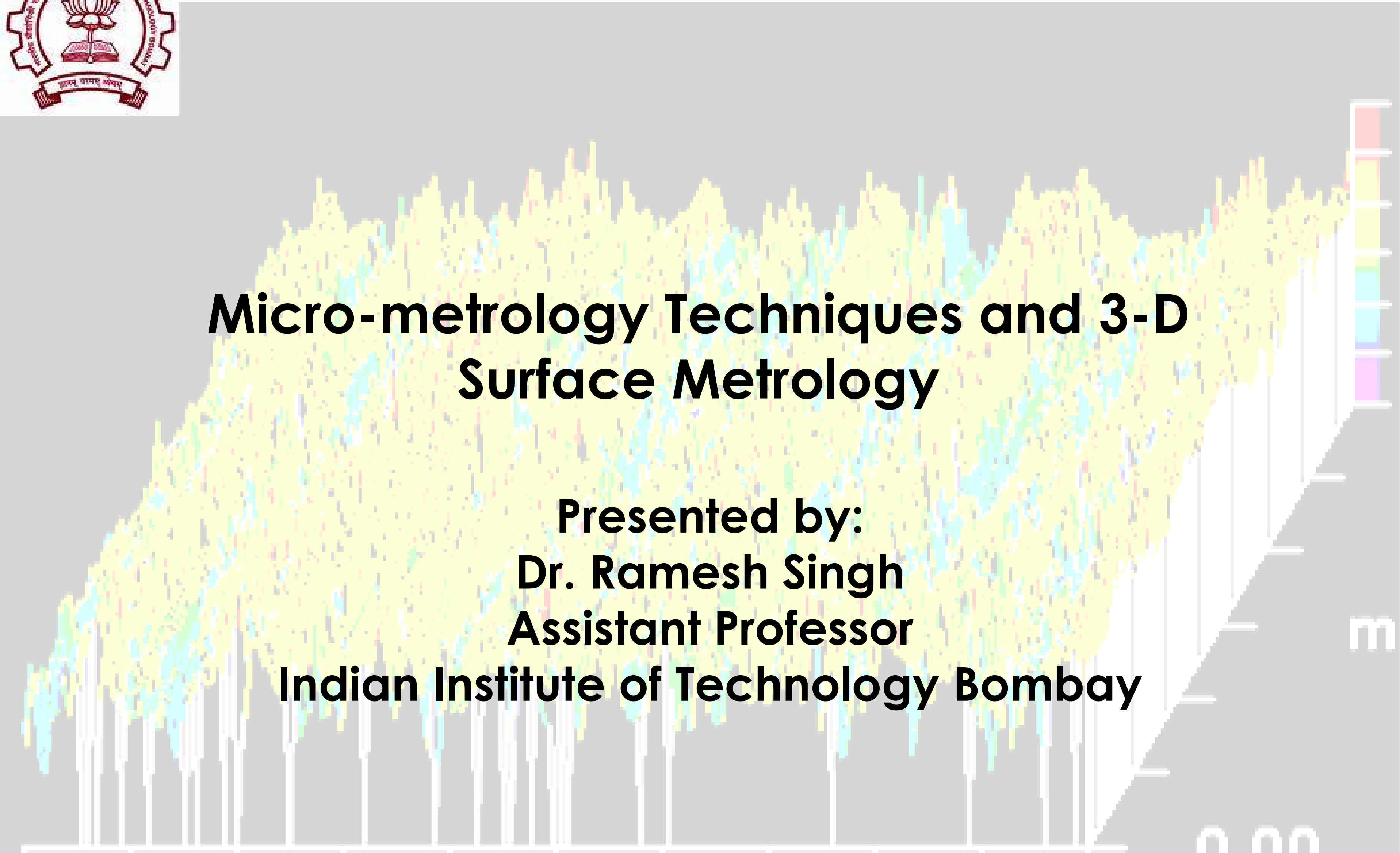
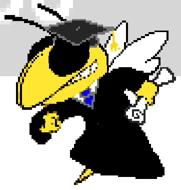
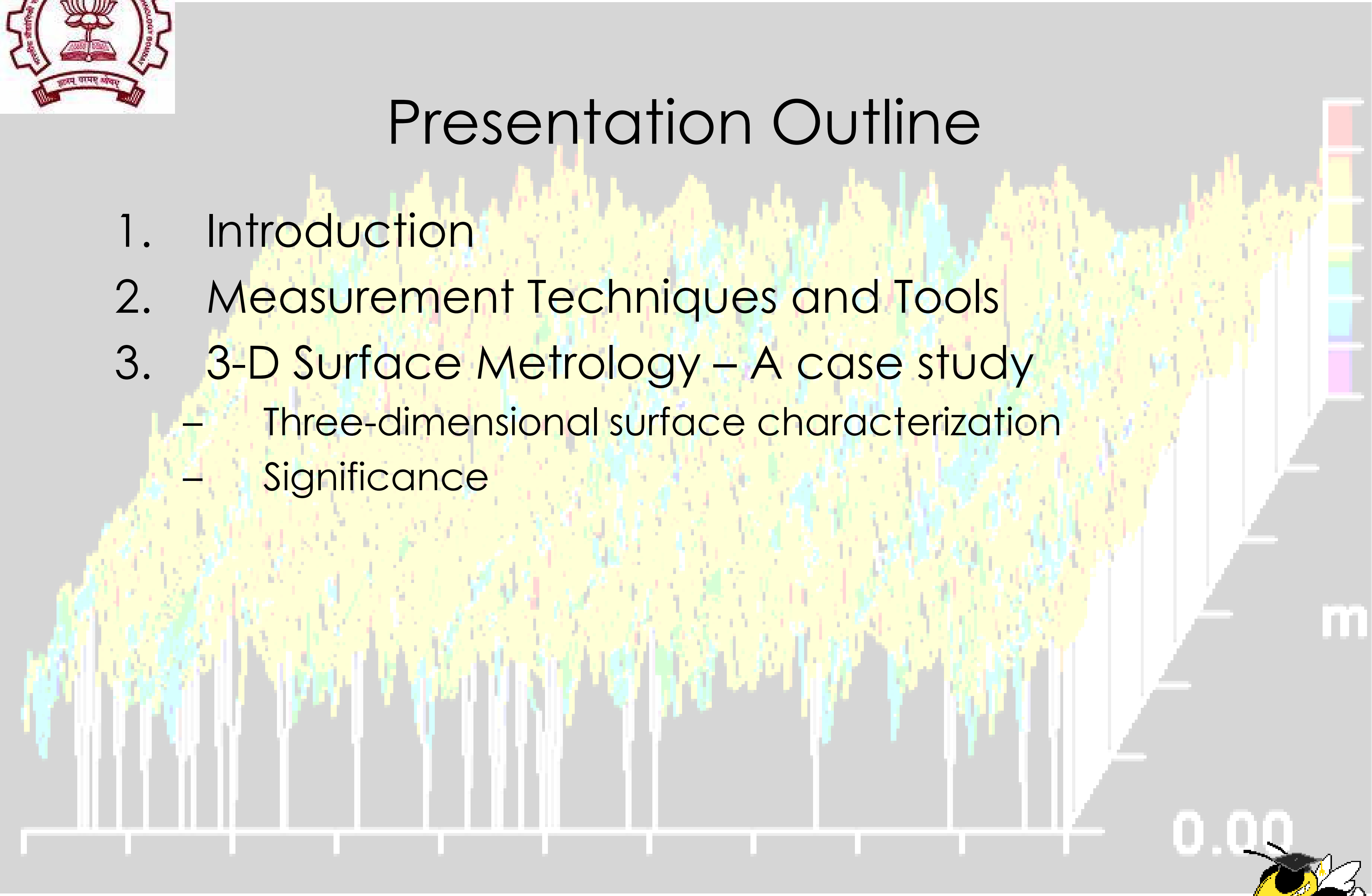


Micro-metrology Techniques and 3-D Surface Metrology

Presented by:
Dr. Ramesh Singh
Assistant Professor
Indian Institute of Technology Bombay

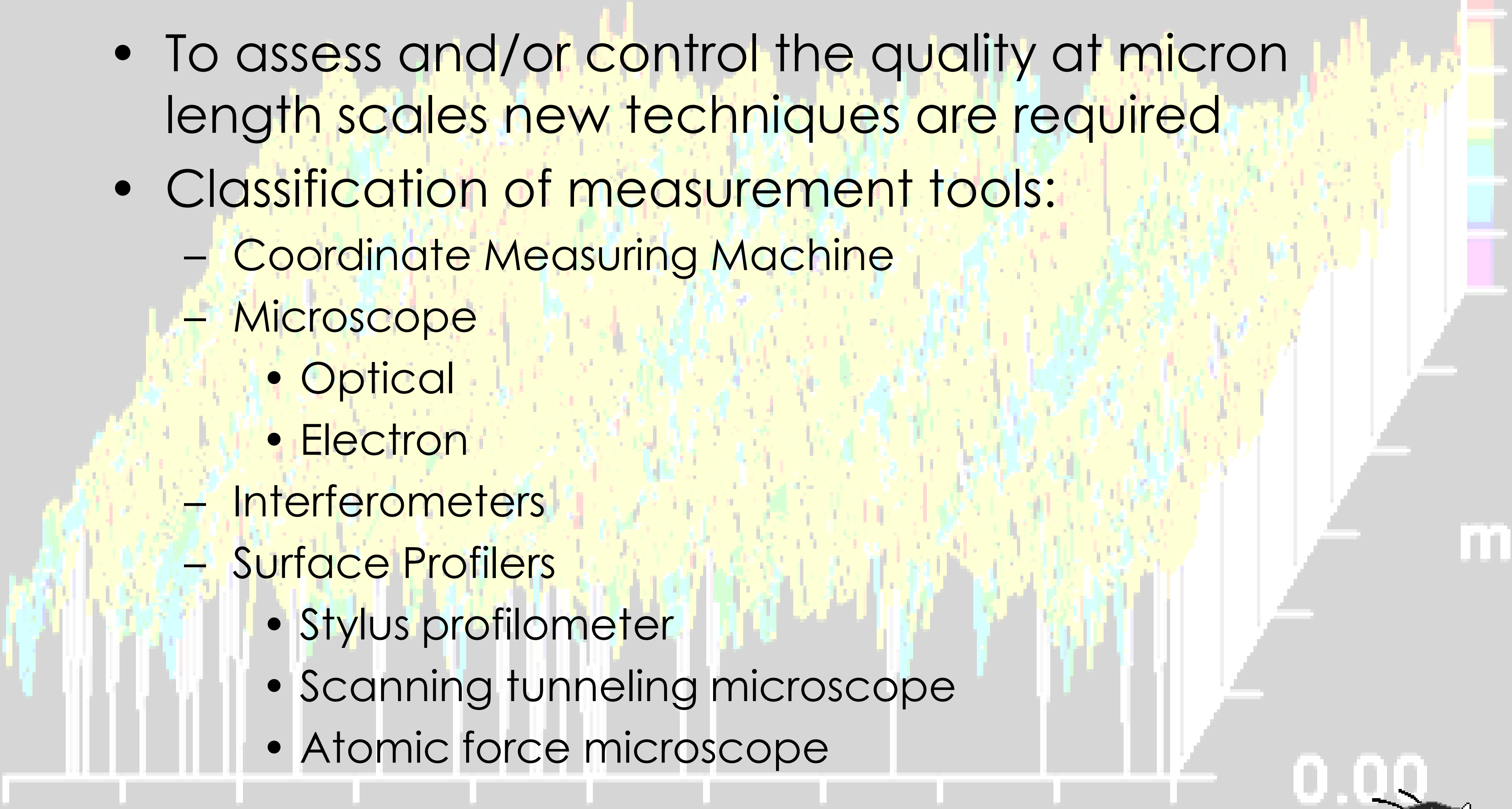


Presentation Outline



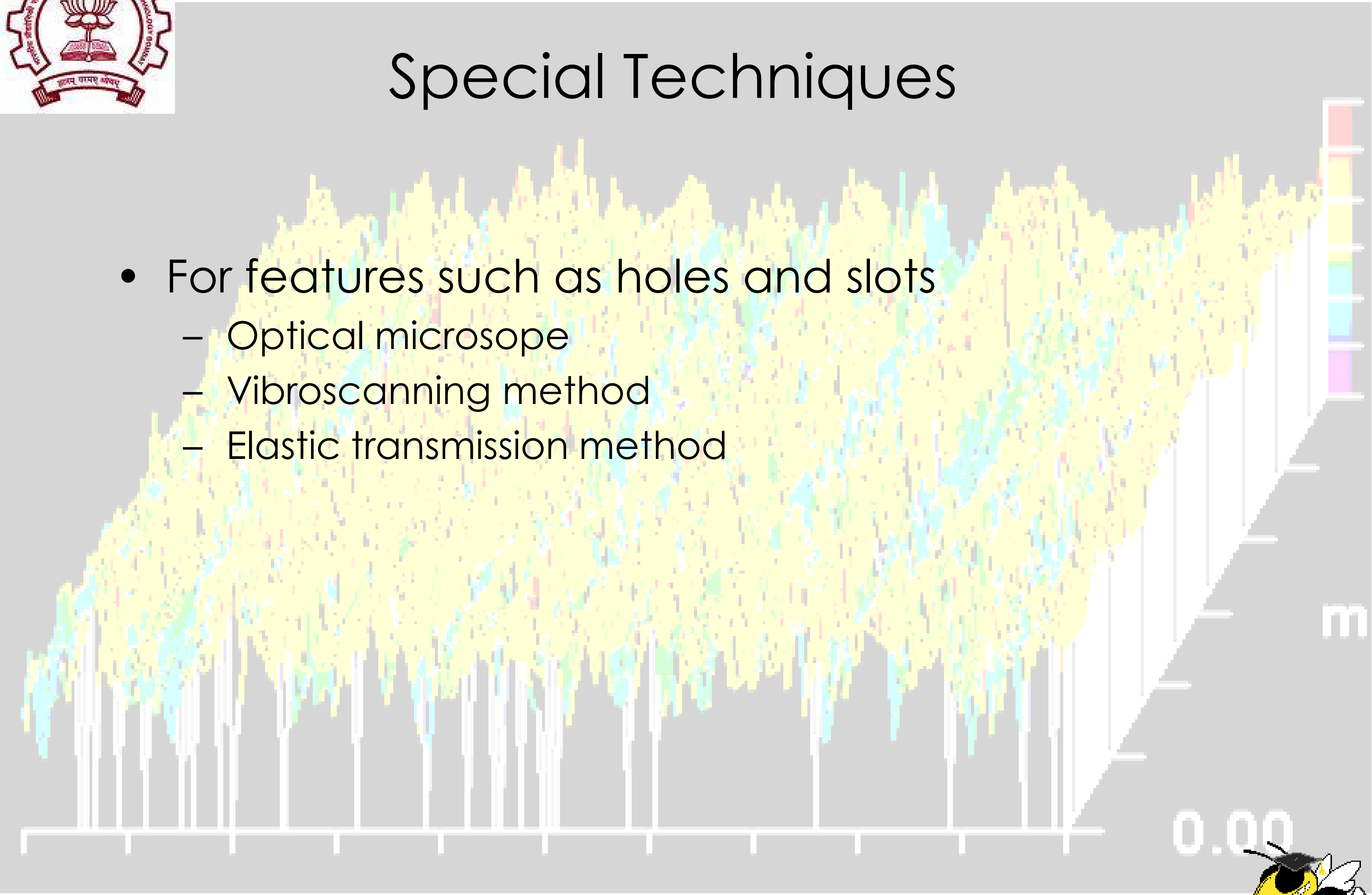
1. Introduction
2. Measurement Techniques and Tools
3. 3-D Surface Metrology – A case study
    - Three-dimensional surface characterization
    - Significance

Micro-metrology Techniques



- To assess and/or control the quality at micron length scales new techniques are required
- Classification of measurement tools:
  - Coordinate Measuring Machine
  - Microscope
    - Optical
    - Electron
  - Interferometers
  - Surface Profilers
    - Stylus profilometer
    - Scanning tunneling microscope
    - Atomic force microscope

Special Techniques

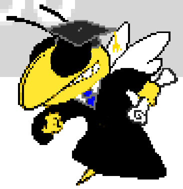


- For features such as holes and slots
  - Optical microsope
  - Vibroscanning method
  - Elastic transmission method

Coordinate Measuring Machine

Features

- Measuring probe obtains the coordinates of points on an object surface.
- Dimensions of target objects can be measured
- Tolerances as small as .0001".
- The machine uses an X-Y-Z grid to determine the location
- There are newer models that have automated probe movement/laser scanning
- Maximum internal dimension is limited by probe tip

