Texture and Friction Rendering for Haptic Display

IMA Workshop on Haptics, Virtual Reality
and Human Computer Interaction
University of Minnesota, June 14-15 2001

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Presentation Overview

- Introduction
- Texture representation and rendering
  - **Surface metrology**
  - **Fractals**
  - **Implementation issues**
  - **Results**
- Friction representation and rendering
  - **Friction models**
  - **Implementation issues**
  - **Results**
- Conclusions and future work

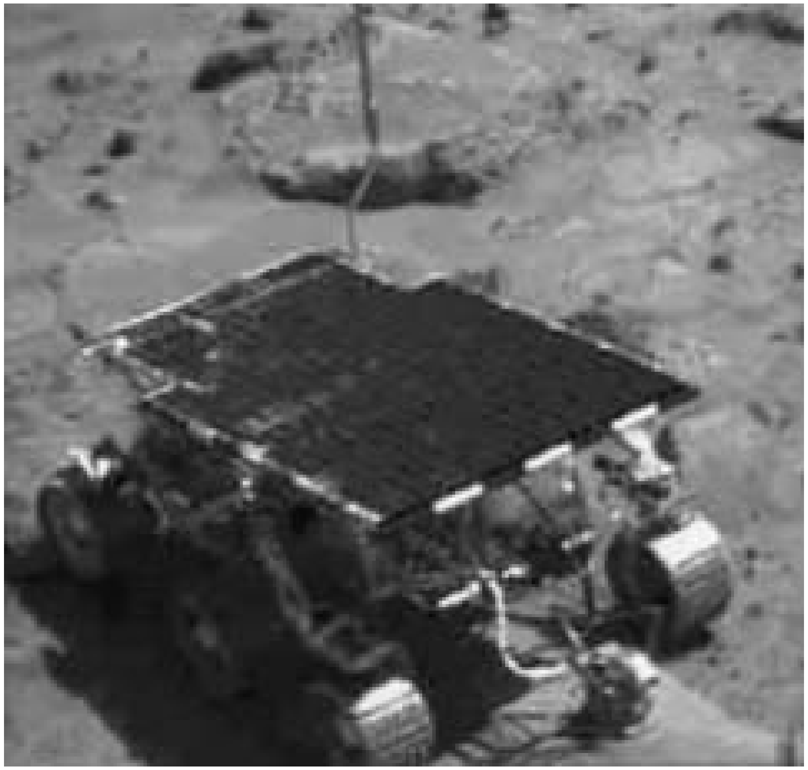
Premise

- Surface properties such as texture and friction are a vital component of the tactile experience -- more important than shape.
- They must be represented and displayed convincingly for haptic interaction with remote or virtual worlds.

Applications: Planetary Exploration

Remote field geology

- Igneous rock - grain size, shape indicate cooling mechanism
- Sedimentary rock - particle size, shape and arrangement indicate erosion and transport mechanism

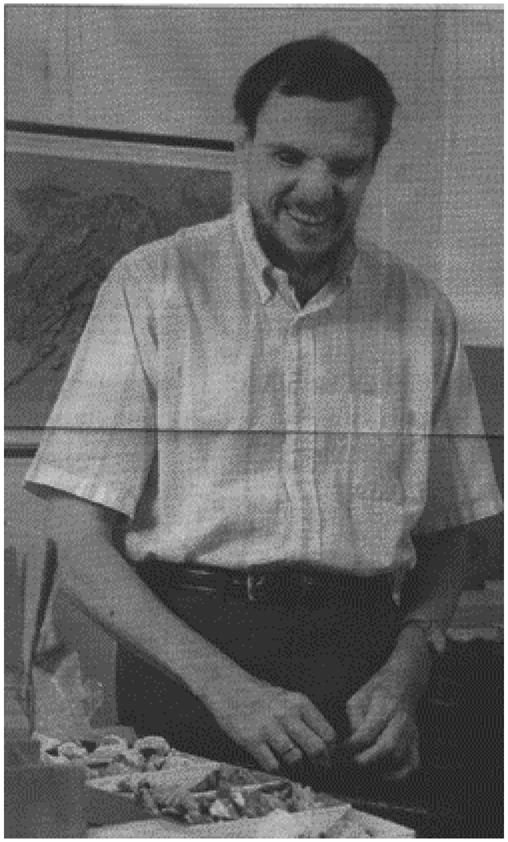


"Field study…absolutely requires human geologists to be involved intimately"
(Taylor & Spudis, 1991)

- Hammer striking a rock
- Grittiness felt between fingertips
- Feel of soil underneath the feet

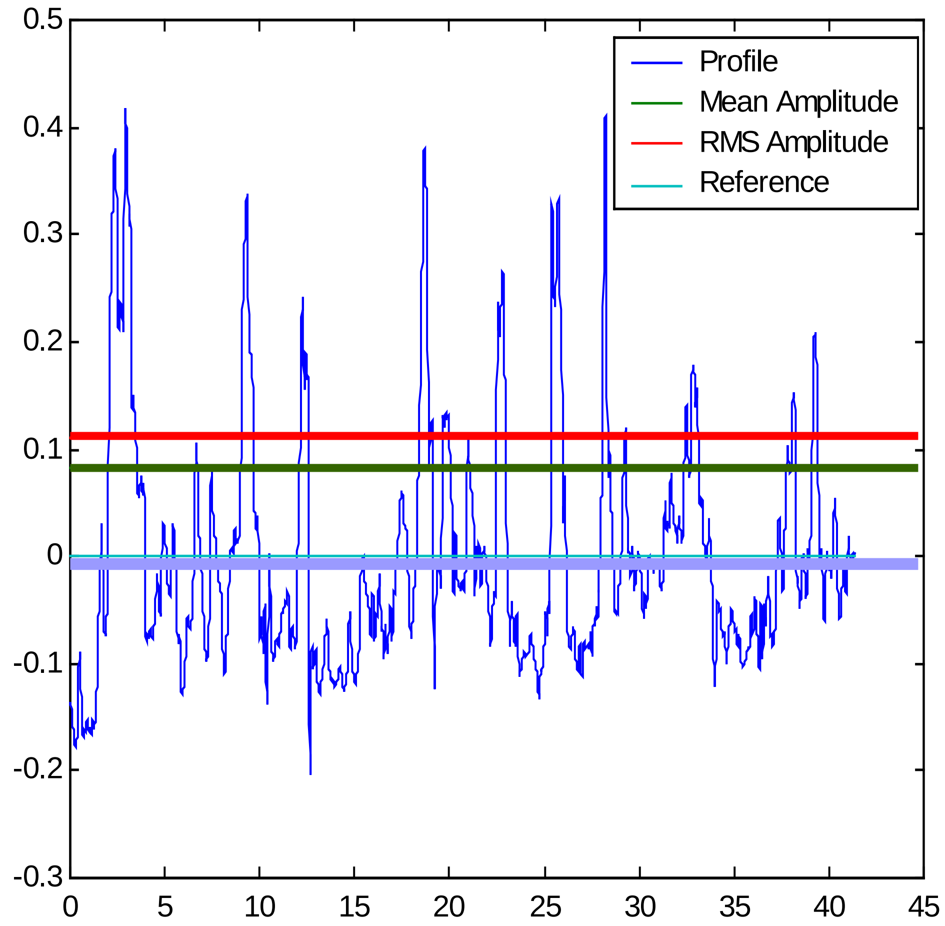
Haptic Paleontology

- G.J. Vermeij
  - Examining Fossil Specimens by Size Scale
    - Finger Tips, Finger Nails, Hypodermic Needle
- Hypodermic Needle as Exploration Tool
  - Fossil Classification
- Model for Virtual Haptic Interaction
  - One point of Contact



