distance in the direction in which the auto-correlation function decays to the value[s] (0.2 by default) the fastest.

$$f_{ACF}(t_x, t_y) = \frac{\iint_A z(x, y) z(x-t_x, y-t_y) dxdy}{\iint_A z(x, y) z(x, y) dxdy}$$

In image processing, an auto-correlation function is a measure of the matching ratio between an image rendered in different coordinates and the original image







When the difference is small, the overlapping area is large, as is the auto-correlation value.
When the difference is large, the overlapping area is small, as is the auto-correlation value

Advanced Surface Analysis (SEM)

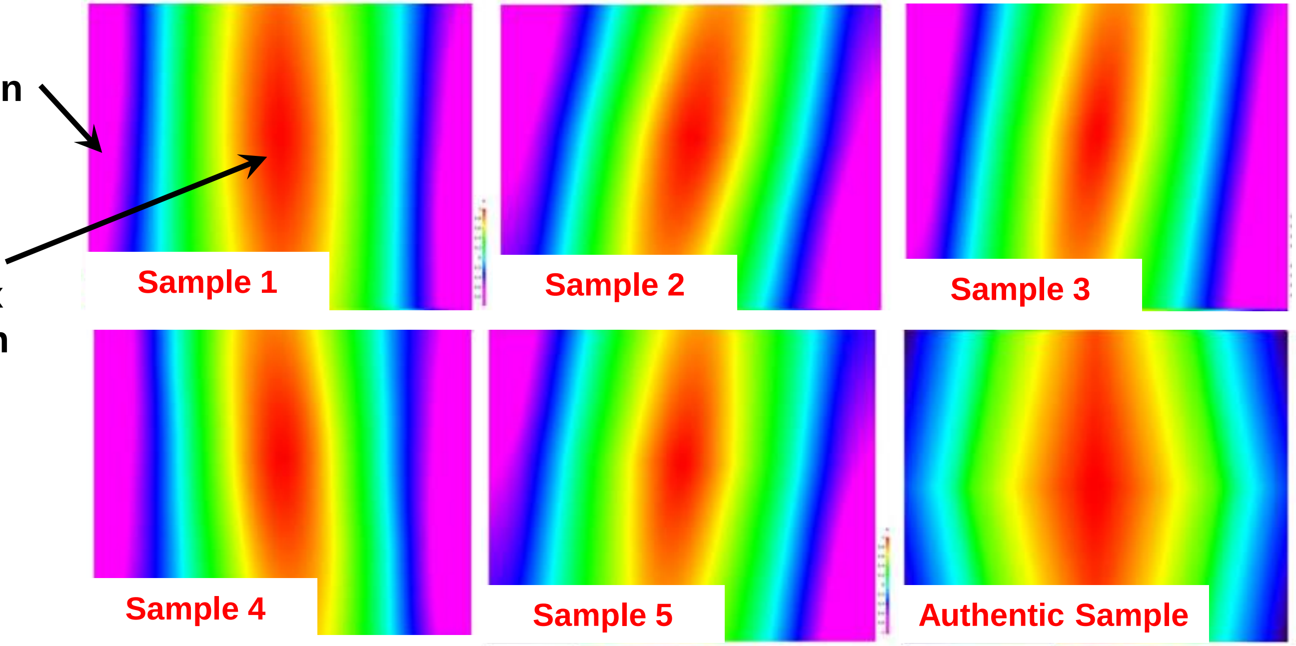
$$R(t_i, t_i) = \frac{1}{(M-i)(N-j)} \sum_{l=1}^{N-j} \sum_{k=l}^{M-i} Z(x_k, y_l) Z\left(x_{k+i}, y_{l+j}\right)$$

$$i = 0,1, \dots.m < M;\ j = 0,1, \dots.n < N;\ t_i = i.\Delta x;\ t_j = j.\Delta y$$

Areal Autocorrelation Function (AACF)