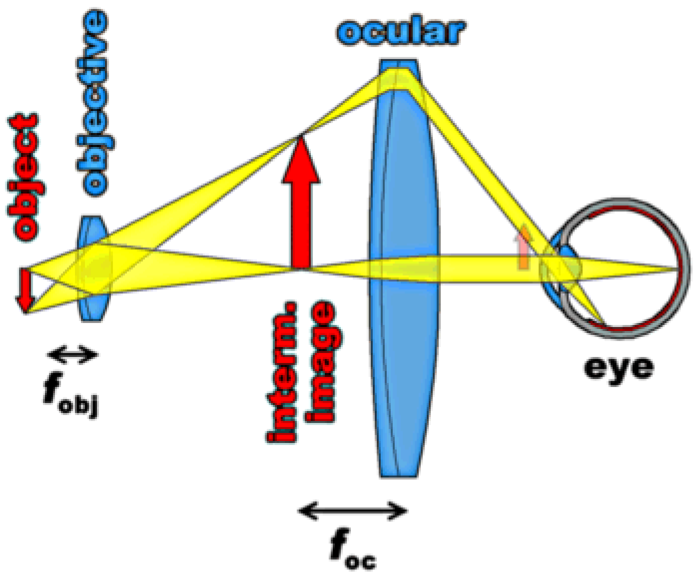


CMM - Operation

- Sensor
  - Mechanical
  - Magnetic
  - Capacitive
  - Optical (images, laser, interferometer)
- Actuator (Precision stages)
  - Ball screw
  - Linear motor
  - Friction drive
  - Piezoelectric
- Displacement Transducer
  - LVDT
  - Optical grating encoders
  - Displacement interferometers

Optical Microscope

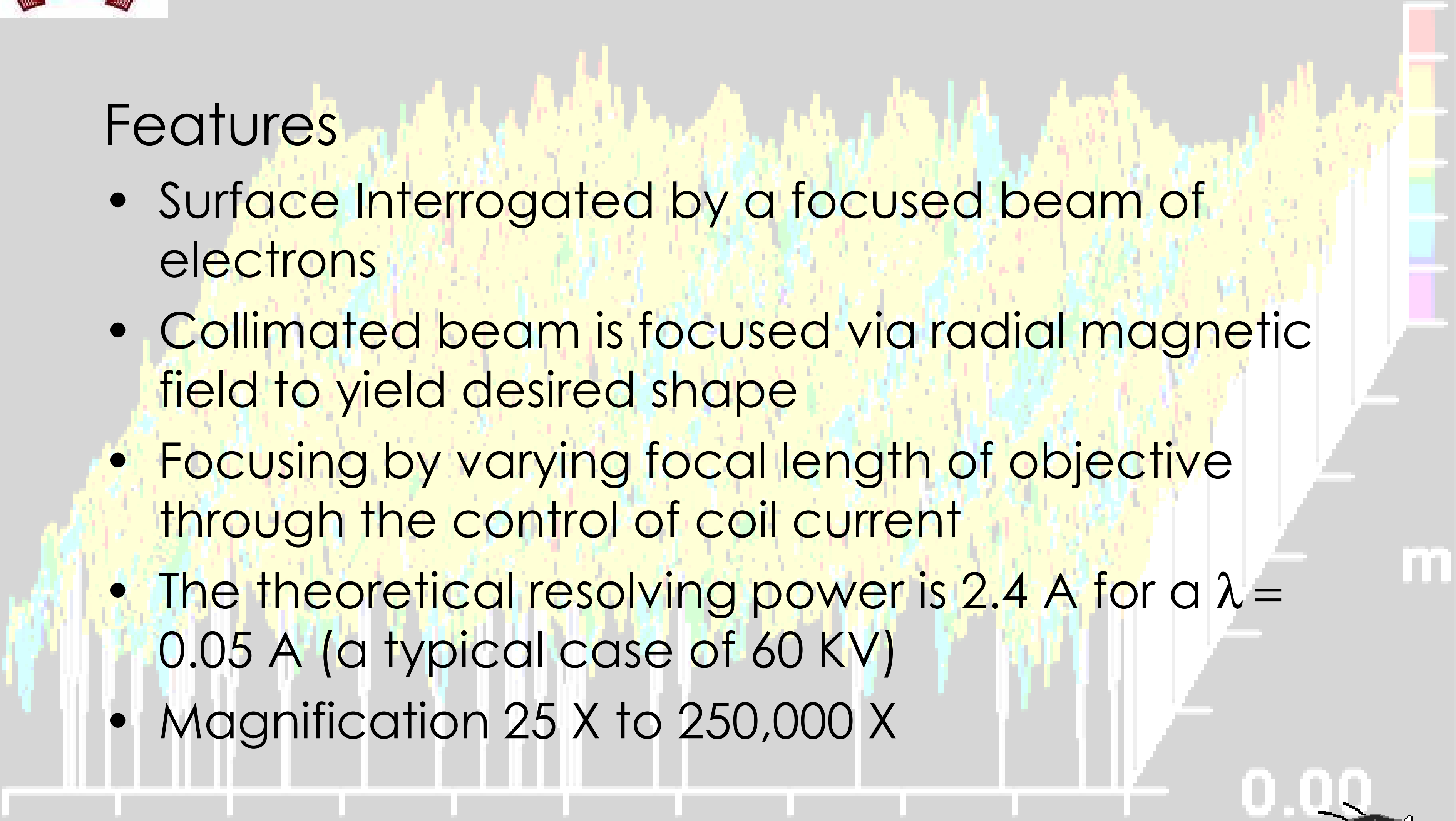
- Short focal length objective
- Longer focal length eye piece
- More than one lens for objective/eye piece
- 2000X magnification
- Confocal (slice)
- Stereo (more room)



http://www.monos.leidenuniv.nl/smo/index.html?basics/microscopy.htm

- Theoretical resolving power for unit NA (nsin(i) =1) is 0.27 µm

Scanning Electron Microscope

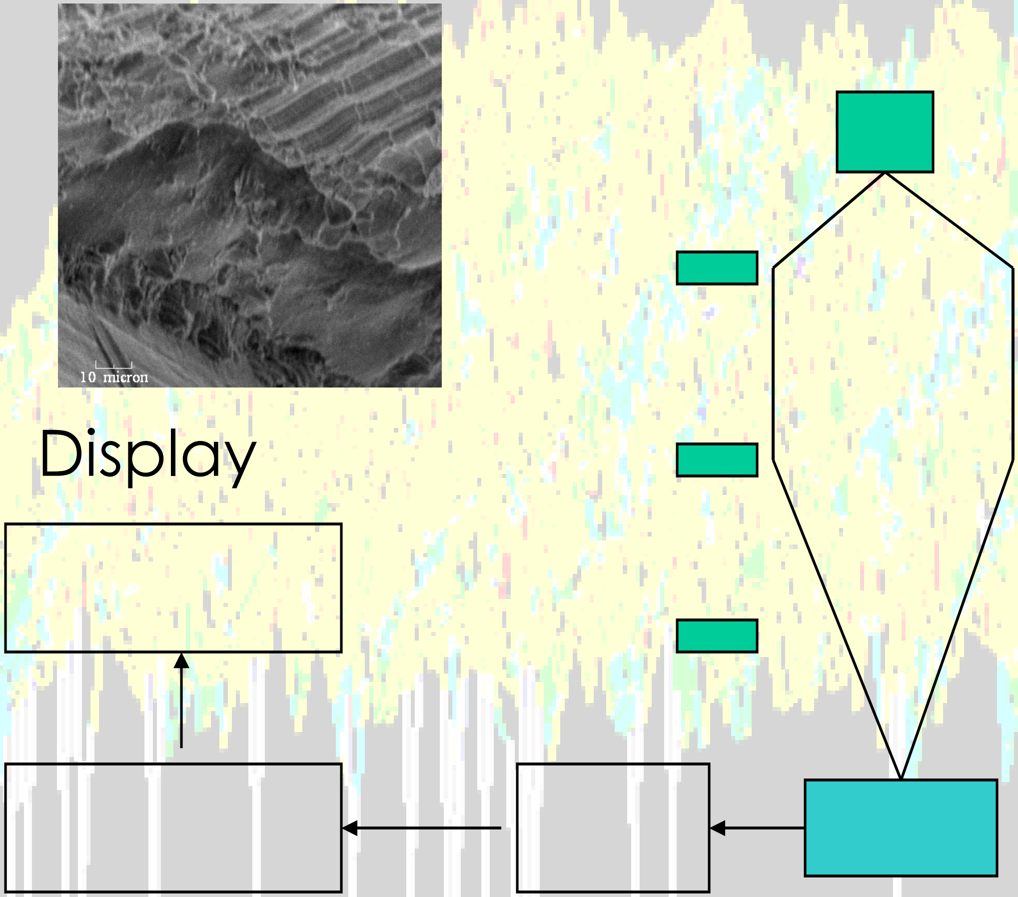


Features

- Surface Interrogated by a focused beam of electrons
- Collimated beam is focused via radial magnetic field to yield desired shape
- Focusing by varying focal length of objective through the control of coil current
- The theoretical resolving power is 2.4 A for a λ = 0.05 A (a typical case of 60 KV)
- Magnification 25 X to 250,000 X

SEM

- Operating Principle



Display

Electron gun

Collimating coil

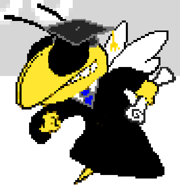
Focusing coil

Deflecting coil

Sample

Detector

Signal Processing



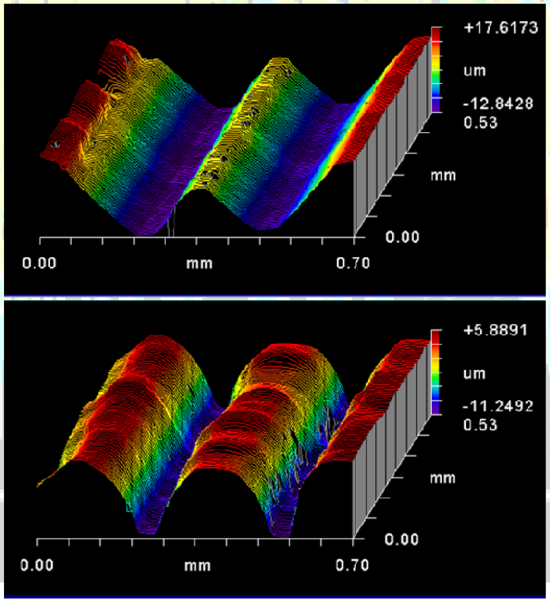
White Light Interferometry

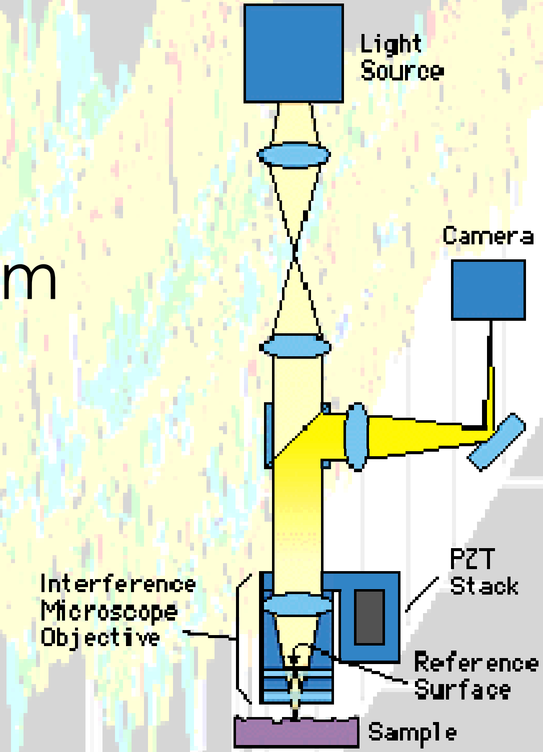
Features

- Surface topography and surface feature measurement
- Z resolution is 0.1 nm
- High resolution vertical scan of 150 µm
- Extended scan of 20 mm
- Lateral resolution is 0.36 – 9 µm (objective dependent)
- Field of view 0.03 mm to 14 mm
- Stitching available

WLI

- Uses broadband light source
- Identifies highest intensity interference fringe and maps its location throughout scan
- All points with matching maximum intensity fringe are of the same height

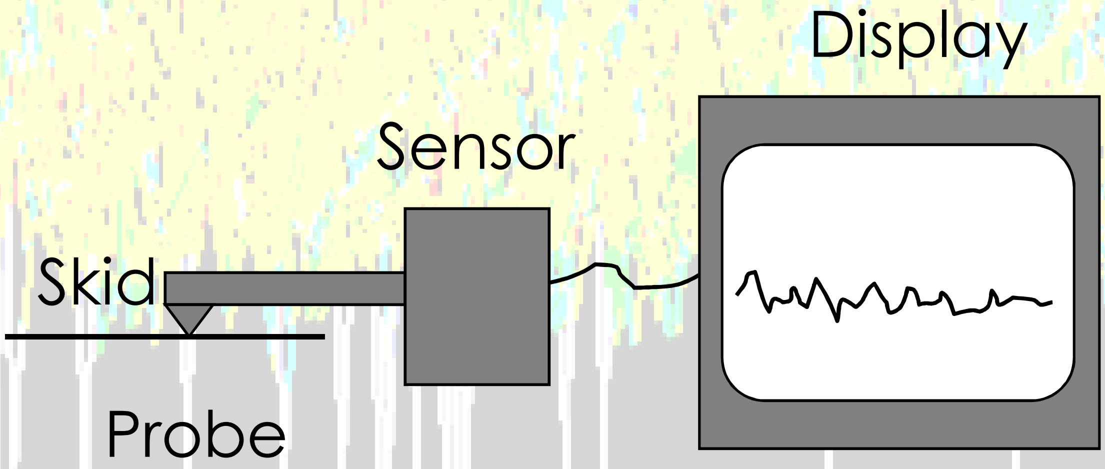




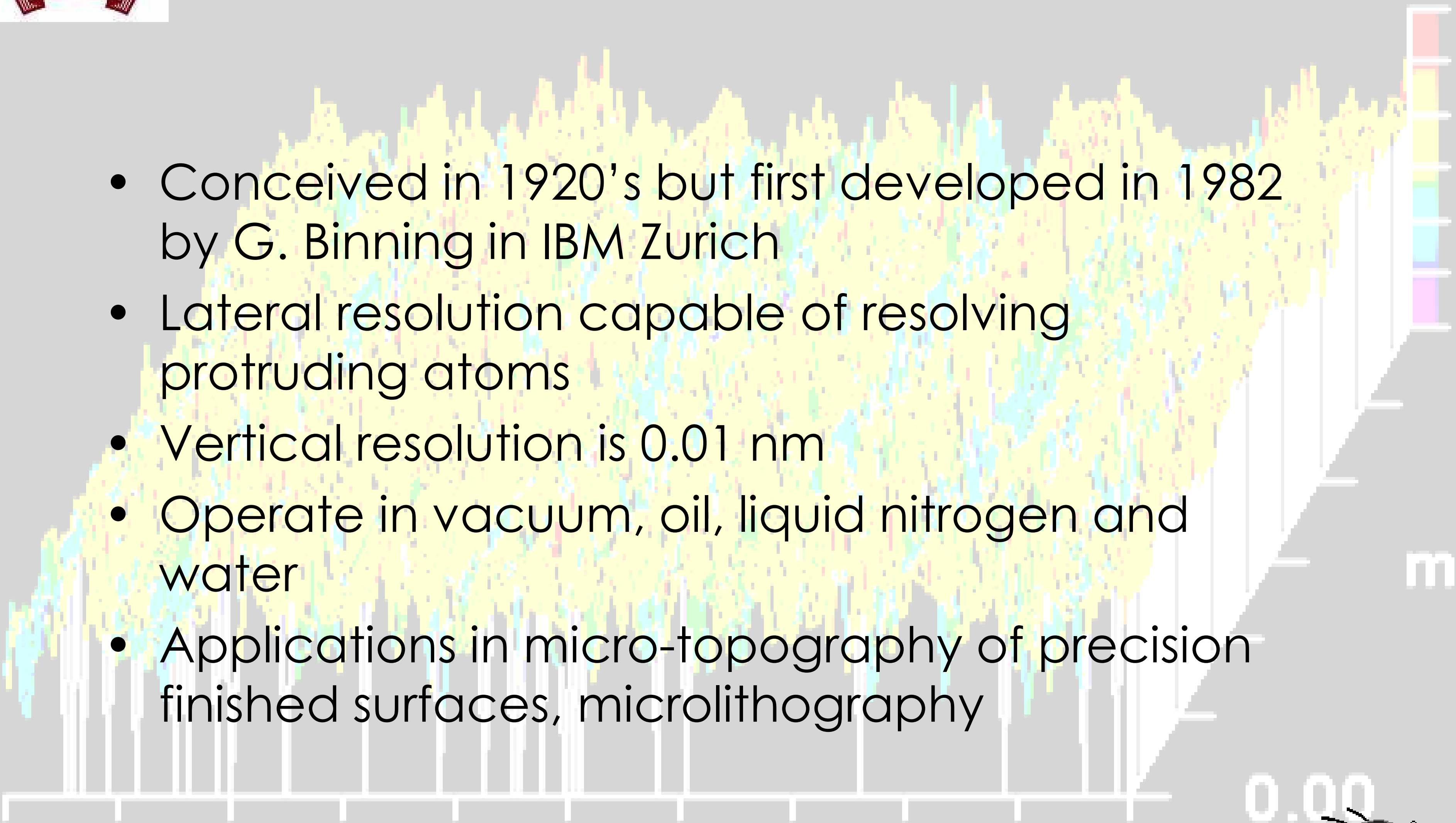
Surface Profilometer

Features

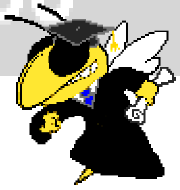
- Resolution of the order of 20 nm
- Scan length 1 mm – 25 mm
- Measuring Speed 1mm/s