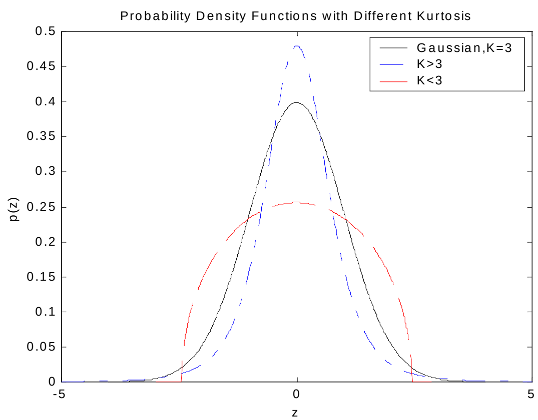
Texture: Quantifying Roughness with Statistical Parameters from metrology

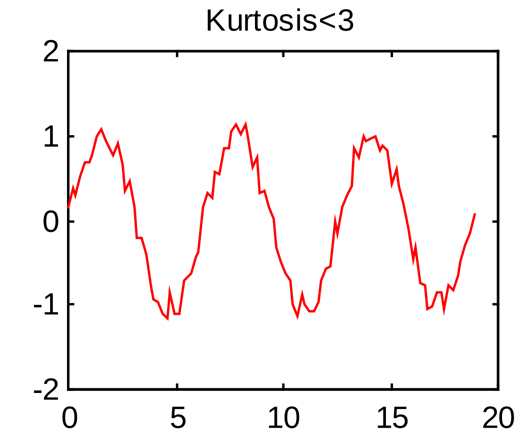
- RMS amplitude
- Peak density
- Amplitude probability density