Pink = no correlation

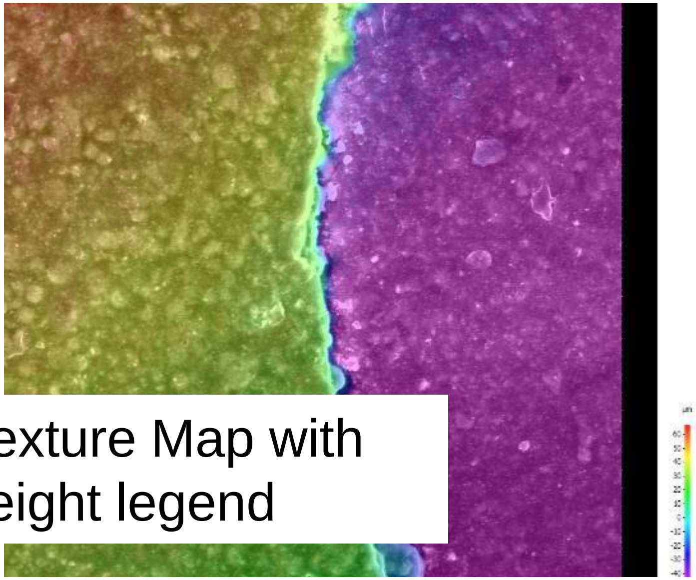
Red = max correlation



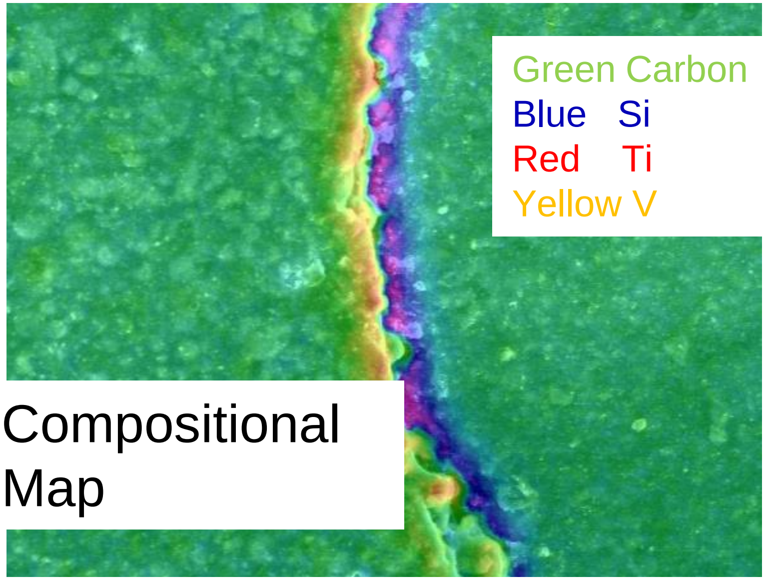
Surface Parameters for quantification

Functional	Smr(c) Areal material (bearing area) ratio Smc(mr) Inverse areal material ratio Sk (Core roughness depth) Spk (Reduced peak height) Svk (reduced dale height (reduced valley depth)) Smr (Peak material portion) Smr2 (Valley material portion) Sxp (Peak extreme height)
Functional volume	Vvv (Dale void volume) Vvc (Core void volume) Vmp (Peak material volume) Vmc (Core material volume)
Feature	Spd (Density of peaks) Spc (Arithmetic mean peak curvature) S10z / S5p / S5v / Sda(c) / Sha(c) / Sdv(c) / Shv(c)