Scanning Tunneling Microscope



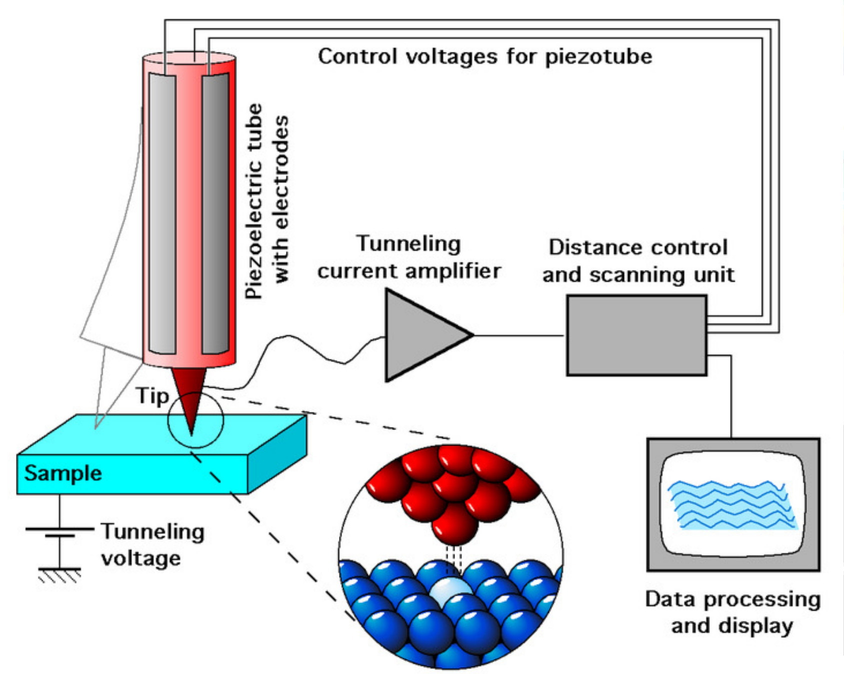
- Conceived in 1920’s but first developed in 1982 by G. Binning in IBM Zurich
- Lateral resolution capable of resolving protruding atoms
- Vertical resolution is 0.01 nm
- Operate in vacuum, oil, liquid nitrogen and water
- Applications in micro-topography of precision finished surfaces, microlithography

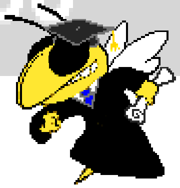


STM

Operating Principle

- Quantum tunneling effect
- Electrons instead of bouncing pass through and current can be sensed
- Tunneling current is a function of local density of states

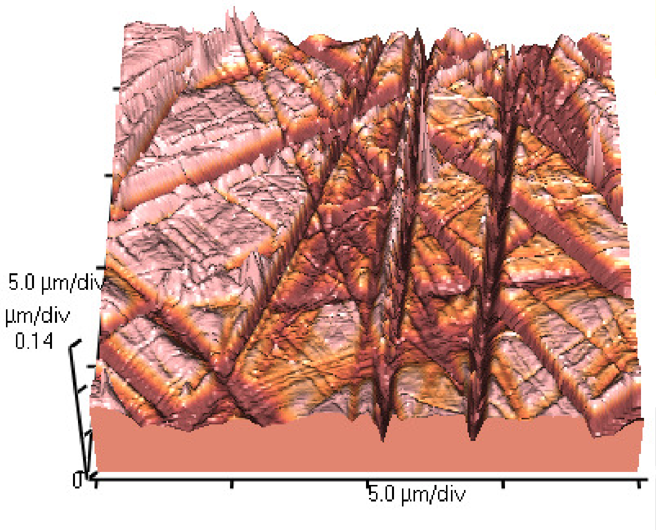




Atomic Force Microscopy

Features

- AFM is a improved form of STM
- Resolutions are a fraction of a nanometer
- Imaging, measuring and manipulating material at the nanoscale

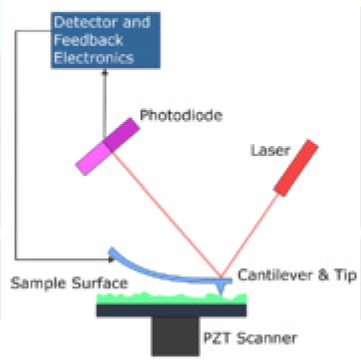


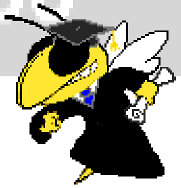
http://nanolab.me.cmu.edu/

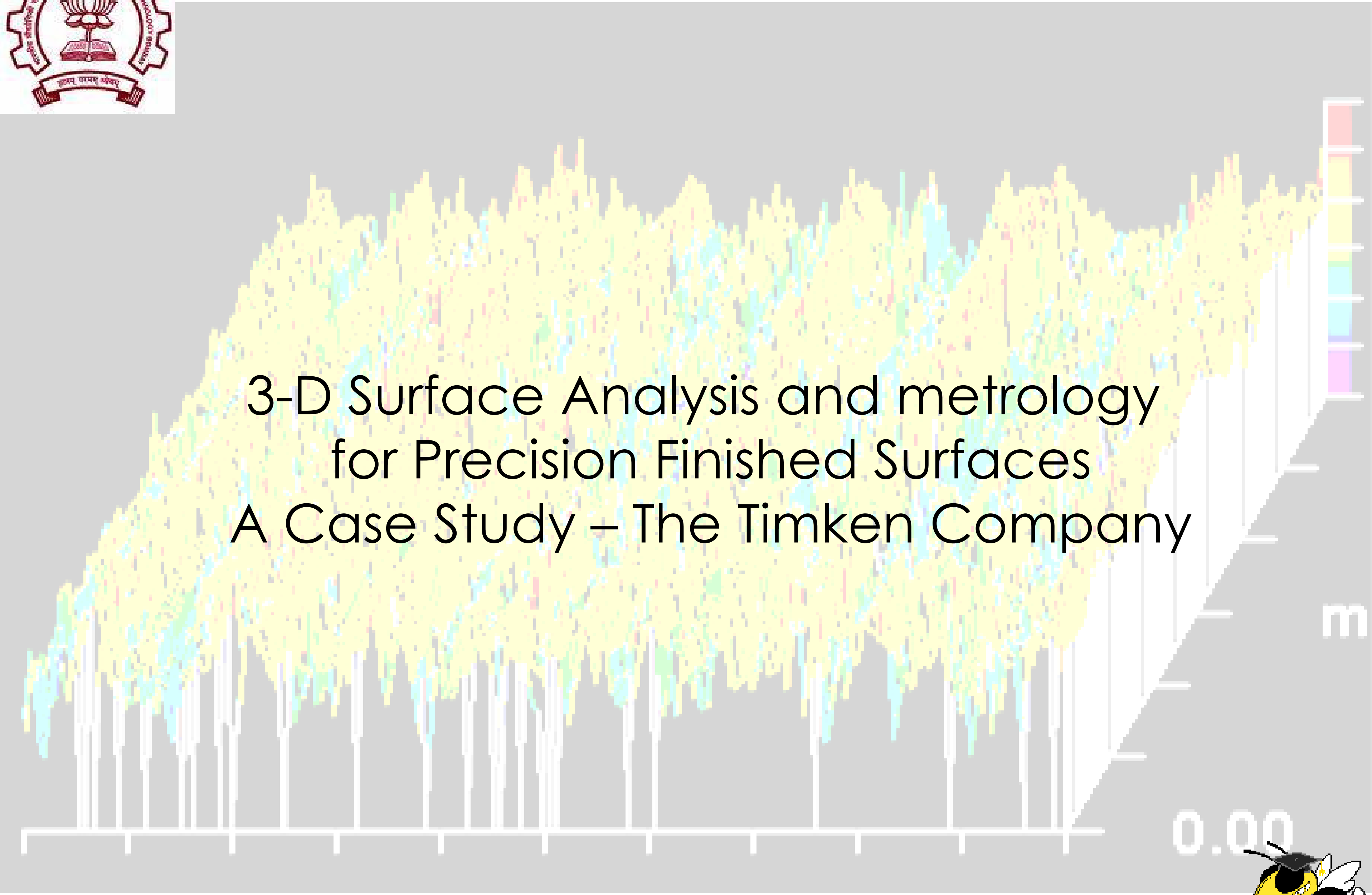
AFM

Operation

- A microscale cantilever with a sharp tip (probe) at its end is used
- Tip radius of curvature on the order of nanometers.
- Proximity of a sample surface to the tip creates forces (mechanical contact force, Van der Waals forces, capillary forces, chemical bonding, electrostatic forces, magnetic forces)
- Forces results in cantilever deflection which is sensed





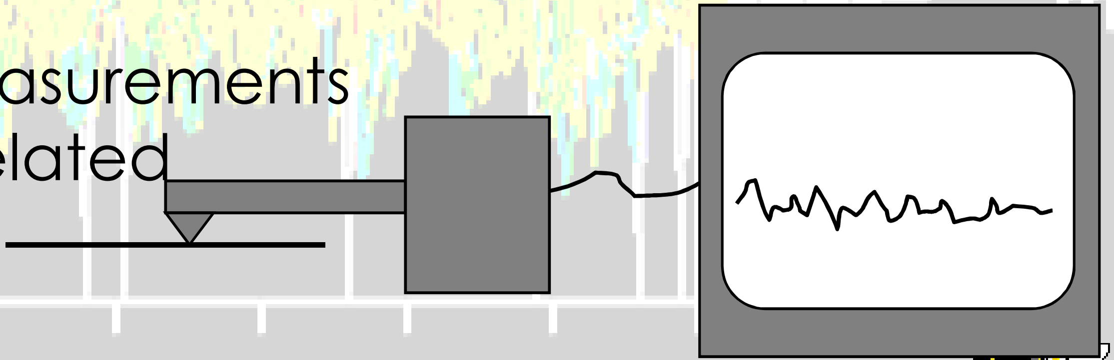


3-D Surface Analysis and metrology for Precision Finished Surfaces
A Case Study – The Timken Company

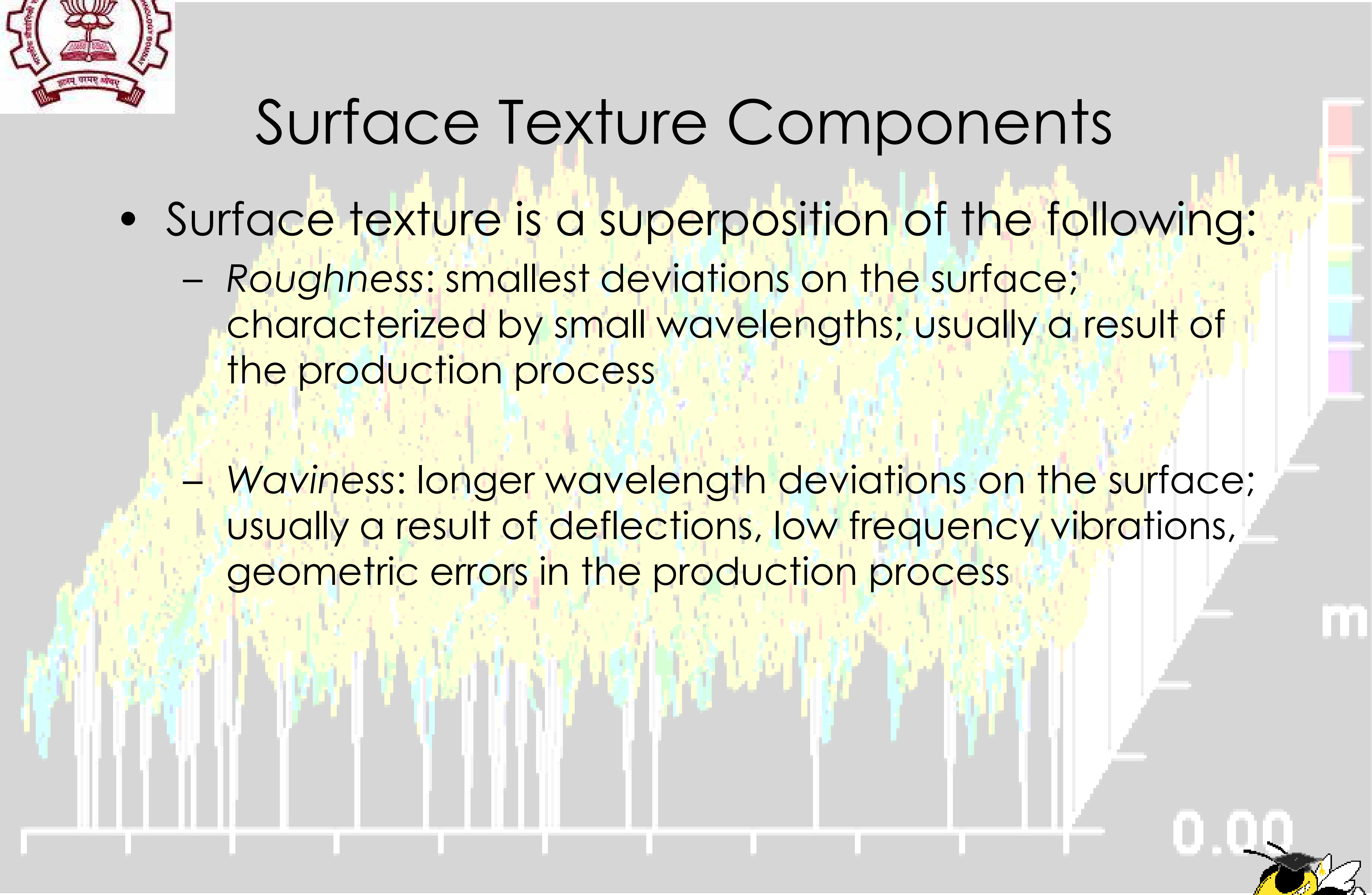
Introduction

Metrology

- Experience shows advantages of certain finishes in certain roles
- 2-D roughness measurements (stylus) often correlated with functionality