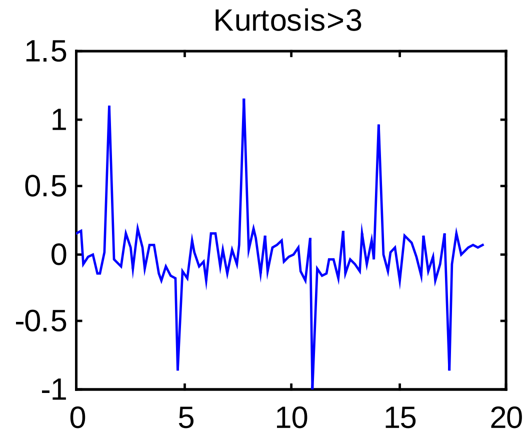


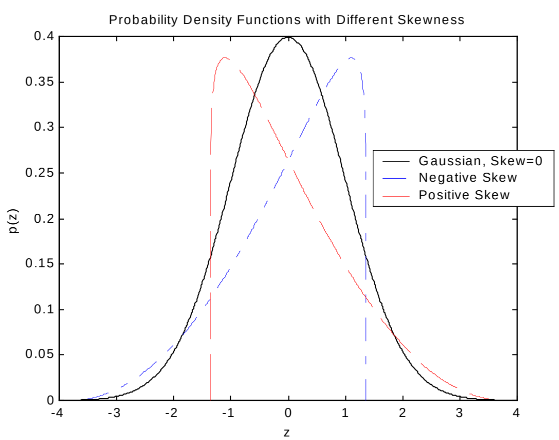
Metrology

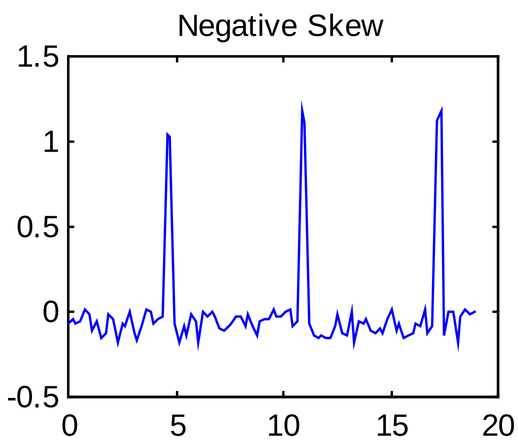
Skew and Kurtosis Examples

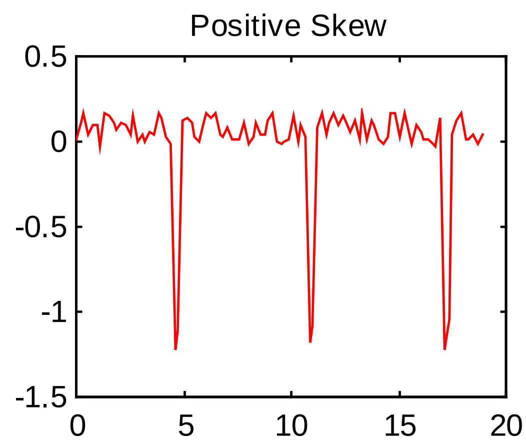




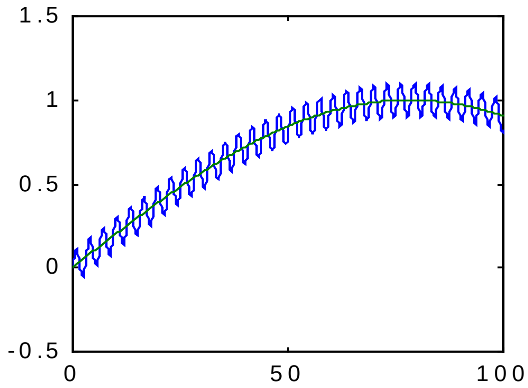








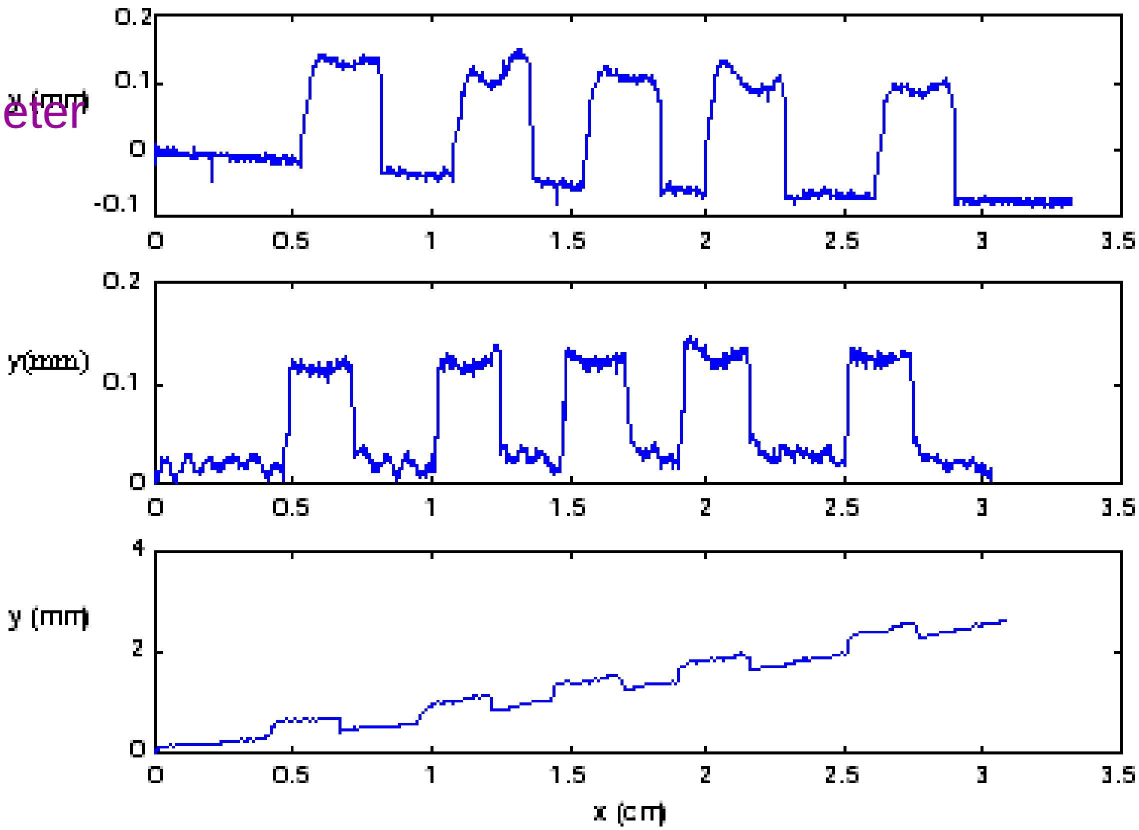
Difficulties with Surface Metrology



- Arbitrary Definitions
  - Leads to Different results
    - What is shape and what is roughness?
    - What is a feature?
    - Peak Definitions
      - 3, 4 or more point definition? Amplitude Band?
  - "Parameter Rash" - D.J. Whitehouse
- Example, Measurement Method leads to Different Values
  - Sensor Resolution
  - Length of Sample
    - $\sigma \propto L^{1/2}$ Sayles, 1978

Collecting Surface Data

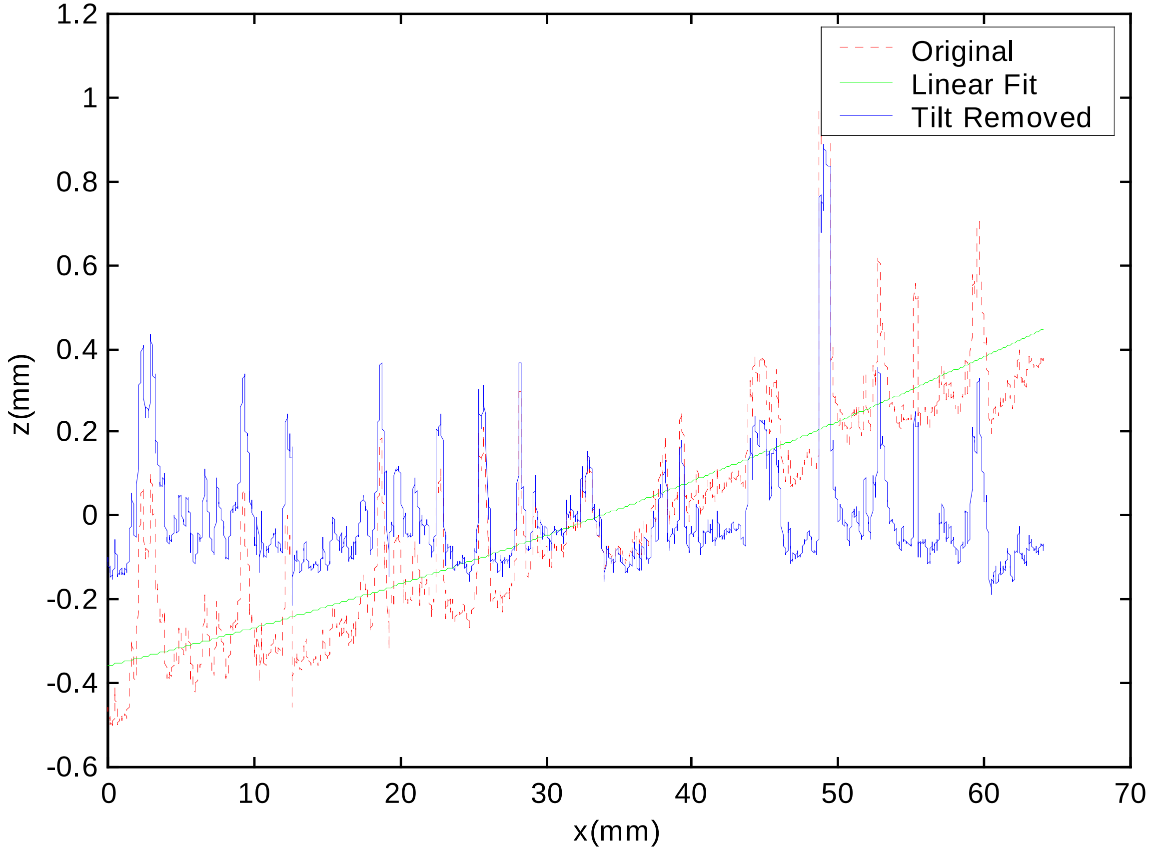
- Analyze 1-D Profiles
  - Profiles Collected by Sensors
    - Stylus
    - Laser Profilometer
    - AFM