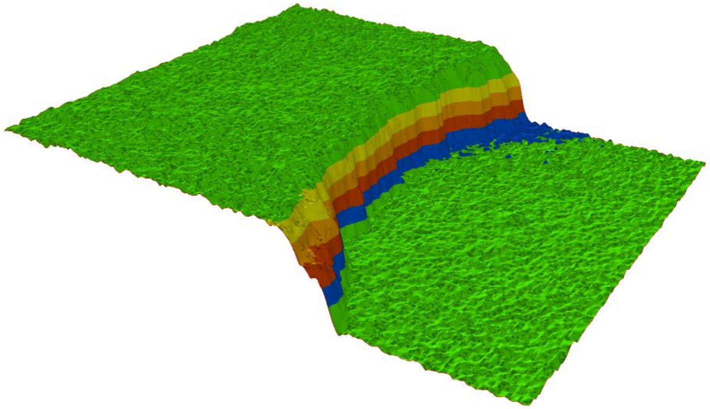
Geometry and Material



Texture Map with height legend

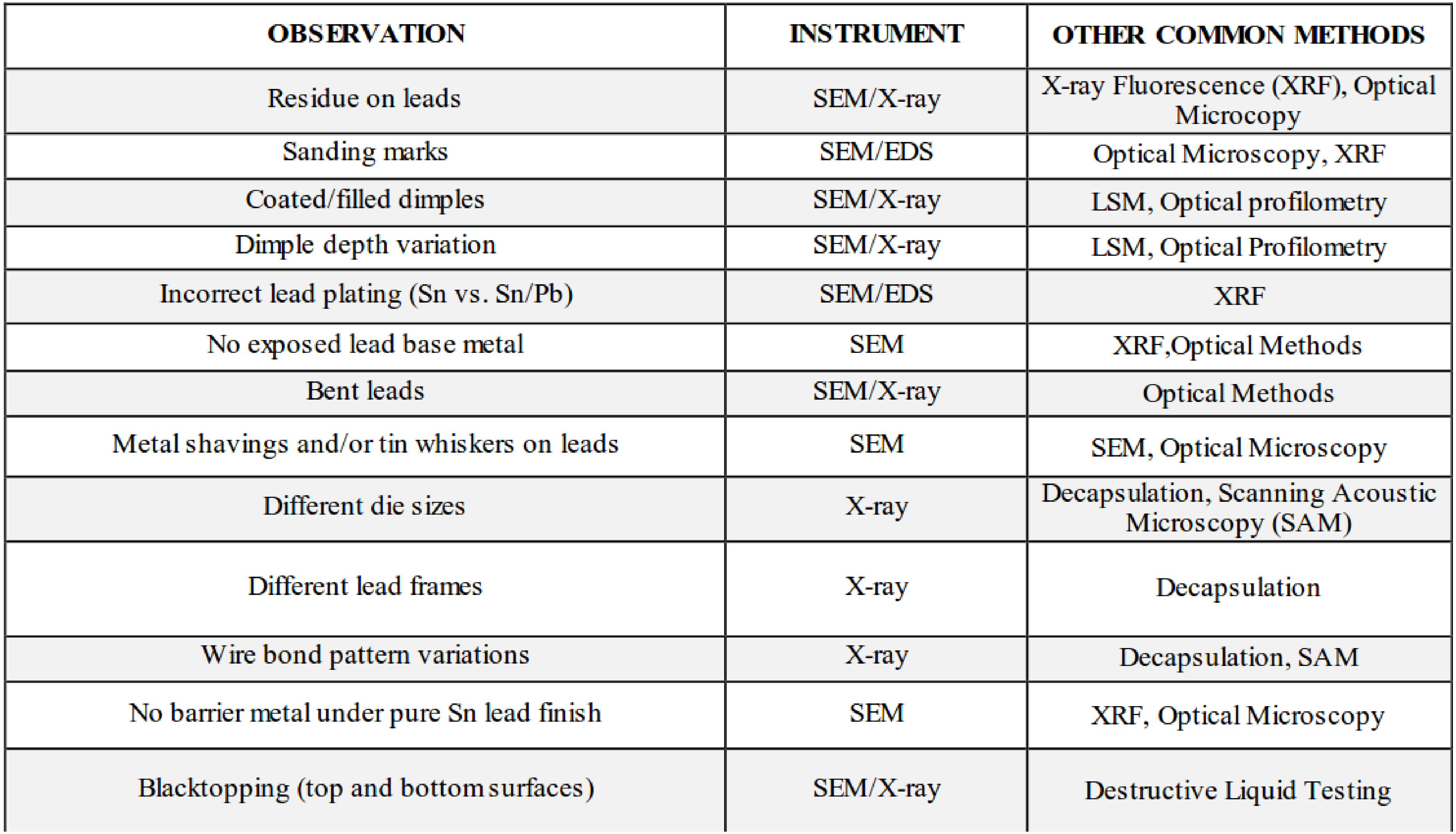


Compositional Map



Compositional Map on the 3D Dimple, green represents Carbon and blue, red and yellow are Si, Ti and V respectively

Tools for Visual Inspection



OBSERVATION	INSTRUMENT	OTHER COMMON METHODS
Residue on leads	SEM/X-ray	X-ray Fluorescence (XRF), Optical Microcopy
Sanding marks	SEM/EDS	Optical Microscopy, XRF
Coated/filled dimples	SEM/X-ray	LSM, Optical profilometry
Dimple depth variation	SEM/X-ray	LSM, Optical Profilometry
Incorrect lead plating (Sn vs. Sn/Pb)	SEM/EDS	XRF
No exposed lead base metal	SEM	XRF,Optical Methods
Bent leads	SEM/X-ray	Optical Methods
Metal shavings and/or tin whiskers on leads	SEM	SEM, Optical Microscopy
Different die sizes	X-ray	Decapsulation, Scanning Acoustic Microscopy (SAM)
Different lead frames	X-ray	Decapsulation
Wire bond pattern variations	X-ray	Decapsulation, SAM
No barrier metal under pure Sn lead finish	SEM	XRF, Optical Microscopy
Blacktopping (top and bottom surfaces)	SEM/X-ray	Destructive Liquid Testing

Reading

- https://www.microscopyu.com/
- ISTFA paper: Advanced Physical Inspection Methods for Counterfeit IC Detection