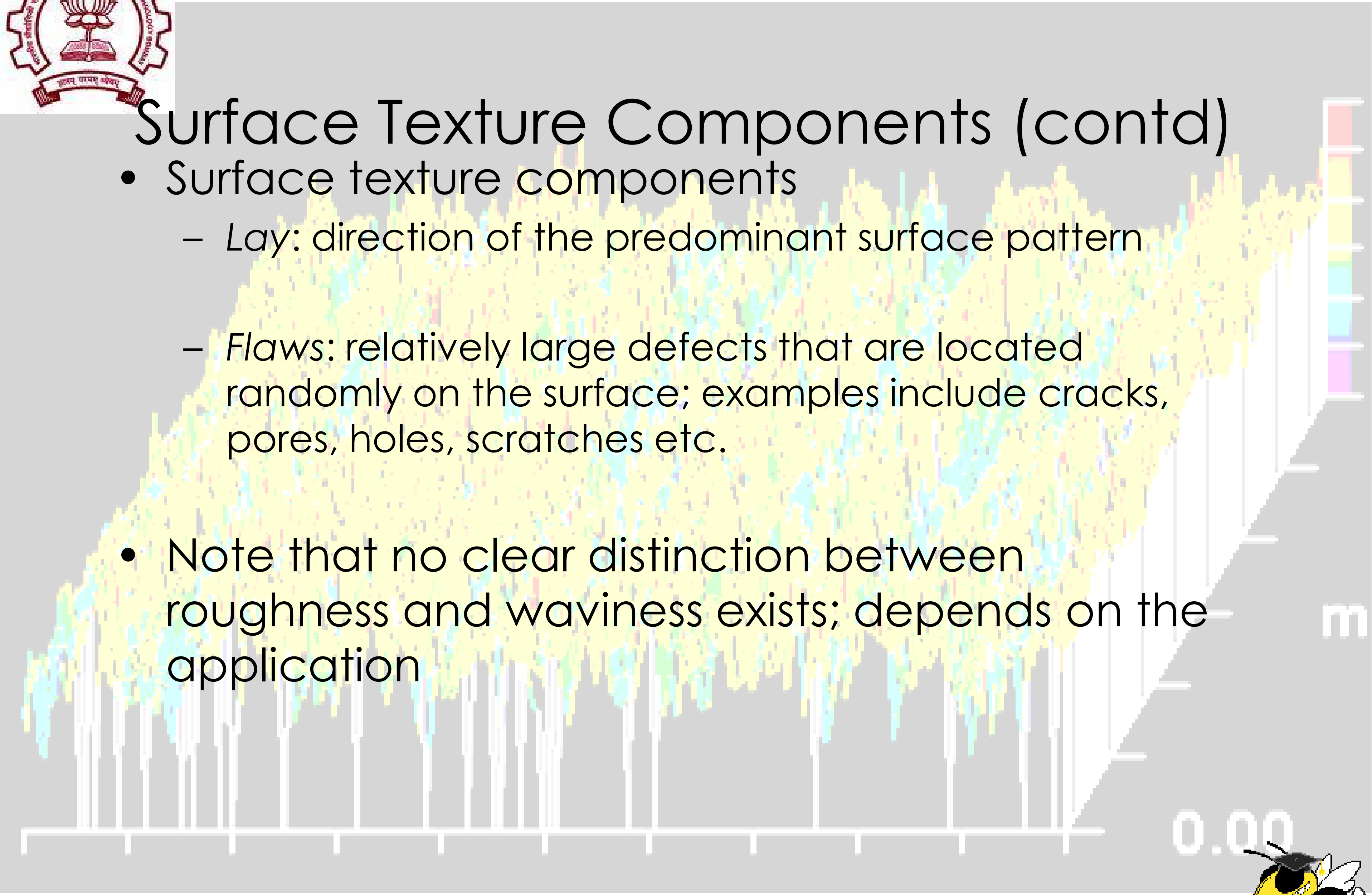


Surface Texture Components



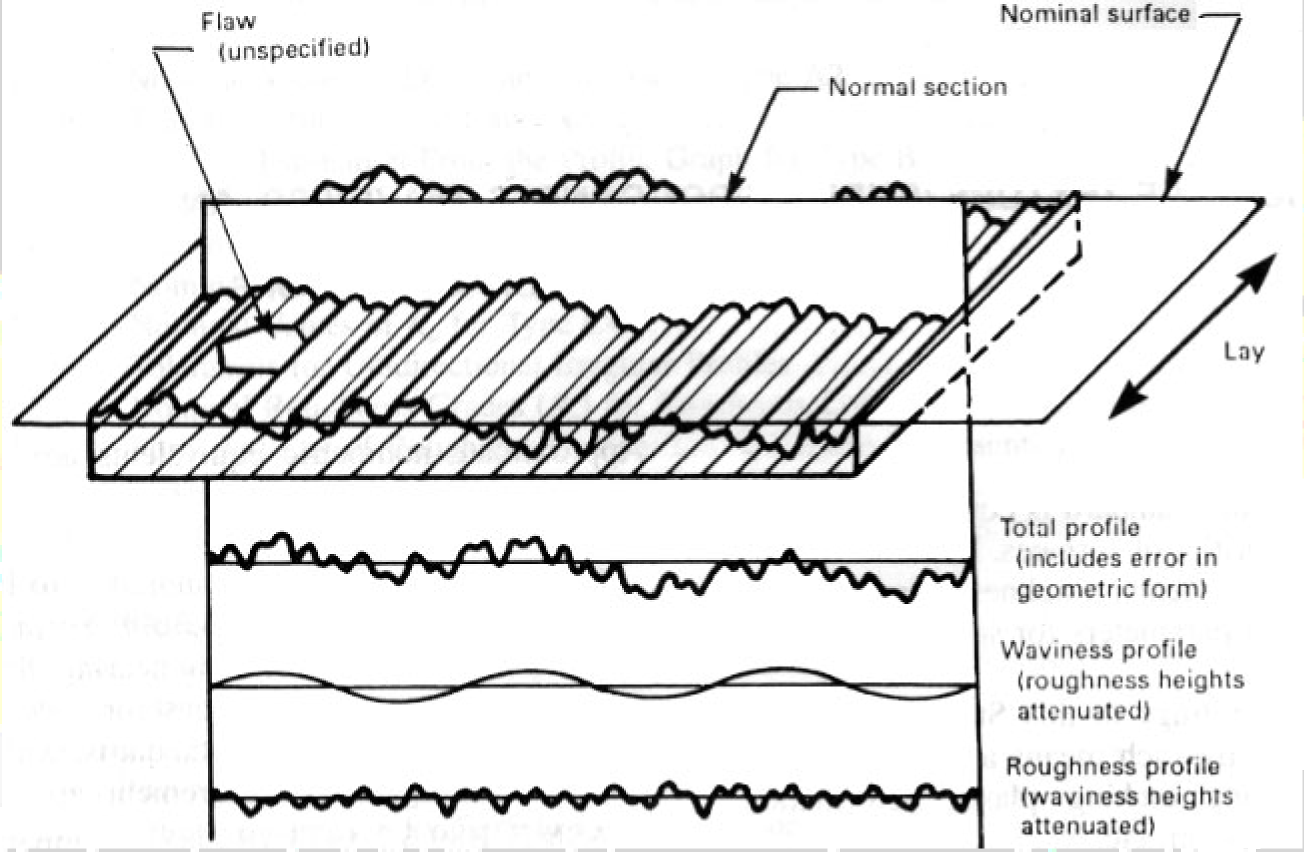
- Surface texture is a superposition of the following:
  - *Roughness*: smallest deviations on the surface; characterized by small wavelengths; usually a result of the production process
  - *Waviness*: longer wavelength deviations on the surface; usually a result of deflections, low frequency vibrations, geometric errors in the production process

Surface Texture Components (contd)



- Surface texture components
  - *Lay*: direction of the predominant surface pattern
  - *Flaws*: relatively large defects that are located randomly on the surface; examples include cracks, pores, holes, scratches etc.
- Note that no clear distinction between roughness and waviness exists; depends on the application

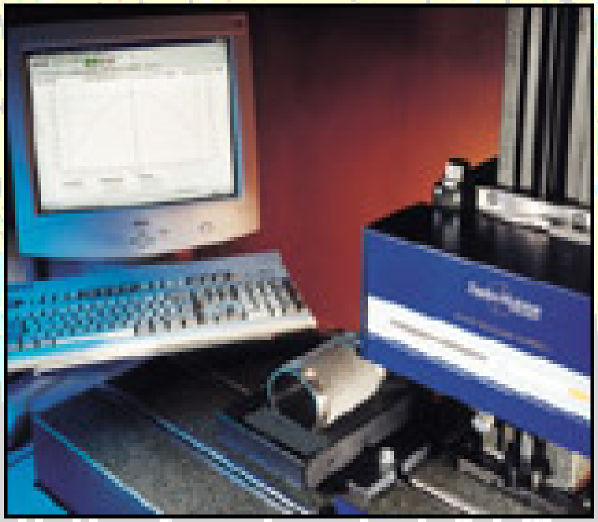
Surface Texture Components (contd)



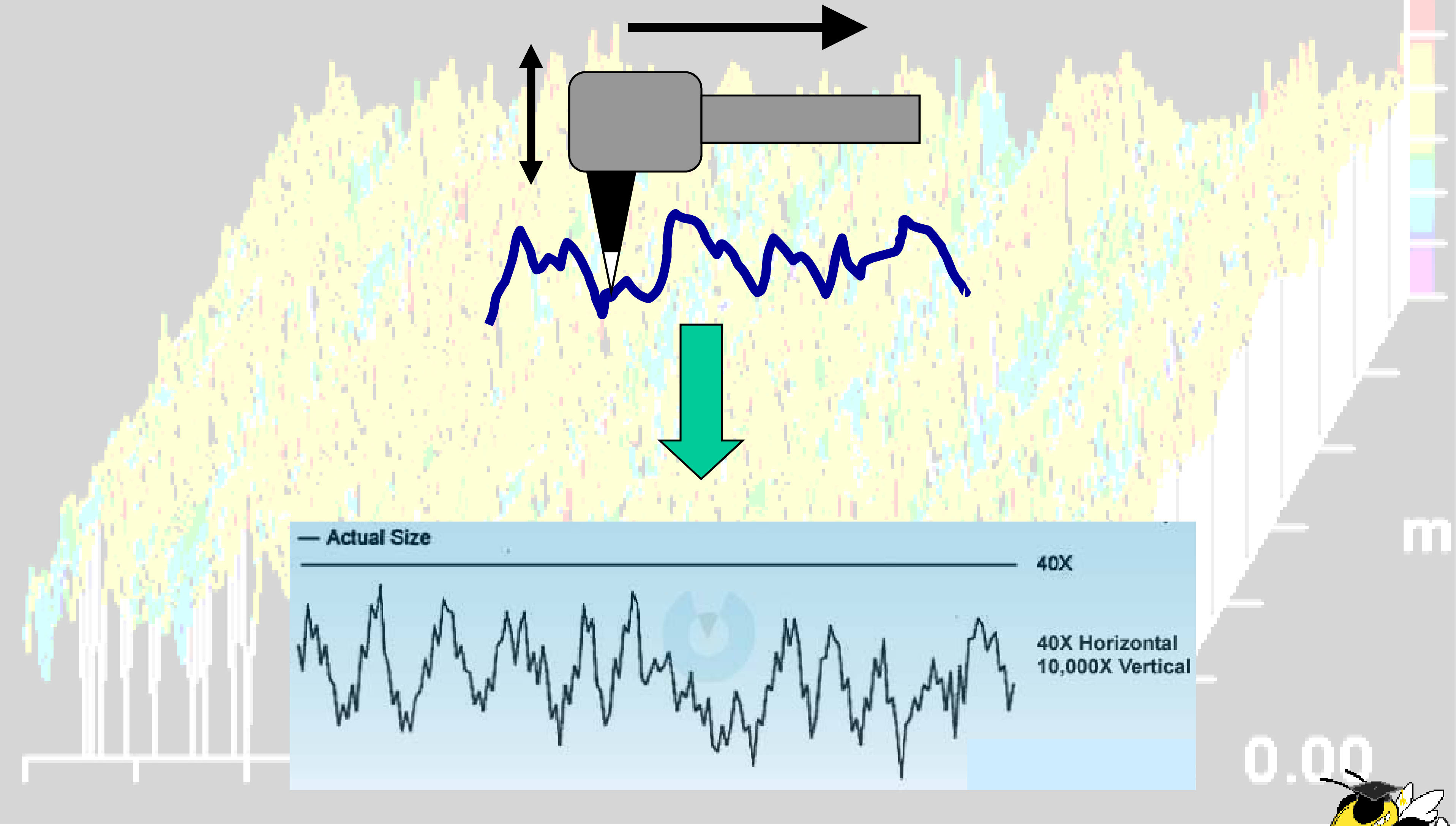
- Taken from ANSI B46.1 Standards

Surface Texture Measurement

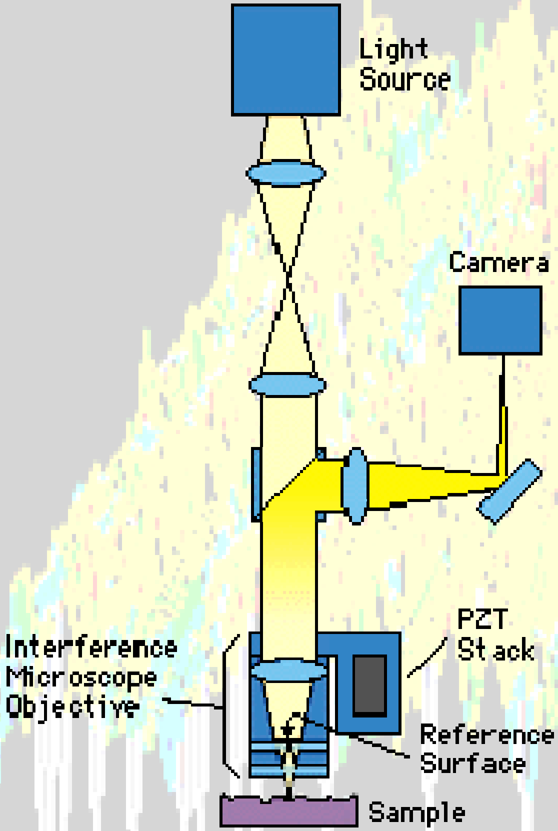
- Profilometer: surface is traced by a diamond stylus and its vertical motion amplified
- Interferometry: non-contact optical method to obtain 3-D surface texture

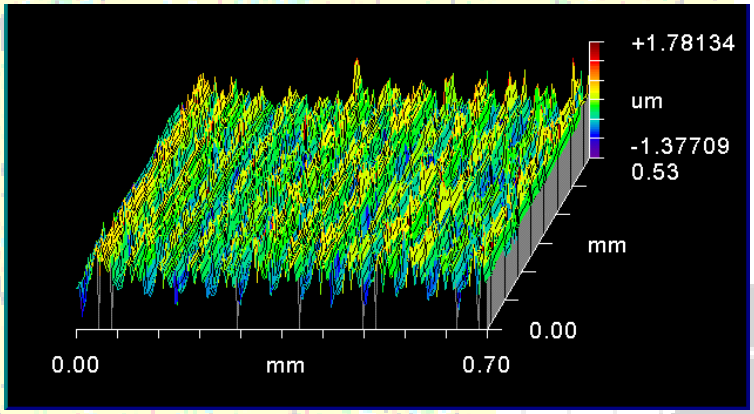


Surface Profilometer



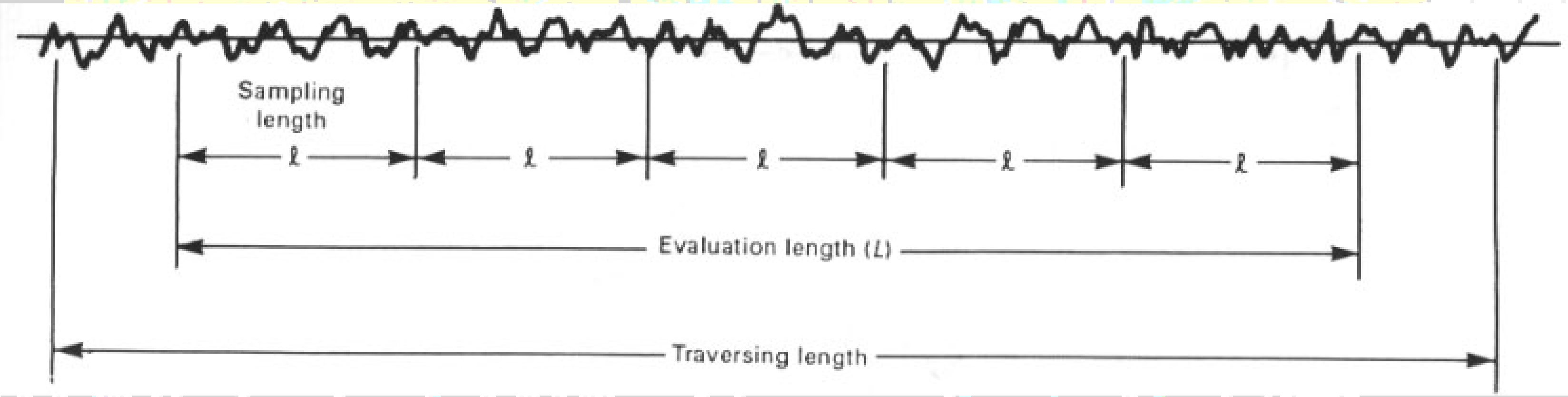
Non-Contact Surface Measurement: Interferometry





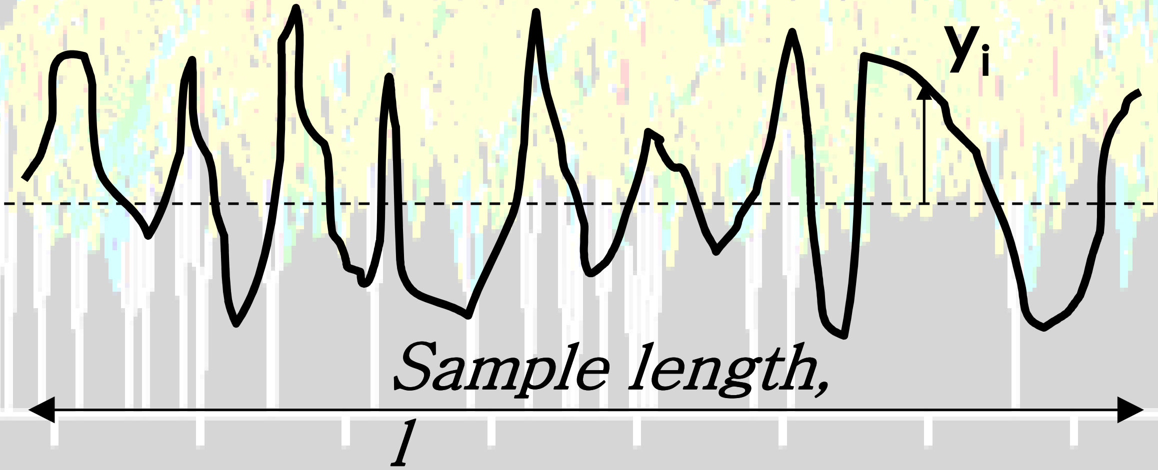
Surface Texture Characterization

- Typical 2-d surface profile and its breakdown for purposes of characterization



Surface Texture Characterization

- Roughness Parameters:
  - *Amplitude parameters*: arithmetic average roughness height (R_a), root mean square roughness height (R_q), peak-to-valley roughness height (R_t), etc.