Removing Form & Waviness

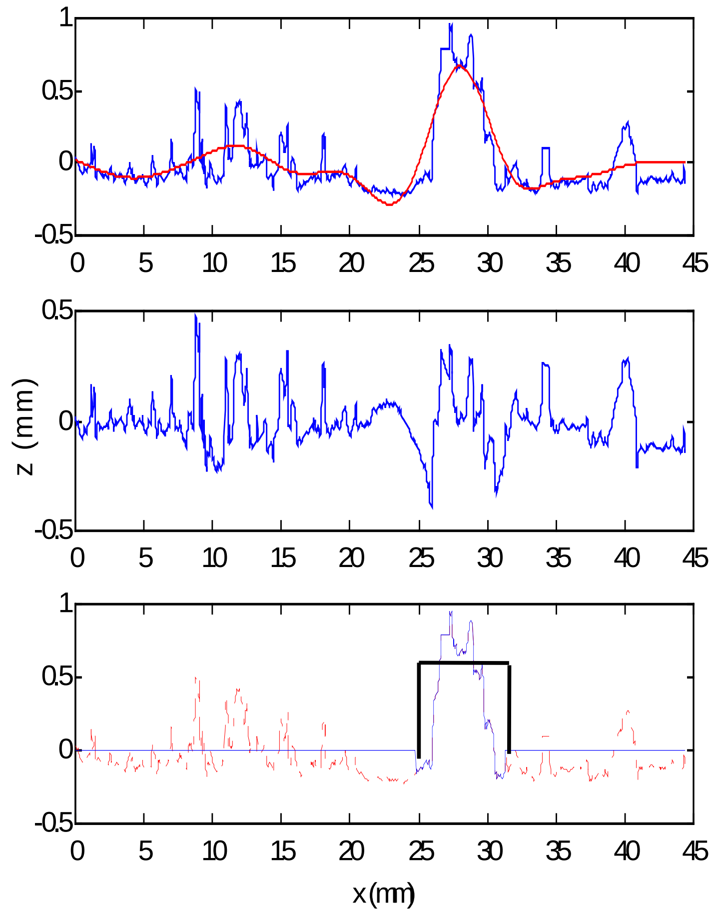
- Fit Profile with 2nd order Polynomial

$$Y(x) = a_0 + a_1 x + a_2 x^2$$



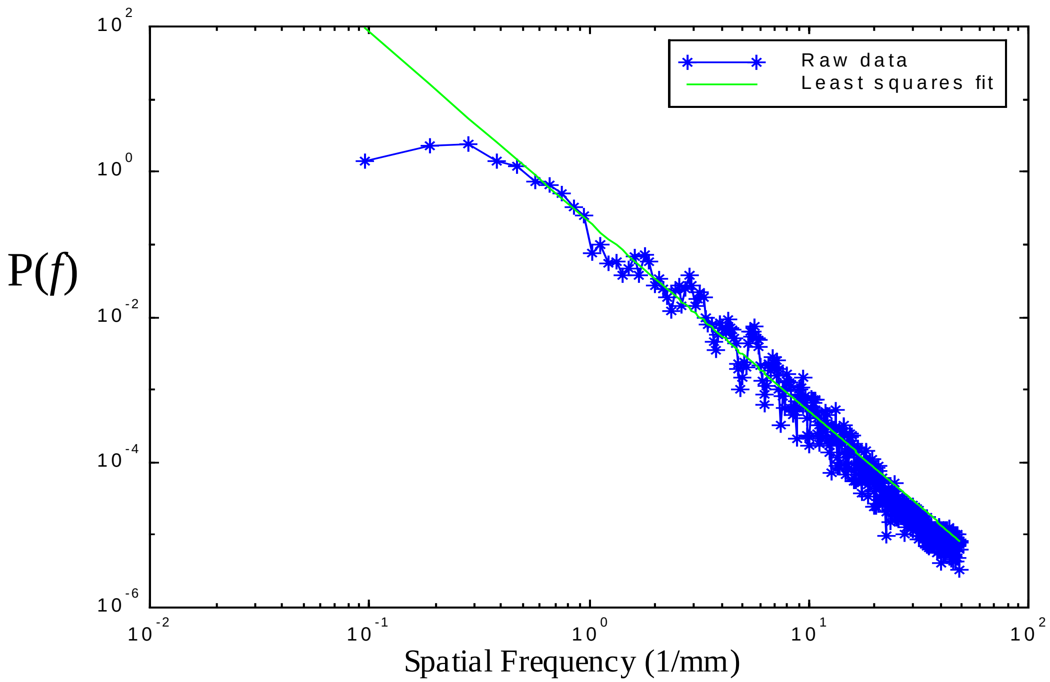
Feature Detection Algorithm

- Low Pass Filtered Profile
- Compute RMS Amplitude (R_q) of high frequency information
- Features are heights over $2*R_q$, plus 30% of lateral distance



Fractal Brownian Motion

- Random Fractal Found in Nature
  - Spectral Density Form $P(f) \propto \frac{1}{f^{\beta}}$
    - ß=0 - White Noise, 1≤ß ≤ 3 - fBm
      - Used in Terrain Modeling
      - Found in Music

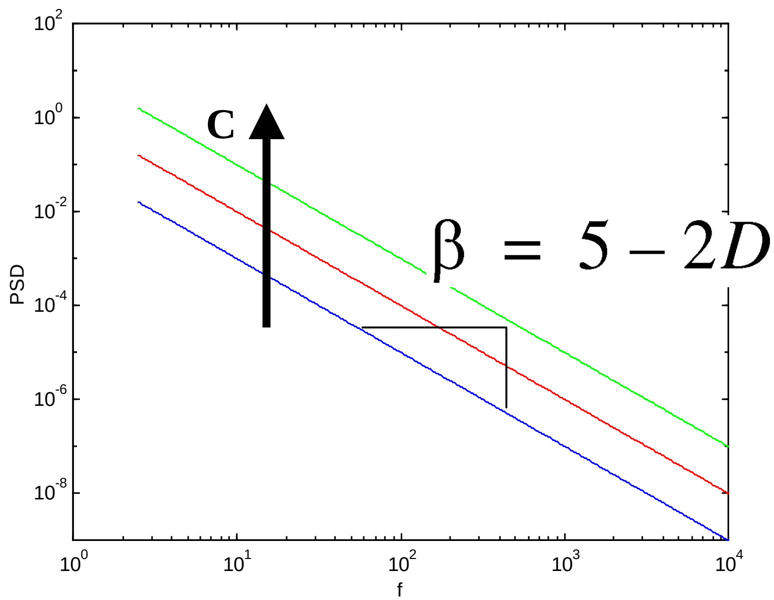


Random Fractals

- Characterize random fractal with two parameters: dimension (D) and amplitude coefficient (C)
- Random Fractal Found in Nature
  - Fractal Brownian Motion
    - Function with Power Spectral Density
      - where $1 \leq \beta \leq 3$
    - Ganti-Bhushan