$$R_a = \frac{1}{l}\int_0^l |y|\,dx$$

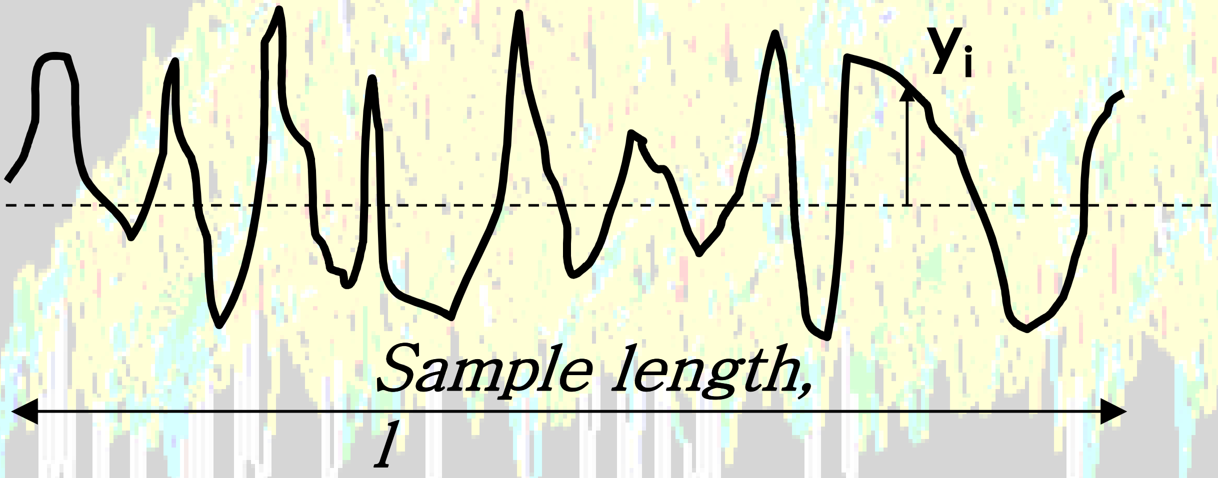
$$R_a \approx \frac{\sum_1^N |y_i|}{N}$$

Surface Texture Characterization

- Roughness Amplitude Parameter: root mean square roughness height, R_q

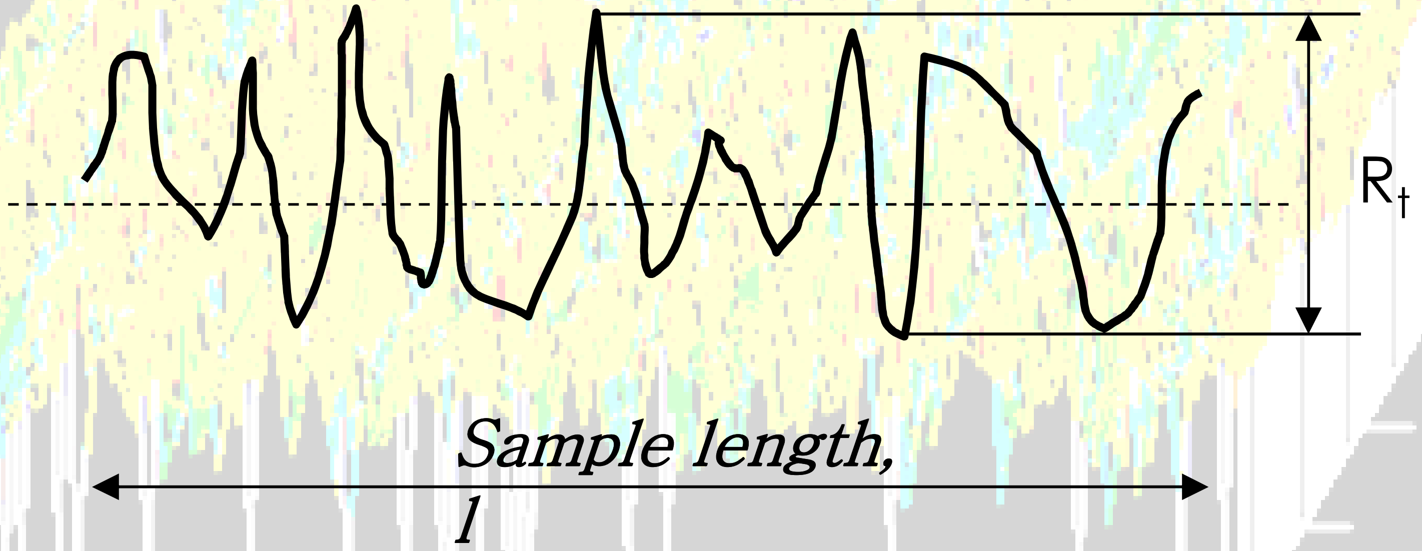
$$R_q = \left[\frac{1}{l} \int_0^l y^2 dx \right]^{0.5}$$

$$R_q \approx \left[\frac{\sum_1^N y_i^2}{N} \right]^{1/2}$$



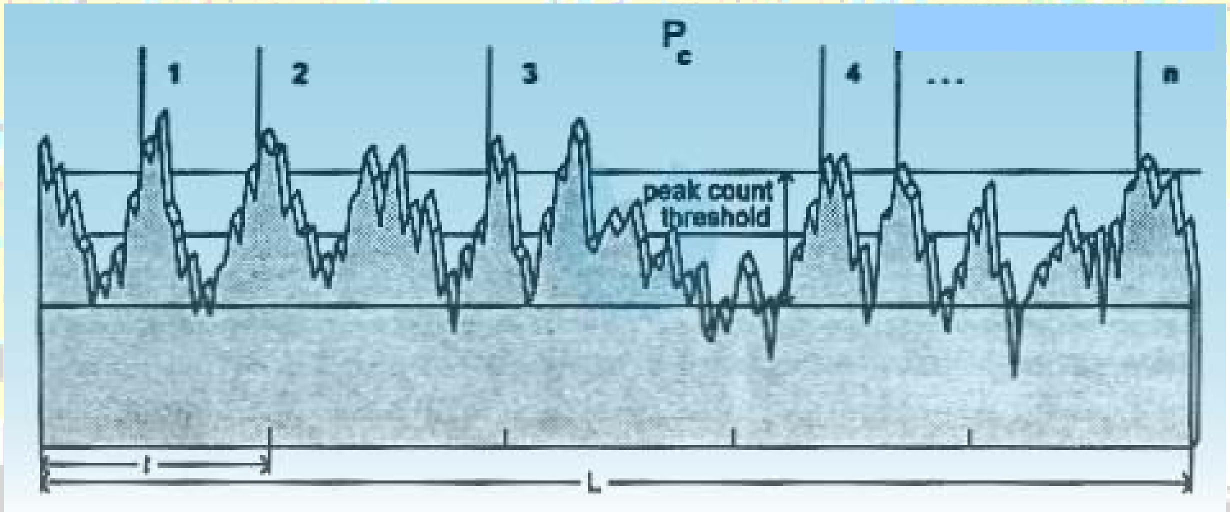
Surface Texture Characterization

- Roughness Amplitude Parameter: maximum height of profile, R_t



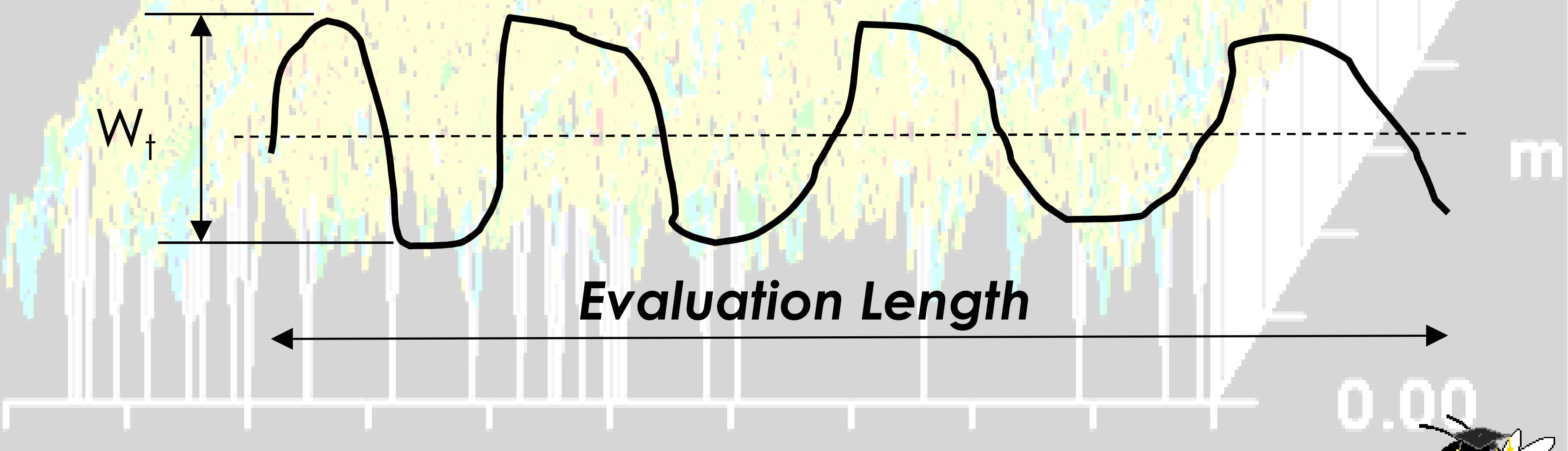
Surface Texture Characterization

- Roughness Spacing Parameter: peak count, P_c = number of peaks in the evaluation length/evaluation length

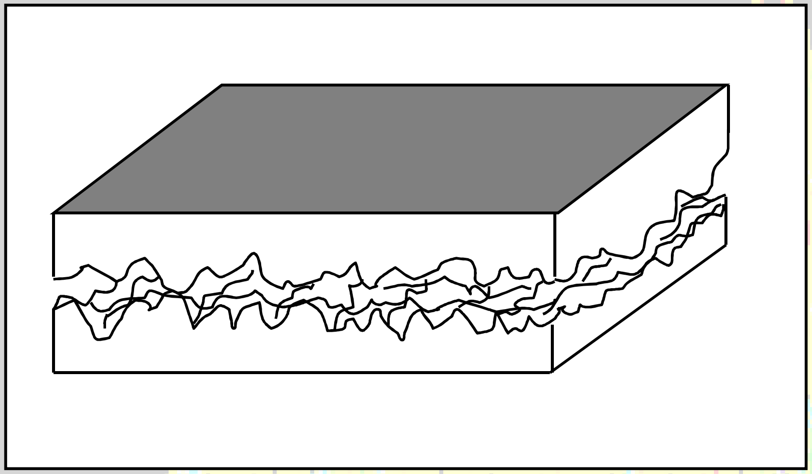


Surface Texture Characterization

- Waviness Height Parameter, W_t : peak-to-valley height of the modified profile from which the roughness and part form have been removed by filtering.



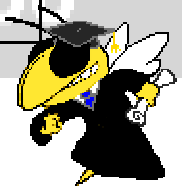
Introduction



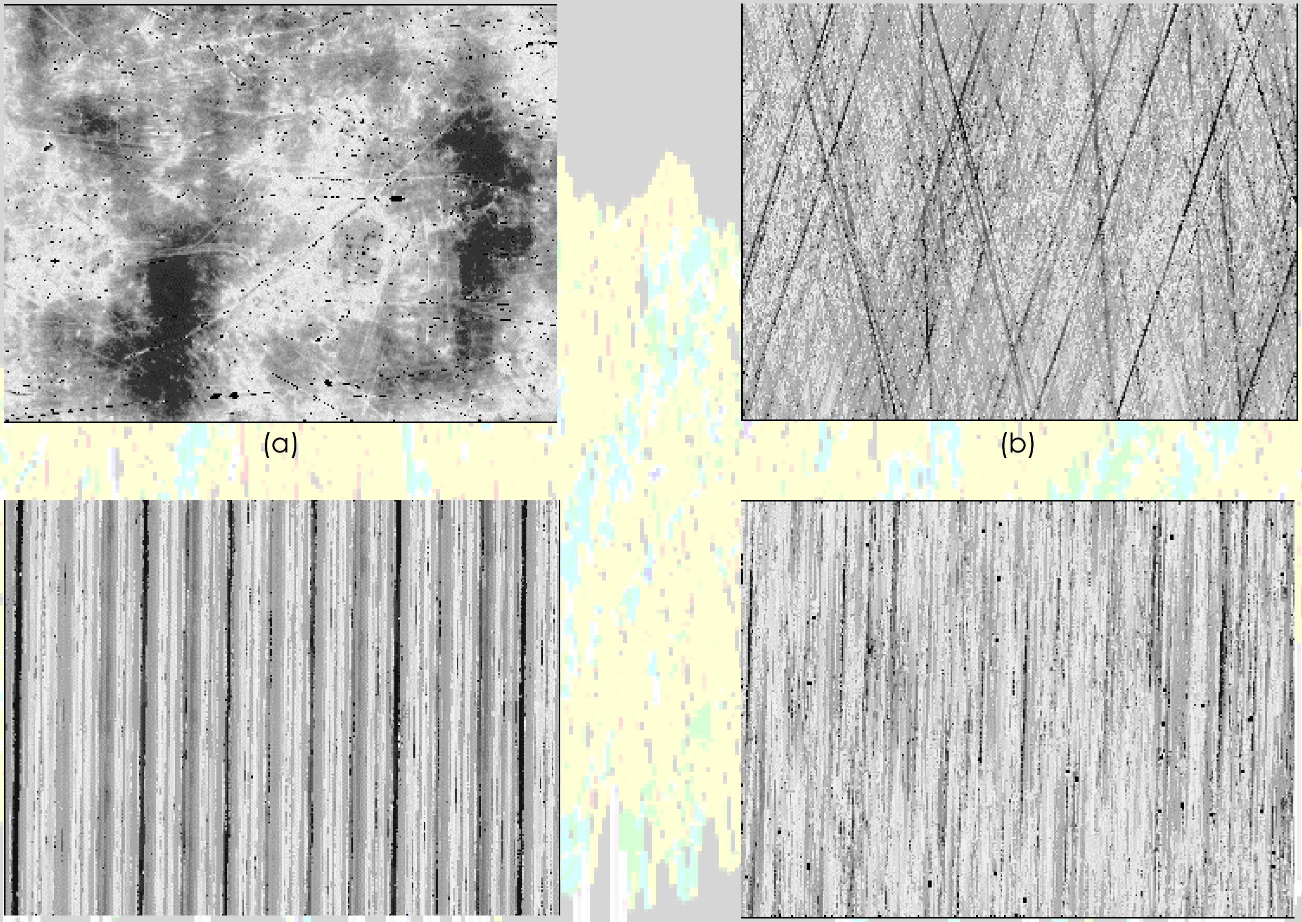
- Surfaces contact in three dimensions
- 3-D texture parameters affect functionality

A list of 3-D Parameters
By Dong et al.

Amplitude Parameters	**Spatial Parameters**	**Hybrid Parameters**	**Functional Parameters**
RMS Deviation S_q	Density of Summits S_{ds}	RMS Slope $S\Delta q$	Surface Bearing Index S_{bi}
Ten point Height S_z	Texture Aspect Ratio, S_{tr}	Mean Summit Curvature S_{sc}	Core Fluid Retention Index S_{ci}
Skewness S_{sk}	Texture Direction S_{td}	Developed Area Ratio S_{dr}	Valley Fluid Retention Index S_{vi}
Kurtosis S_{ku}	Fastest Decay Autocorrelation Length S_{al}		

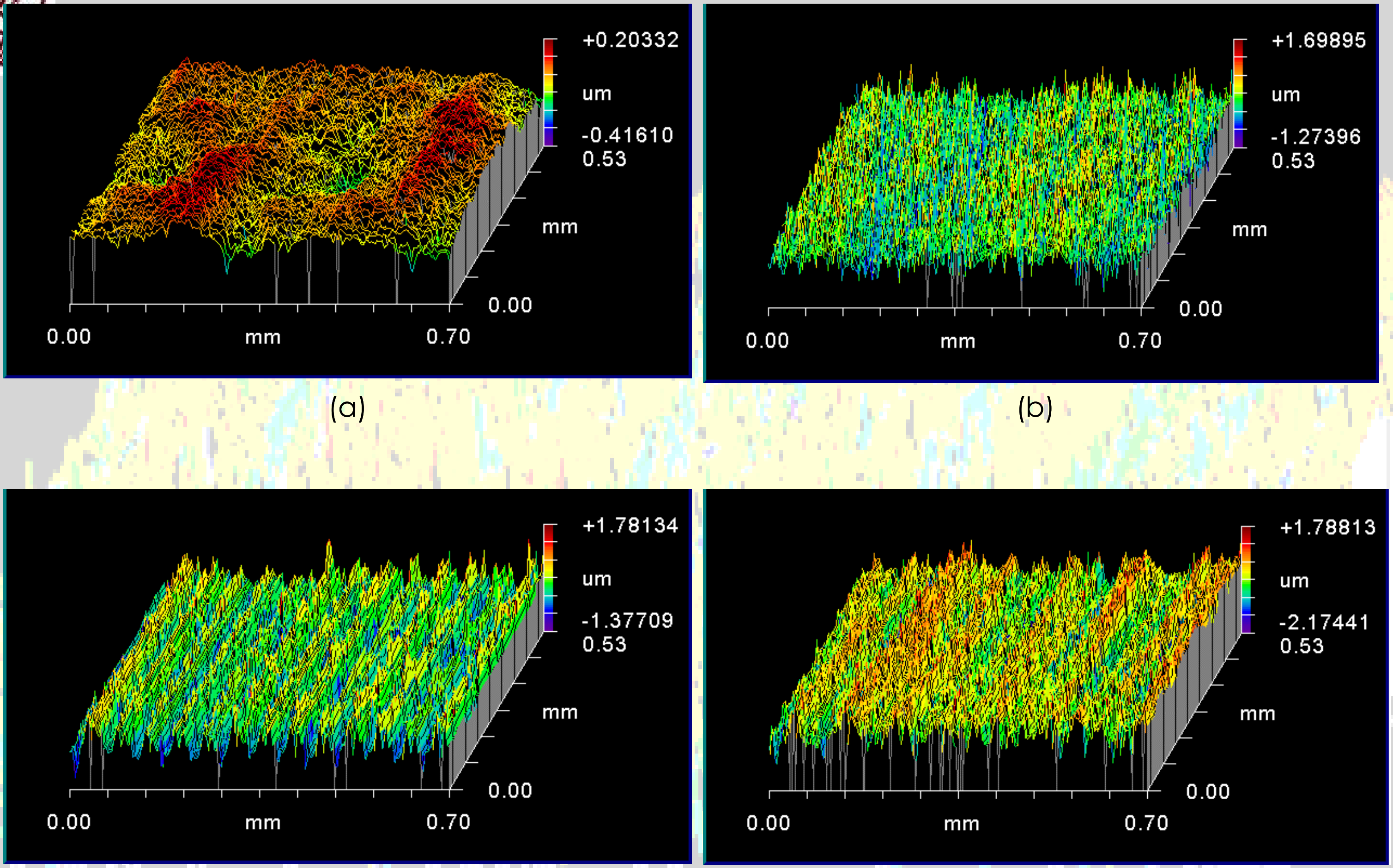


3-D Surface Characterization


(a)
(b)
(c)
(d)

Gray Scale Images of (a) IF, (b) HN, (c) HT and (d) GD

3-D Surface Characterization

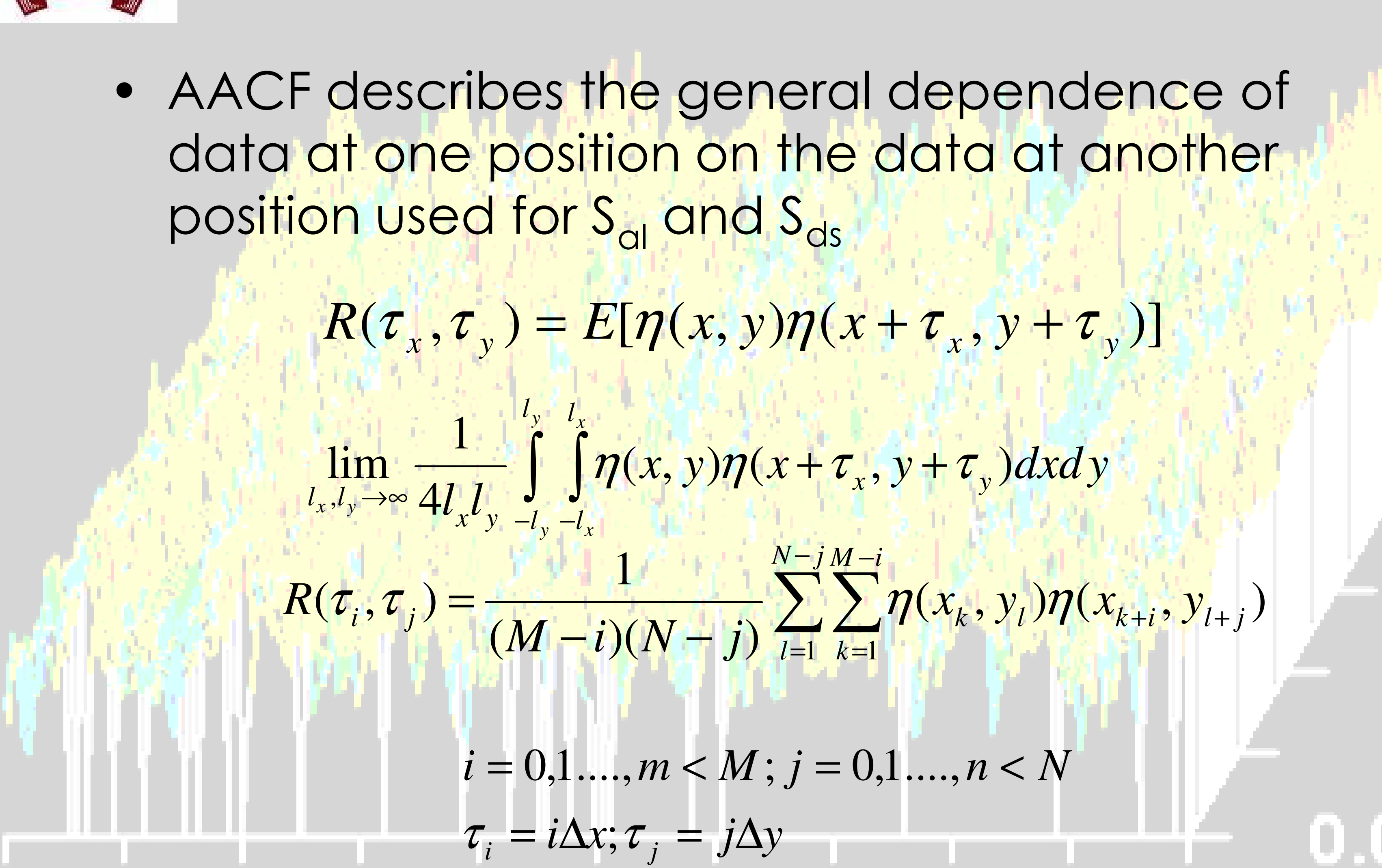


(a) (b)

(c) (d)

Topographic Maps of (a) IF, (b) HN, (c) HT, and (d) GD

Areal Autocorrelation Function (AACF)



- AACF describes the general dependence of data at one position on the data at another position used for S_{al} and S_{ds}

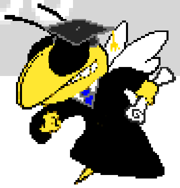
$$R(\tau_x, \tau_y) = E[\eta(x,y)\eta(x+\tau_x, y+\tau_y)]$$

$$\lim_{l_x, l_y \to \infty} \frac{1}{4 l_x l_y} \int_{-l_y}^{l_y} \int_{-l_x}^{l_x} \eta(x,y)\eta(x+\tau_x, y+\tau_y)\,dx\,dy$$

$$R(\tau_i, \tau_j) = \frac{1}{(M-i)(N-j)} \sum_{l=1}^{N-j} \sum_{k=1}^{M-i} \eta(x_k, y_l)\eta(x_{k+i}, y_{l+j})$$

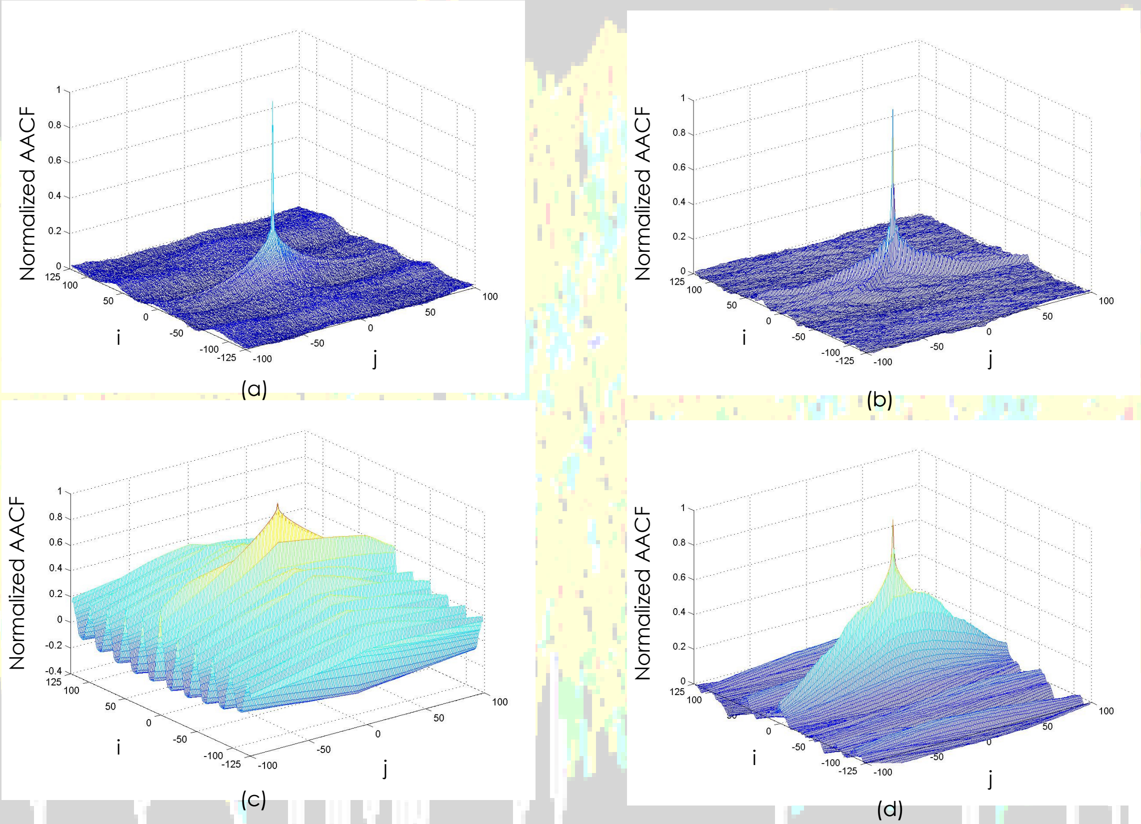
$$i = 0,1\ldots., m < M;\ j = 0,1\ldots., n < N$$

$$\tau_i = i\Delta x; \tau_j = j\Delta y$$



3-D Surface Characterization (6)

To calculate the spatial parameters the AACF, APSD, and Angular spectra for each surface must be analyzed



(a) (b) (c) (d)

AACF plots for (a) IF, (b) HN, (c) HT, and (d) GD

Areal Power Spectral Density (APSD)

- Spectral analysis condenses the time/space domain information into the frequency domain it is used in S_{td}

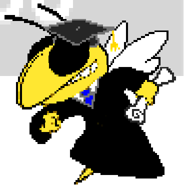
$$F(\varpi_x,\varpi_y)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\eta(x,y)e^{-j2\pi(\varpi_x x+\varpi_y y)}dxdy$$

$$F(\varpi_p,\varpi_q)=\sum_{l=1}^{N-1}\sum_{k=1}^{M-1}\eta(x_{k+1},y_{l+1})e^{-j2\pi(\frac{p}{M}k+\frac{q}{N}l)}$$

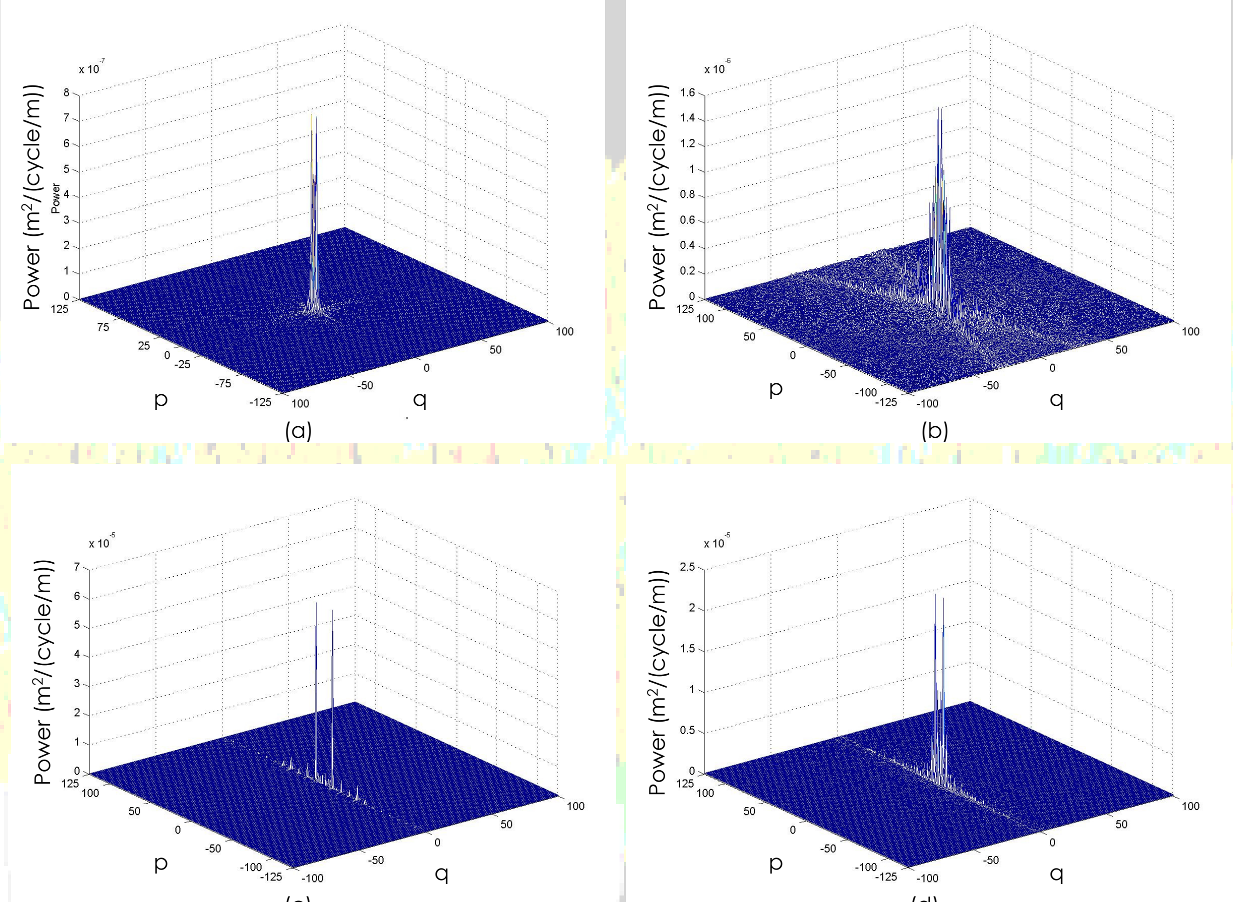
Discrete Fourier Transform

$$G(\varpi_p,\varpi_q)=F(\varpi_p,\varpi_q)F^*(\varpi_p,\varpi_q)$$

F* is complex conjugate

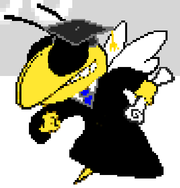


3-D Surface Characterization (7)



(a) (b) (c) (d)

APSD plots for (a) IF, (b) HN, (c) HT, and (d) GD

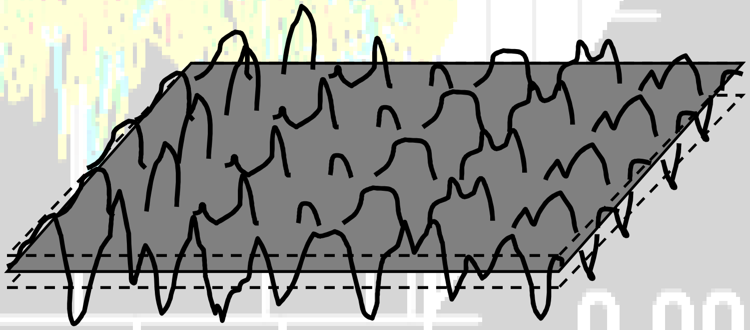


Pertinent 3-D Parameters (1)

- Amplitude Parameters
  - ***Root mean square deviation of surface topography (S_q)*** gives a conservative estimate of average surface asperity height. This is the 3-D factor related to 2-D roughness.