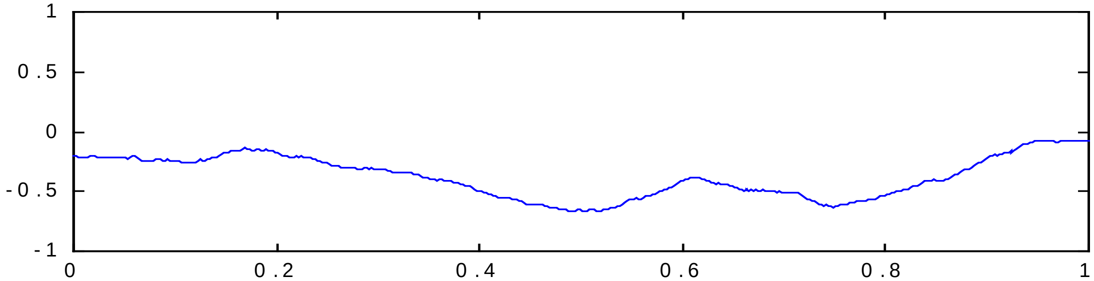
$$P(f) \propto \frac{1}{f^{\beta}}$$

$$P(f) = \frac{C}{f^{5-2D}}$$

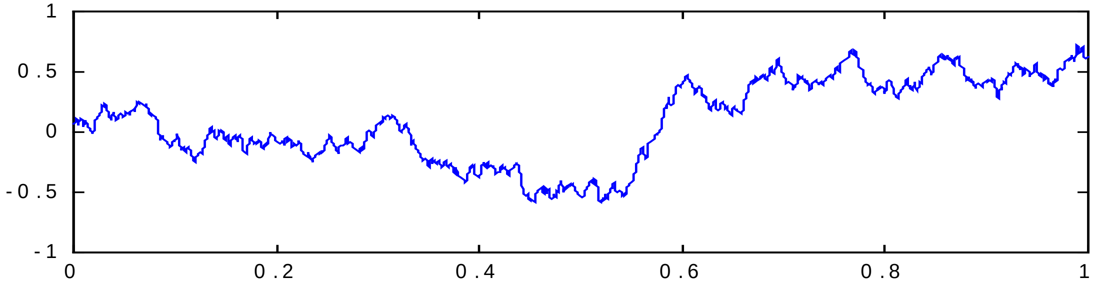


Fractal Dimension

- Measures How Much Space the Fractal Fills
  - Non-integer number 1.2, 2.3, etc.
  - Most Significant Digit Represents Euclidean Dimension. 1 - Line, 2 - Plane, 3 - Volume



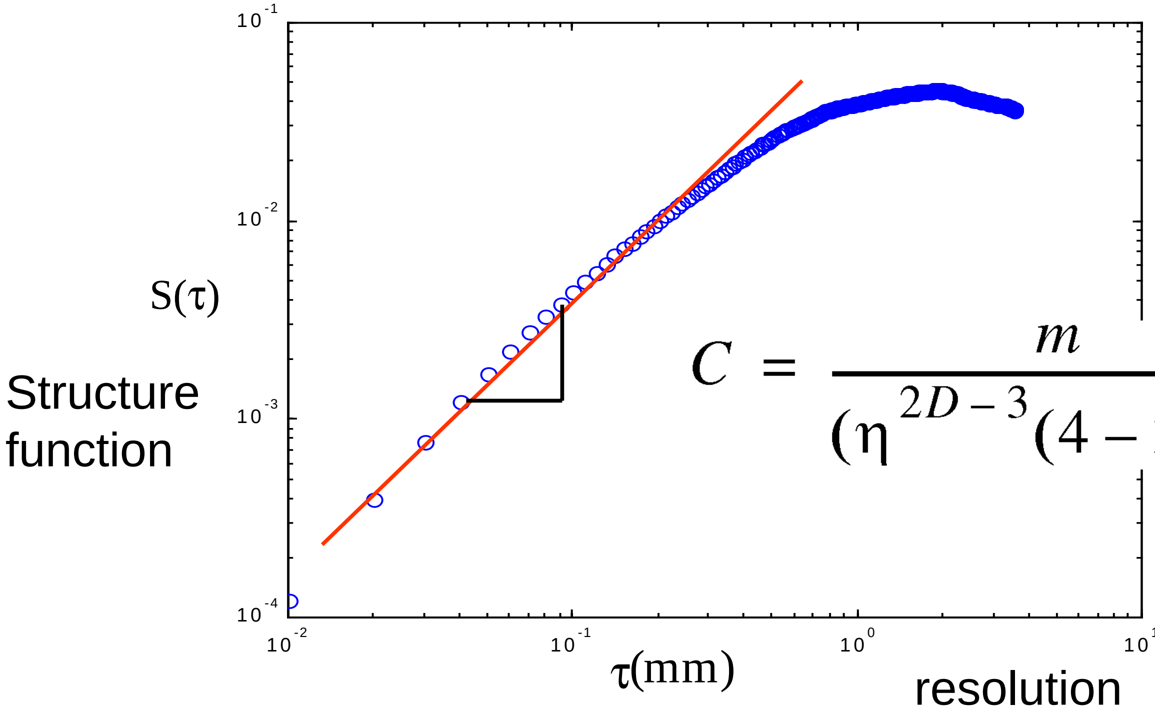
D=1.1



D=1.45

Amplitude coefficient

- Use Amplitude Coefficient C to scale Power Magnitudes
- Expected Mean Square Difference of the Heights
  - Able to Measure Amplitude Coefficient C
  - C increases with Variance of the Profile Heights