$$S_q = \sqrt{\frac{1}{MN}\sum_{j=1}^{N}\sum_{i=1}^{M}\eta^2(x_i, y_j)}$$

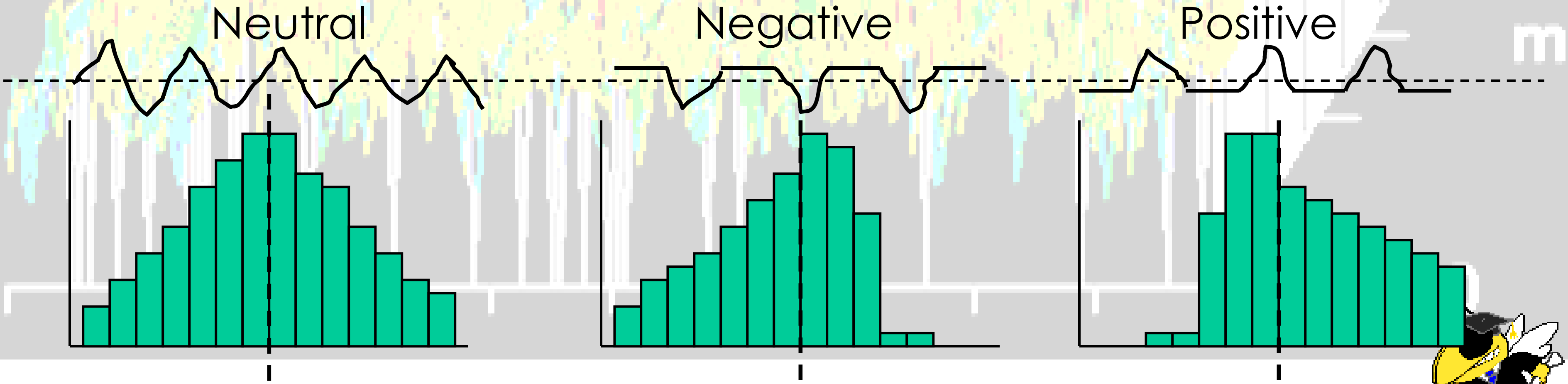

2-D RMS roughness


3-D RMS roughness

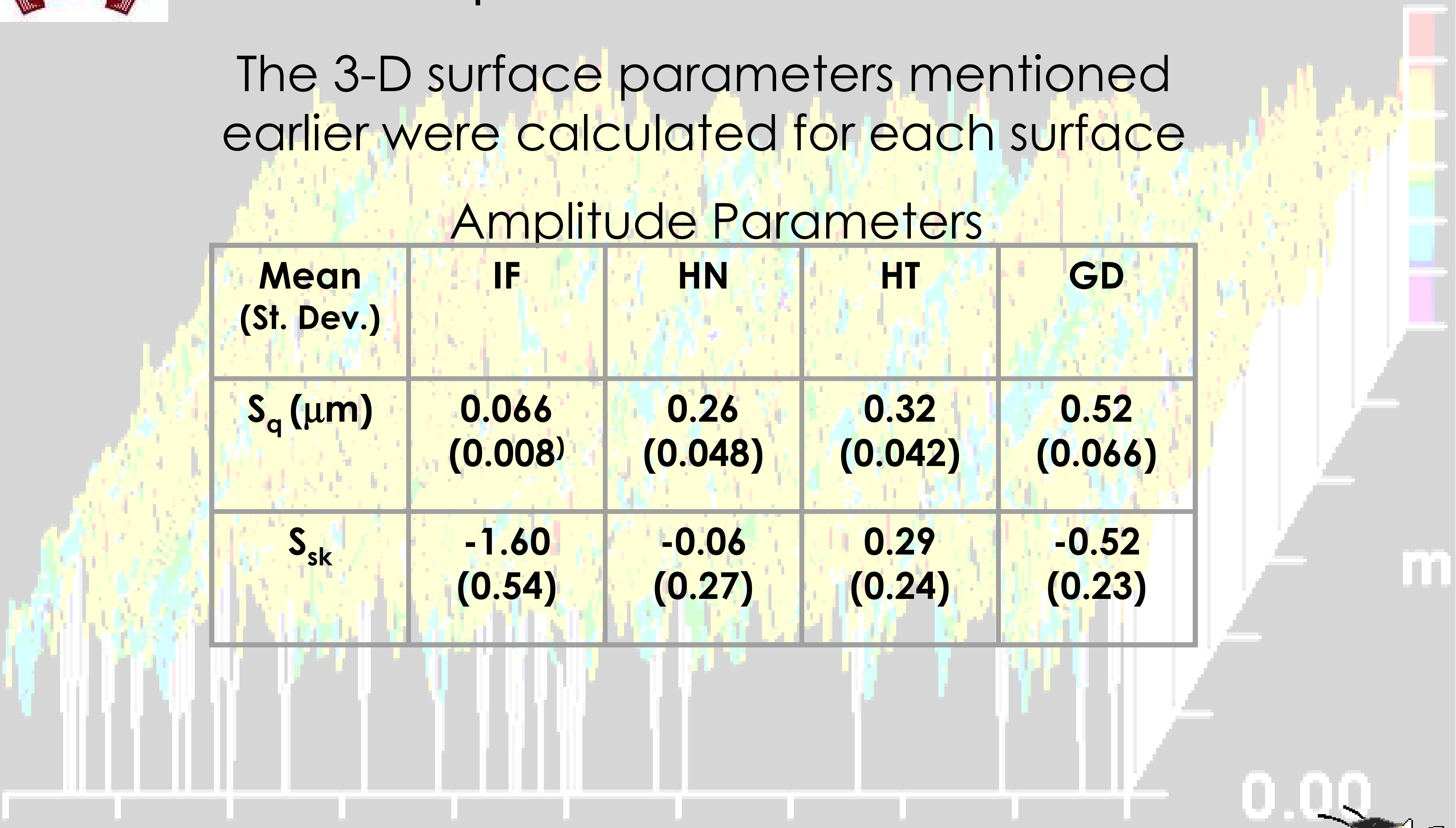
Pertinent 3-D Parameters (2)

- Amplitude Parameters
  - ***Skewness of Topography Height Distribution (S_{sk})*** reveals the peak or valley dominance of a surface's texture. Positive values represent peak dominance while negative values identify valley dominance. Most abraded material removal processes will leave a valley dominant surface.

$$S_{sk} = \frac{1}{MNS_q^3}\sum_{j=1}^{N}\sum_{i=1}^{M}\eta^3(x_i, y_j)$$



Amplitude Parameters

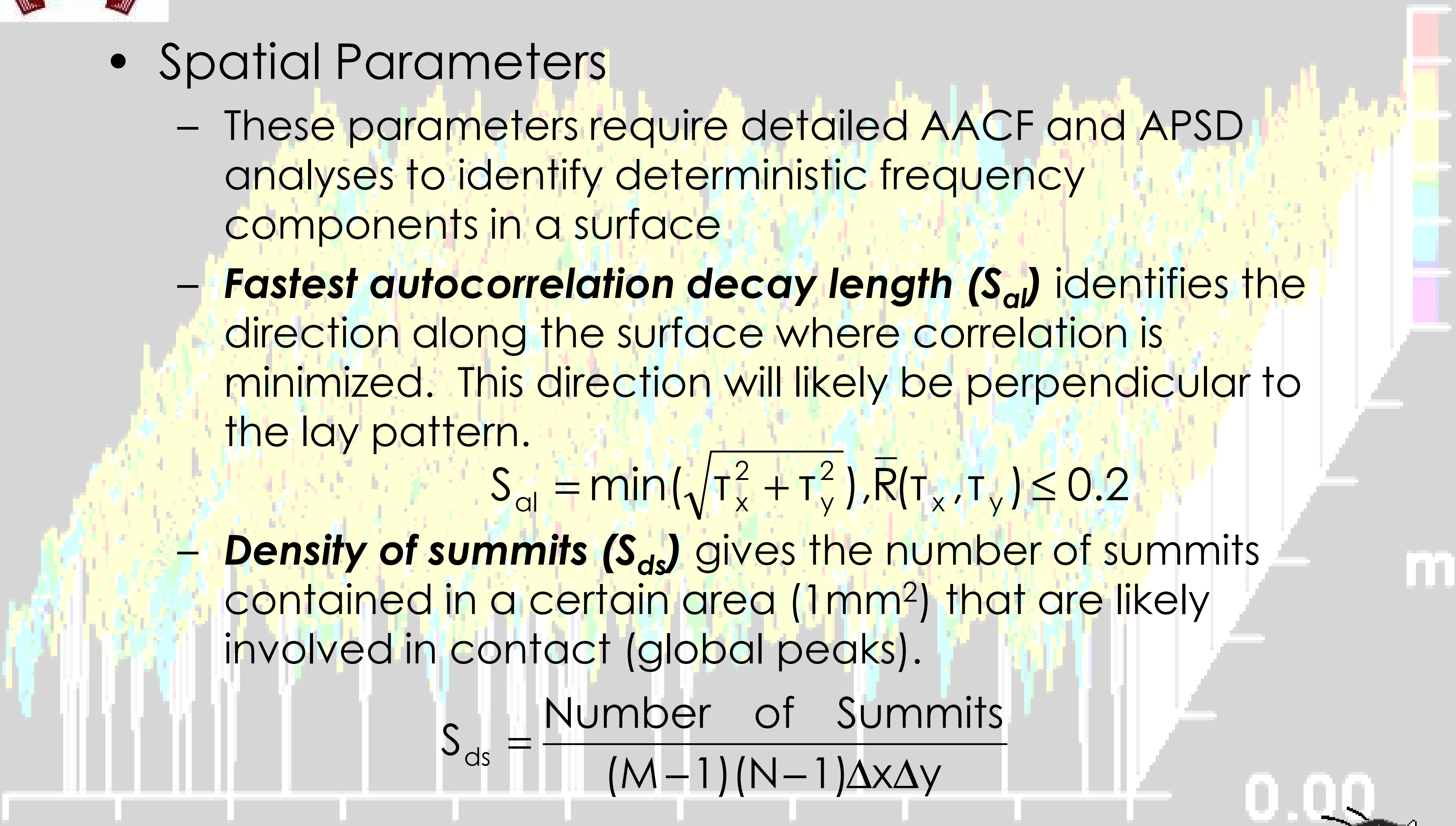


The 3-D surface parameters mentioned earlier were calculated for each surface

Amplitude Parameters

Mean (St. Dev.)	IF	HN	HT	GD
S_q (μm)	0.066 (0.008)	0.26 (0.048)	0.32 (0.042)	0.52 (0.066)
S_{sk}	-1.60 (0.54)	-0.06 (0.27)	0.29 (0.24)	-0.52 (0.23)

Pertinent 3-D Parameters (3)



- Spatial Parameters
  - These parameters require detailed AACF and APSD analyses to identify deterministic frequency components in a surface
  - ***Fastest autocorrelation decay length (S_{al})*** identifies the direction along the surface where correlation is minimized. This direction will likely be perpendicular to the lay pattern.

$$S_{al} = \min\left(\sqrt{\tau_x^2 + \tau_y^2}\right), \overline{R}(\tau_x, \tau_y) \leq 0.2$$

  - ***Density of summits (S_{ds})*** gives the number of summits contained in a certain area (1mm^2) that are likely involved in contact (global peaks).

$$S_{ds} = \frac{\text{Number of Summits}}{(M-1)(N-1)\Delta x \Delta y}$$

Pertinent 3-D Parameters (4)

- Spatial Parameters
  - ***Texture aspect ratio (S_{tr})*** identifies the level of isotropy in a surface. Values greater than 0.5 indicate isotropic nature while values less than 0.4 indicate anisotropic texture.

$$S_{tr} = \frac{\text{Distance that the normalised AACF decays fastest to 0.2 in any direction}}{\text{Distance that the normalised AACF decays slowest to 0.2 in any direction}}$$

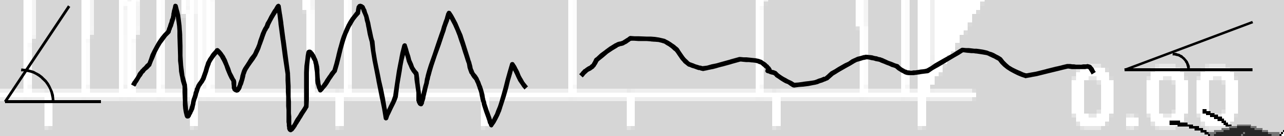
  - ***Texture direction (S_{td})*** gives the pronounced direction of the lay pattern if any lay pattern is present.

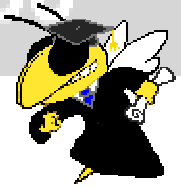
$$S_{td} = -\beta, \beta \le \pi/2$$

$$= \pi - \beta, \pi/2 < \beta \le \pi$$

- Hybrid Parameter
  - ***Root mean square slope ($S_{\Delta q}$)*** assigns a value to the typical steepness of the sides of a surface's asperities.

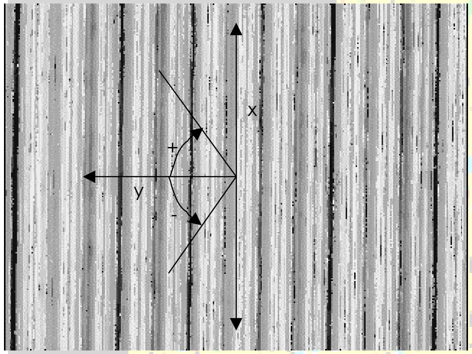
$$S_{\Delta q} = \left(\frac{\sum_{j=2}^{N} \sum_{i=2}^{M} \rho_{ij}^{2}}{(M-1)(N-1)} \right)^{0.5}$$

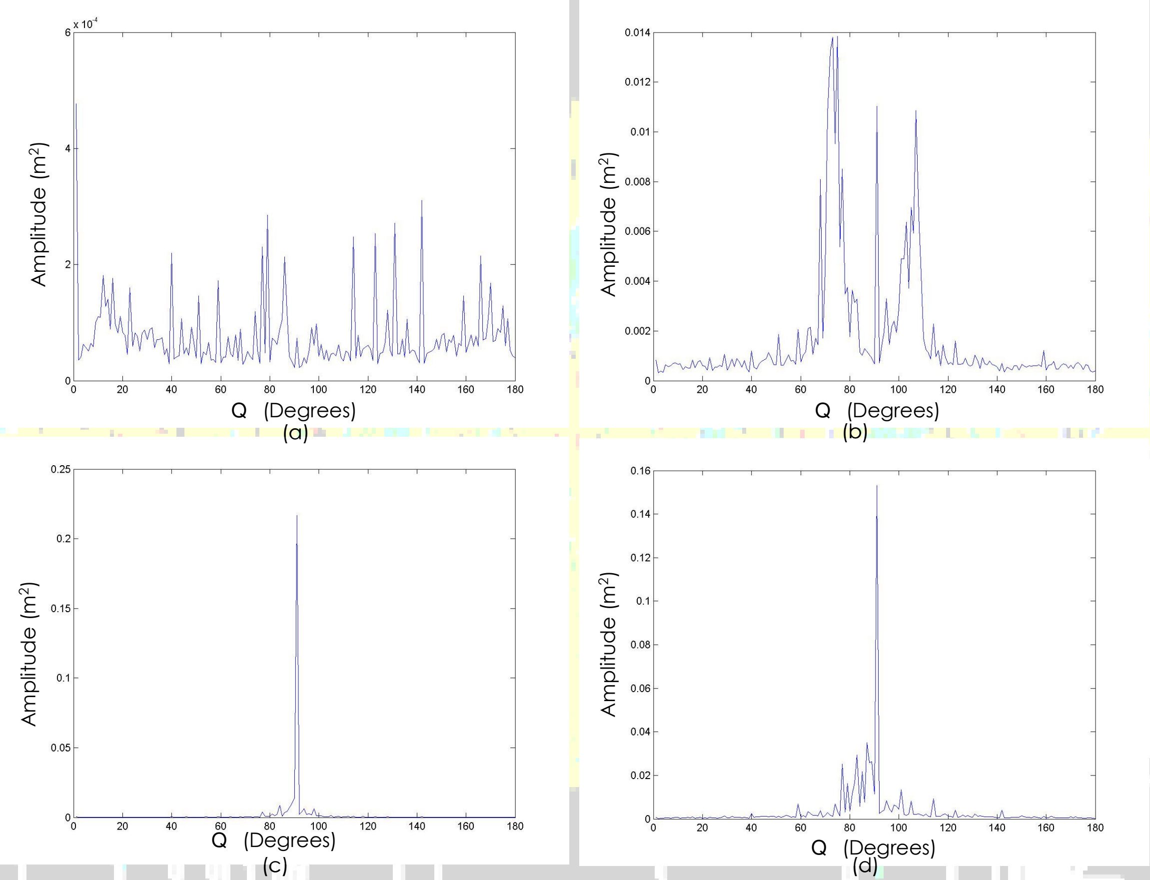




3-D Surface Characterization (5)

Texture direction defined





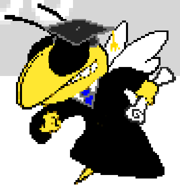
Angular Spectra for (a) IF, (b) HN, (c) HT, and (d) GD