$$C = \frac{m}{(\eta^{2D-3}(4-2D))}$$

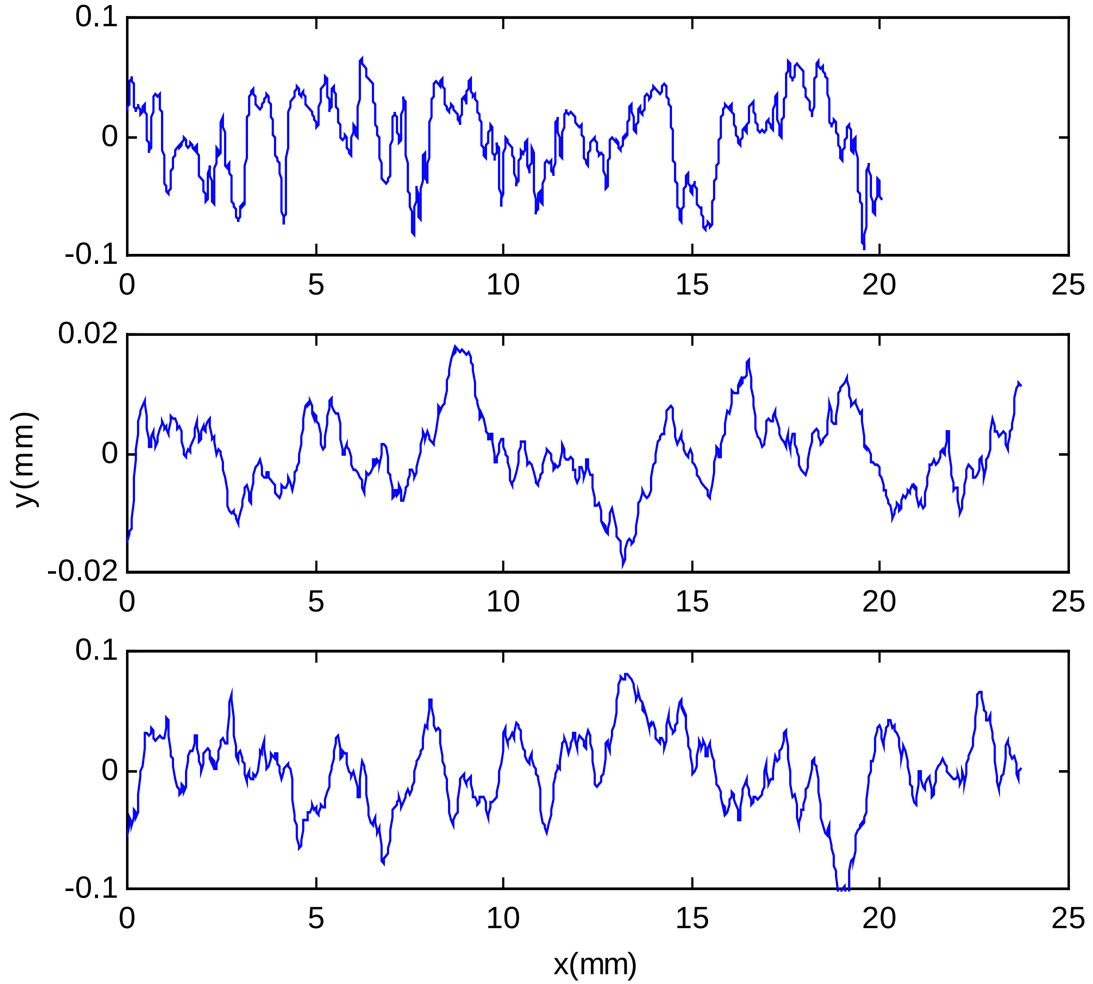
Synthesizing Fractals

We can Synthesize Fractals with a set D and C

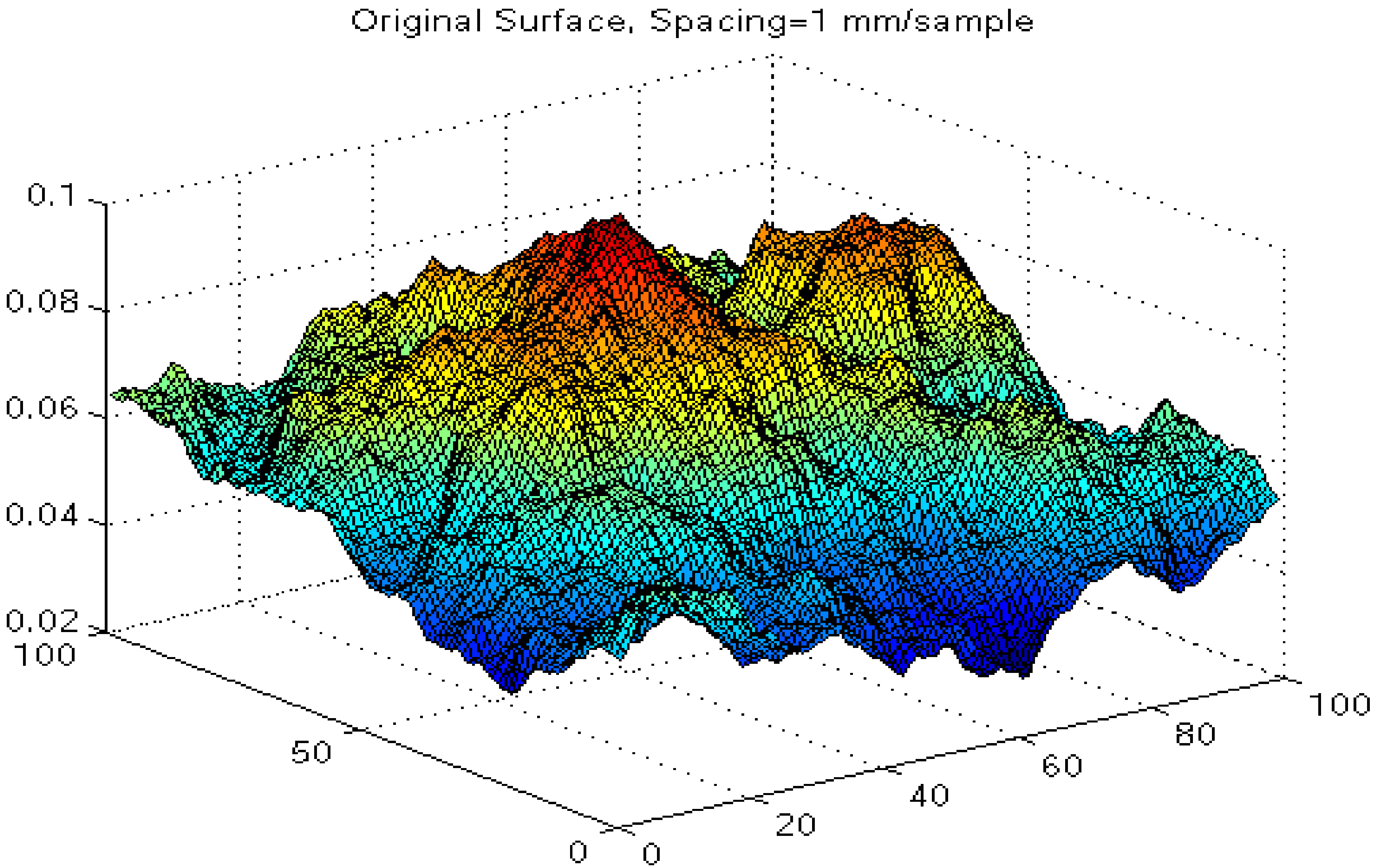
Use Inverse Fourier Transform

$$X(t) = \sum_{k=0}^{N-1} H_k e^{2\pi i k t}$$

Painter's 100 Grit Sandpaper, Fractal Simulations
D=1.166, C=.0063, C=.12

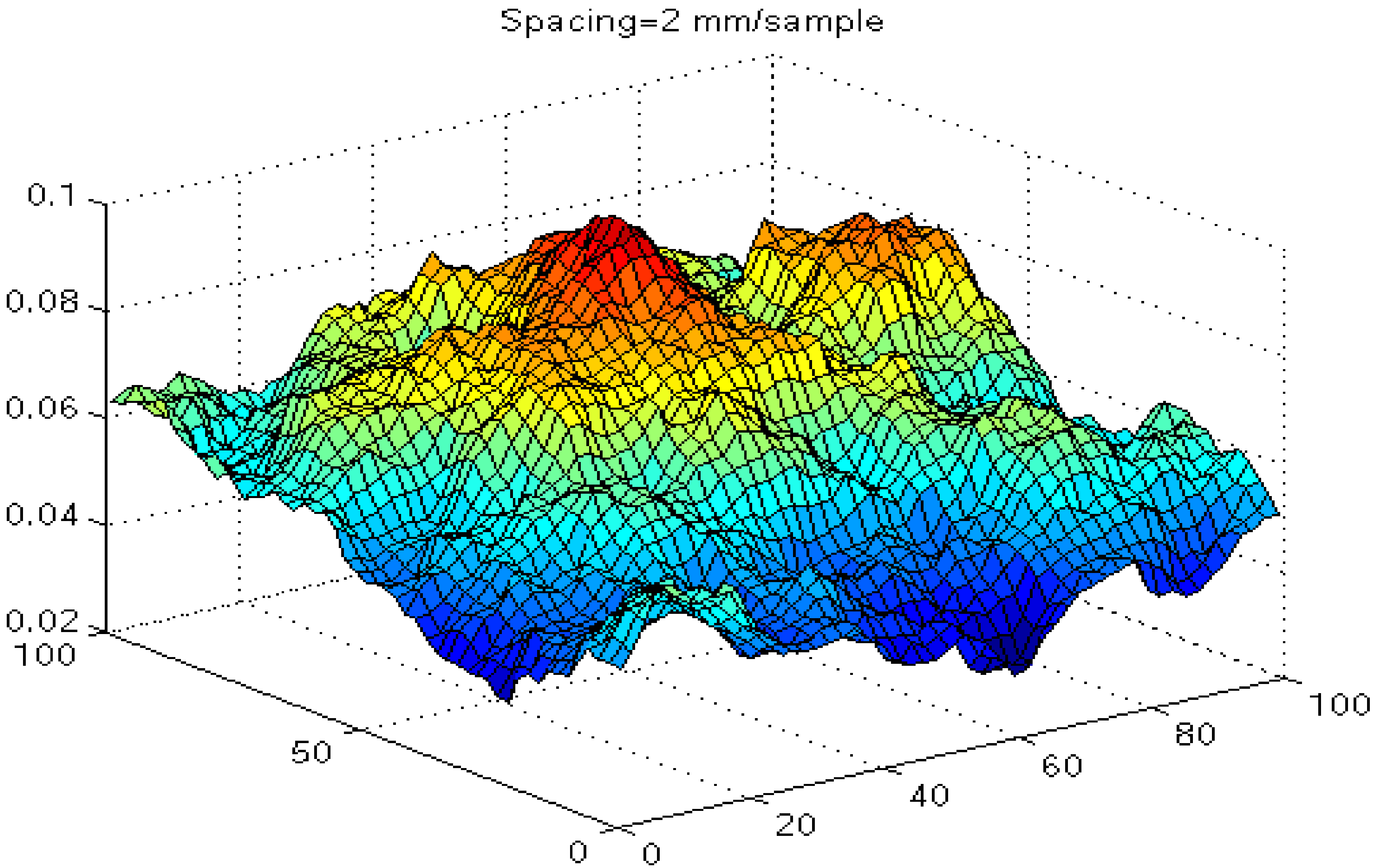


Synthesized Sampled Surfaces

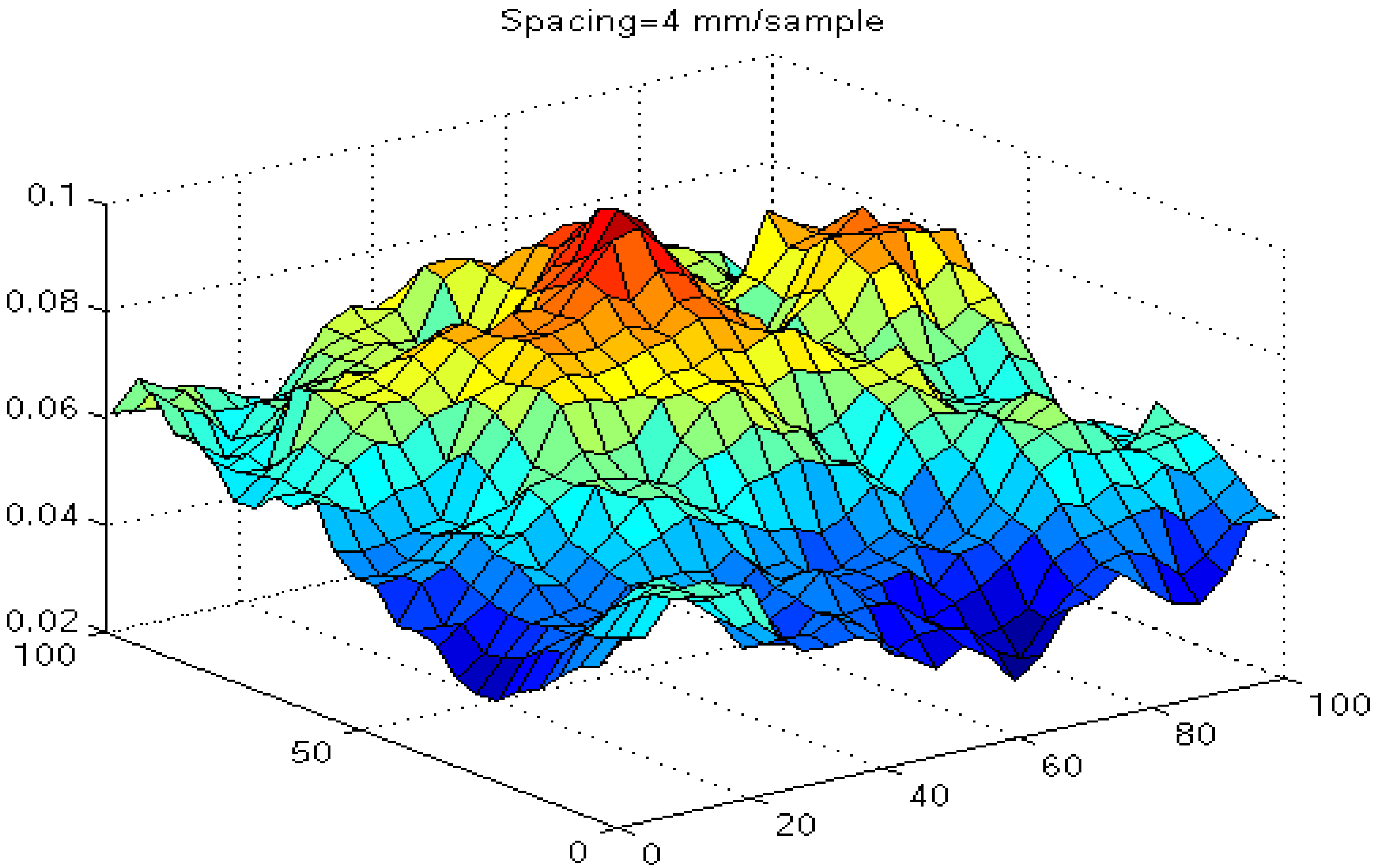


Surfaces

Synthesized Sampled Surface



Synthesized Sampled Surface



Implementation issues

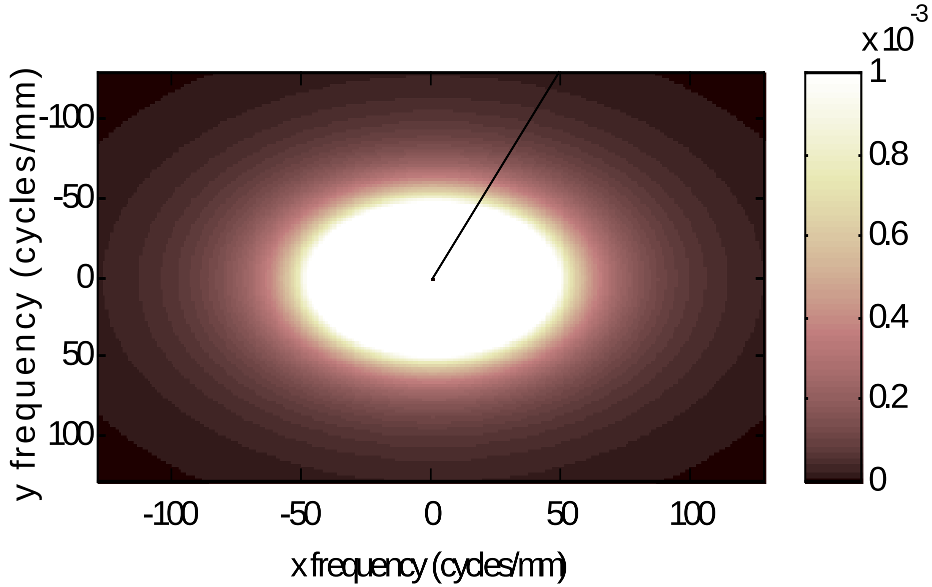
- Measured amplitude coefficients decrease as sample resolution drops
- Sampled functions experience a reduction in their Fourier coefficients (~ 1/spacing in each direction)
- 2D structure function not suited for anisotropic surfaces
- Apply Fourier transform sampling theorem