Spatial Parameters

Using AACF, APSD, and Angular spectra, the spatial parameters were calculated

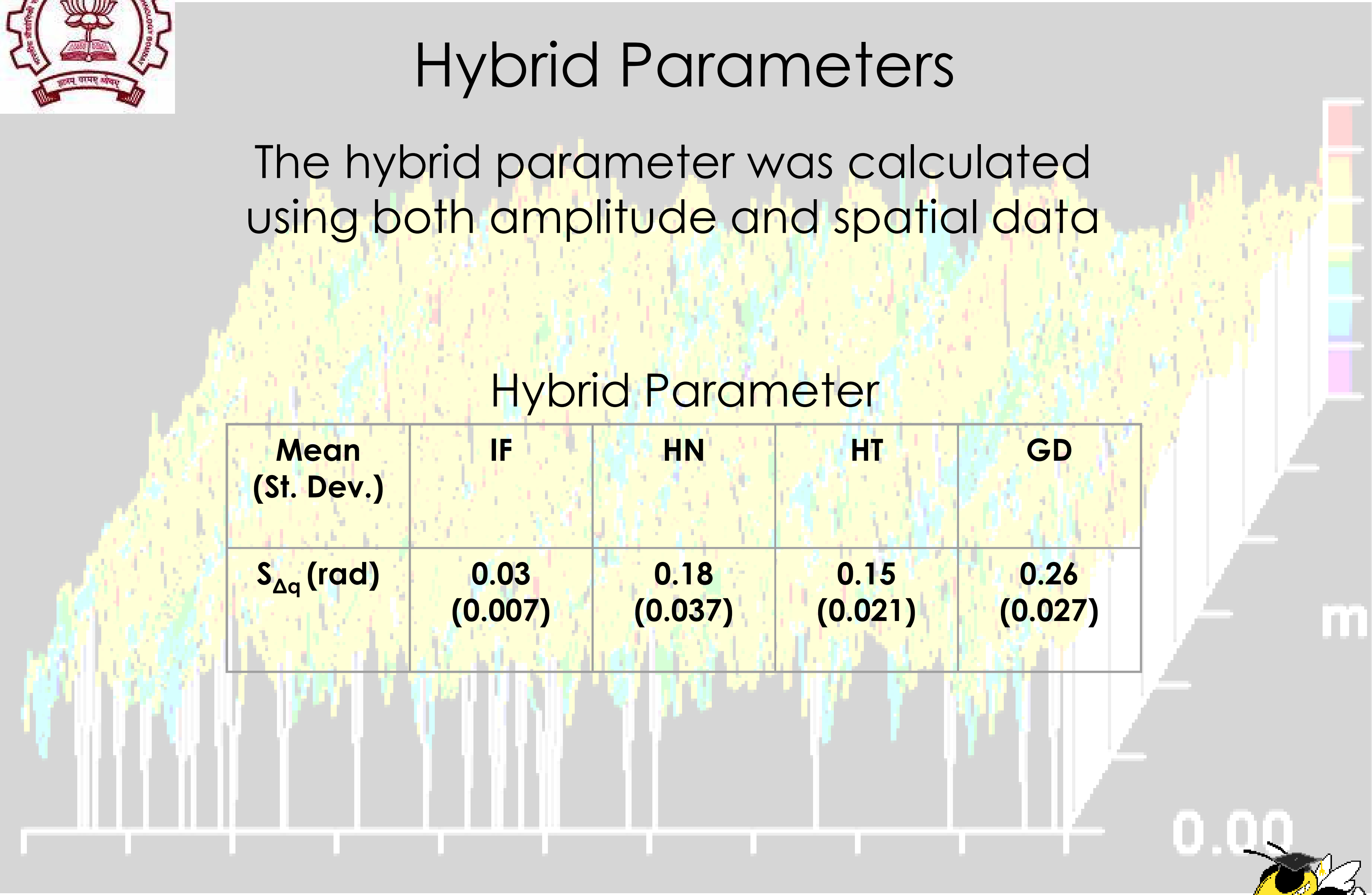
Spatial Parameters

Mean (St. Dev.)	**IF**	**HN**	**HT**	**GD**
S_{al} (μm)	**43.84 (13.03)**	**8.79 (4.83)**	**44.79 (19.86)**	**18.21 (11.95)**
S_{ds} (/mm^2)	**72.97 (10.45)**	**2,129.68 (52.55)**	**92.25 (22.11)**	**636.40 (35.09)**
S_{tr}	**0.68 (0.12)**	**0.27 (0.13)**	**0.19 (0.09)**	**0.10 (0.07)**
S_{td}	**none**	**-75 °, 75 °**	**90°**	**90°**



Hybrid Parameters

The hybrid parameter was calculated using both amplitude and spatial data

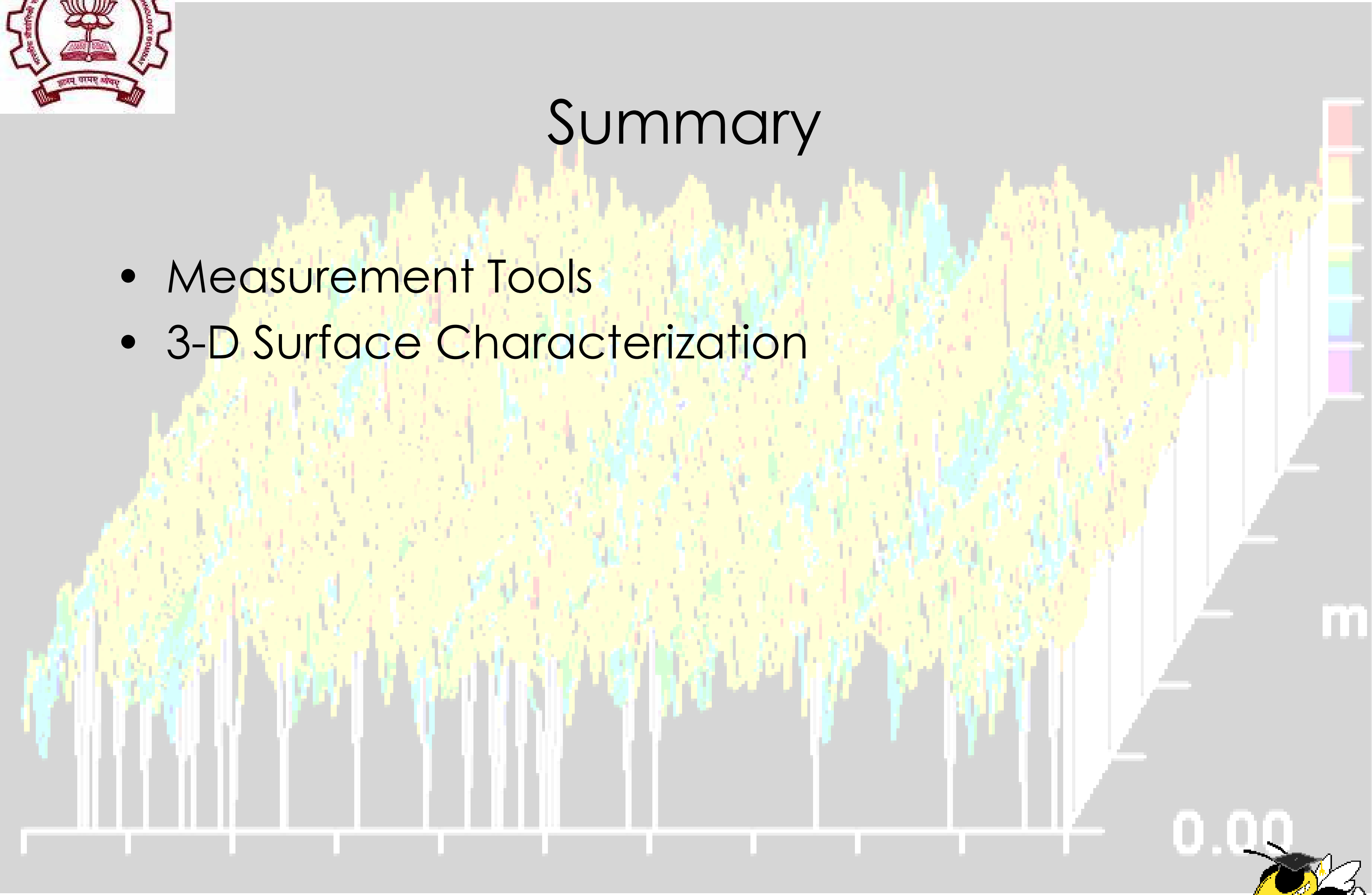


Hybrid Parameter

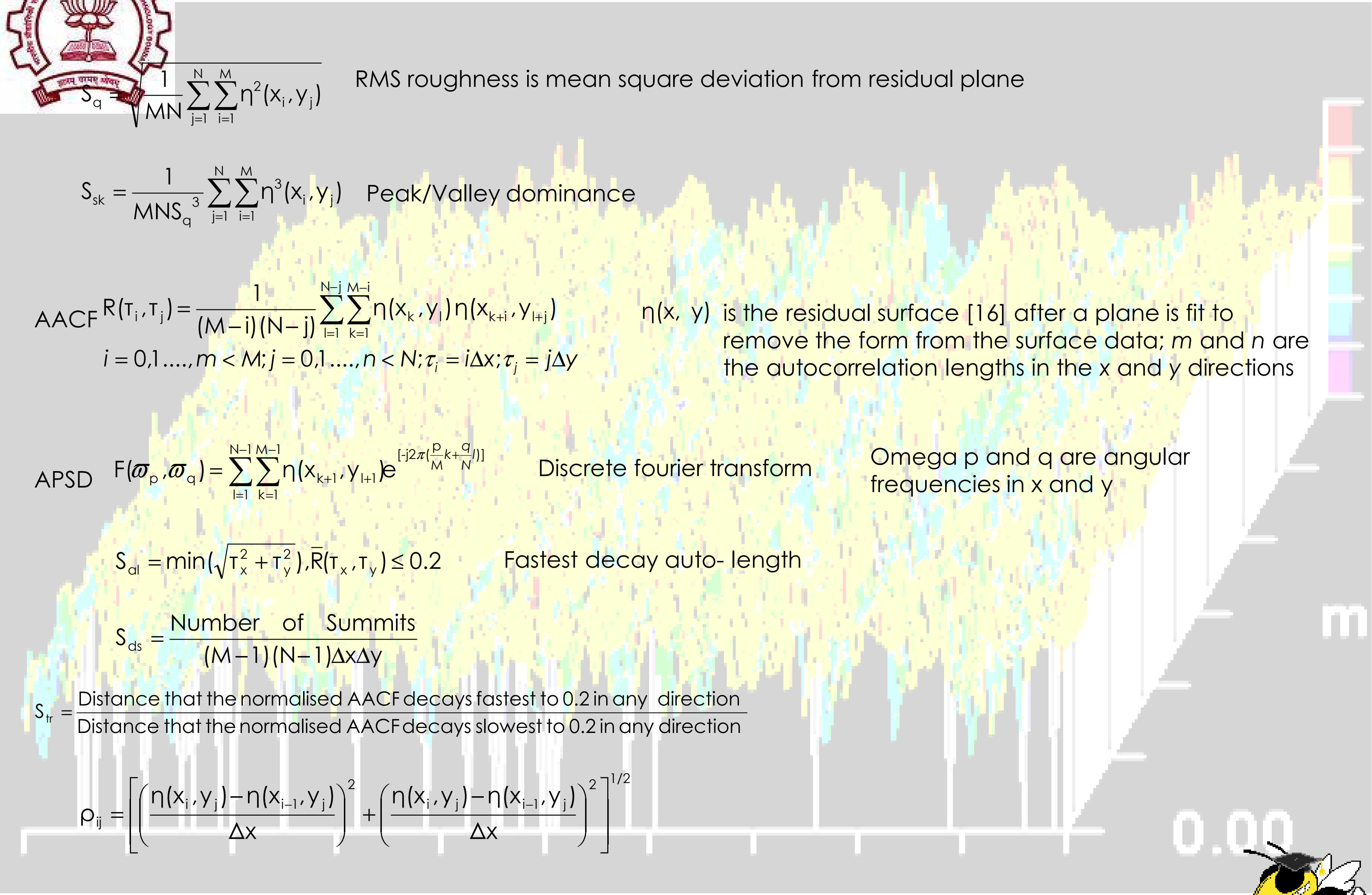
Mean (St. Dev.)	**IF**	**HN**	**HT**	**GD**
$S_{\Delta q}$ (rad)	**0.03 (0.007)**	**0.18 (0.037)**	**0.15 (0.021)**	**0.26 (0.027)**

Summary

- Measurement Tools
- 3-D Surface Characterization



Questions?



$$S_q = \sqrt{\frac{1}{MN}\sum_{j=1}^{N}\sum_{i=1}^{M}\eta^2(x_i, y_j)}$$

RMS roughness is mean square deviation from residual plane

$$S_{sk} = \frac{1}{MNS_q^{\ 3}}\sum_{j=1}^{N}\sum_{i=1}^{M}\eta^3(x_i, y_j)$$

Peak/Valley dominance

AACF $$R(\tau_i, \tau_j) = \frac{1}{(M-i)(N-j)}\sum_{l=1}^{N-j}\sum_{k=1}^{M-i}\eta(x_k, y_l)\,\eta(x_{k+i}, y_{l+j})$$

$$i = 0,1 \ldots., m < M; j = 0,1 \ldots., n < N; \tau_i = i\Delta x; \tau_j = j\Delta y$$

$\eta(x, y)$ is the residual surface [16] after a plane is fit to remove the form from the surface data; *m* and *n* are the autocorrelation lengths in the x and y directions

APSD $$F(\varpi_p, \varpi_q) = \sum_{l=1}^{N-1}\sum_{k=1}^{M-1}\eta(x_{k+1}, y_{l+1})e^{[-j2\pi(\frac{p}{M}k+\frac{q}{N}l)]}$$

Discrete fourier transform

Omega p and q are angular frequencies in x and y

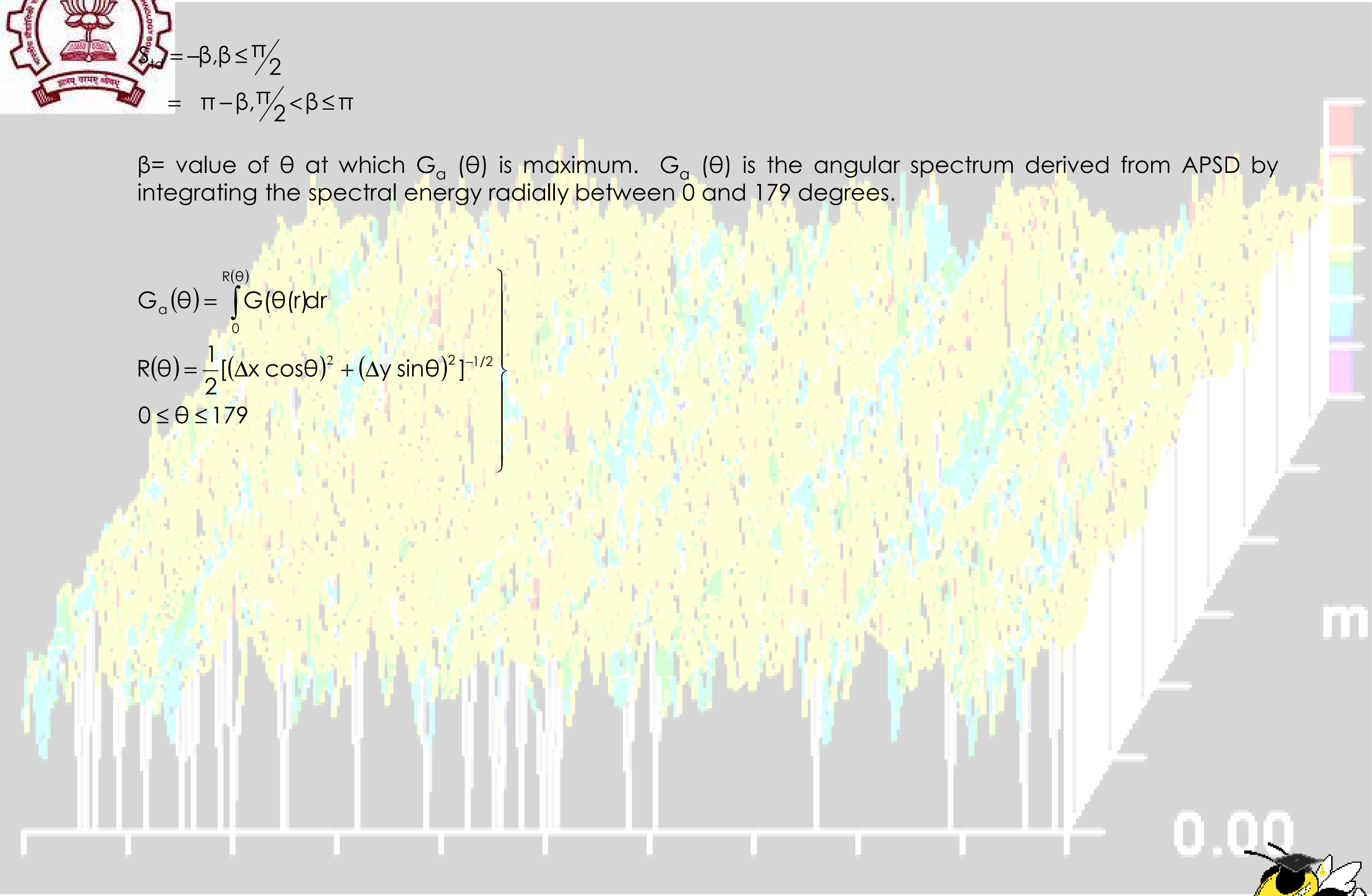
$$S_{al} = \min(\sqrt{\tau_x^2 + \tau_y^2}), \bar{R}(\tau_x, \tau_y) \le 0.2$$

Fastest decay auto- length

$$S_{ds} = \frac{\text{Number of Summits}}{(M-1)(N-1)\Delta x\Delta y}$$

$$S_{tr} = \frac{\text{Distance that the normalised AACF decays fastest to 0.2 in any direction}}{\text{Distance that the normalised AACF decays slowest to 0.2 in any direction}}$$

$$\rho_{ij} = \left[\left(\frac{\eta(x_i, y_j) - \eta(x_{i-1}, y_j)}{\Delta x}\right)^2 + \left(\frac{\eta(x_i, y_j) - \eta(x_{i-1}, y_j)}{\Delta x}\right)^2\right]^{1/2}$$



$$\delta_{td} = -\beta, \beta \le \pi/2$$
$$= \pi - \beta, \pi/2 < \beta \le \pi$$

β= value of θ at which G_a (θ) is maximum. G_a (θ) is the angular spectrum derived from APSD by integrating the spectral energy radially between 0 and 179 degrees.

$$\left.\begin{array}{l} G_a(\theta) = \int_0^{R(\theta)} G(\theta(r)dr \\ R(\theta) = \frac{1}{2}[(\Delta x \cos\theta)^2 + (\Delta y \sin\theta)^2]^{-1/2} \\ 0 \le \theta \le 179 \end{array}\right\}$$