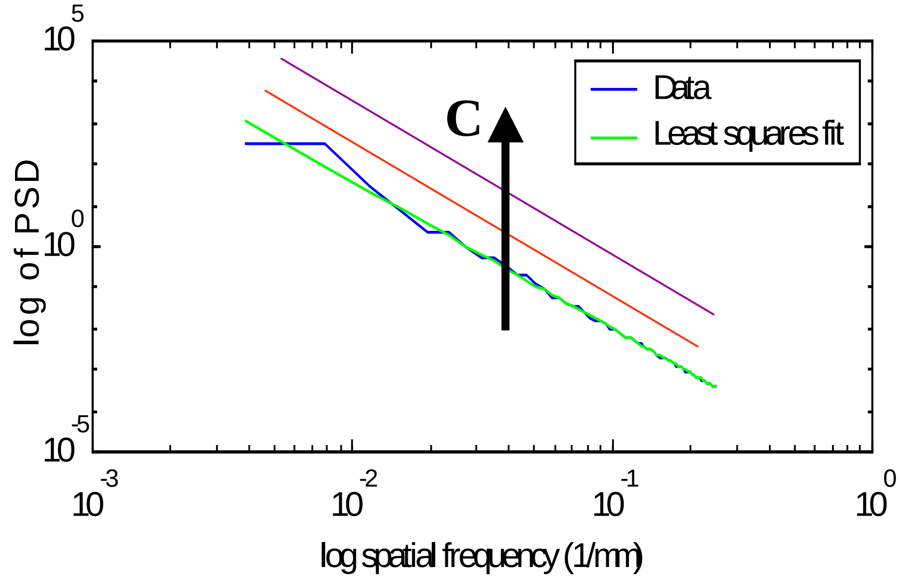
$$P(\boldsymbol{k}) = |A(\boldsymbol{k})|^2 = \frac{1}{\Delta w^2}\frac{1}{\Delta q^2}\frac{C}{\|\boldsymbol{k}\|^{8-2D}}$$

Measuring Amplitude

- Compute Power Spectral Density on log scale
  - Ω intercept of least squares fit to PSD
  - Data is resampled in both directions with equal resolutions

$$C = (10^{\Omega}) \cdot (\Delta w^2 \Delta q^2)$$

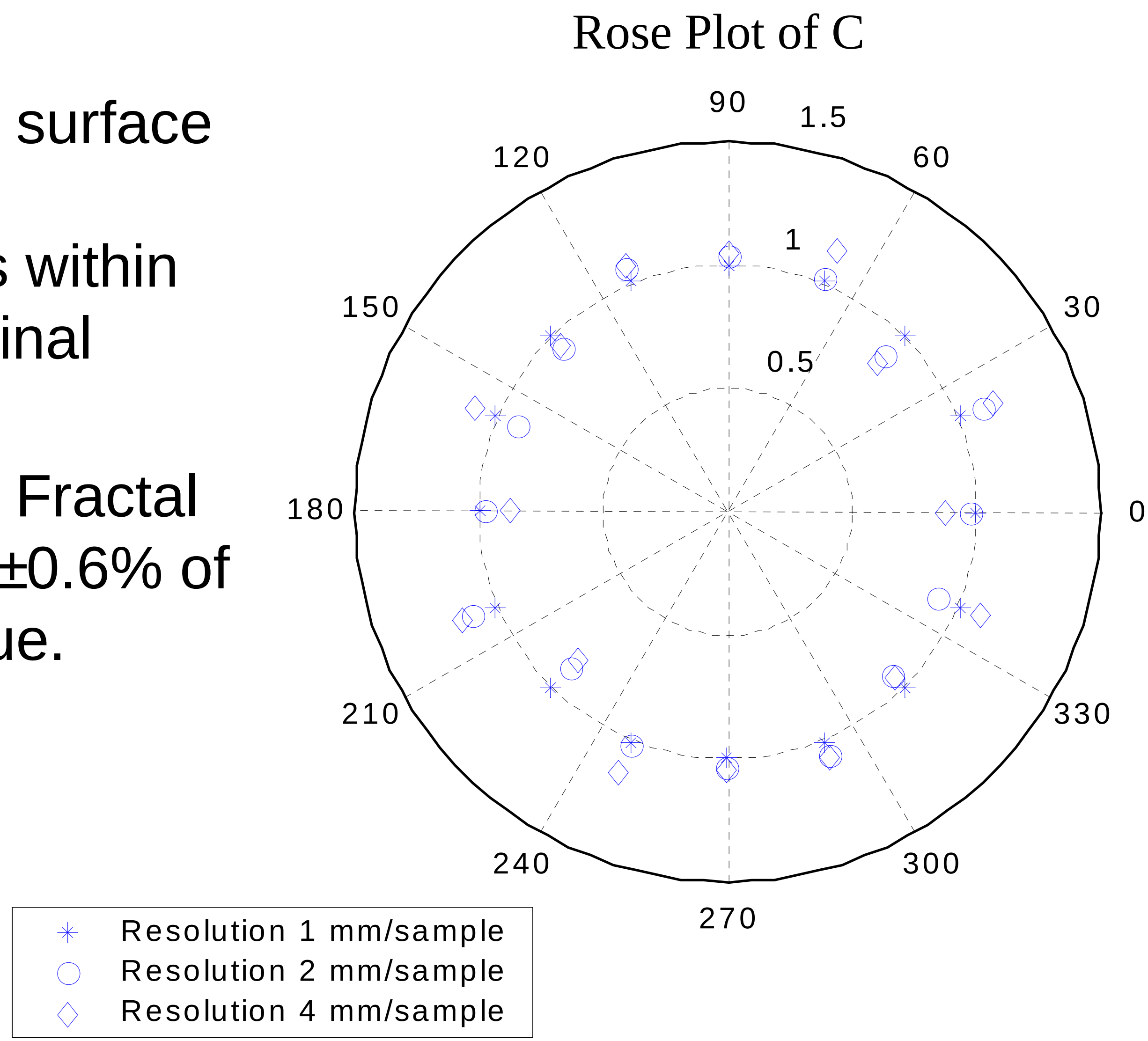




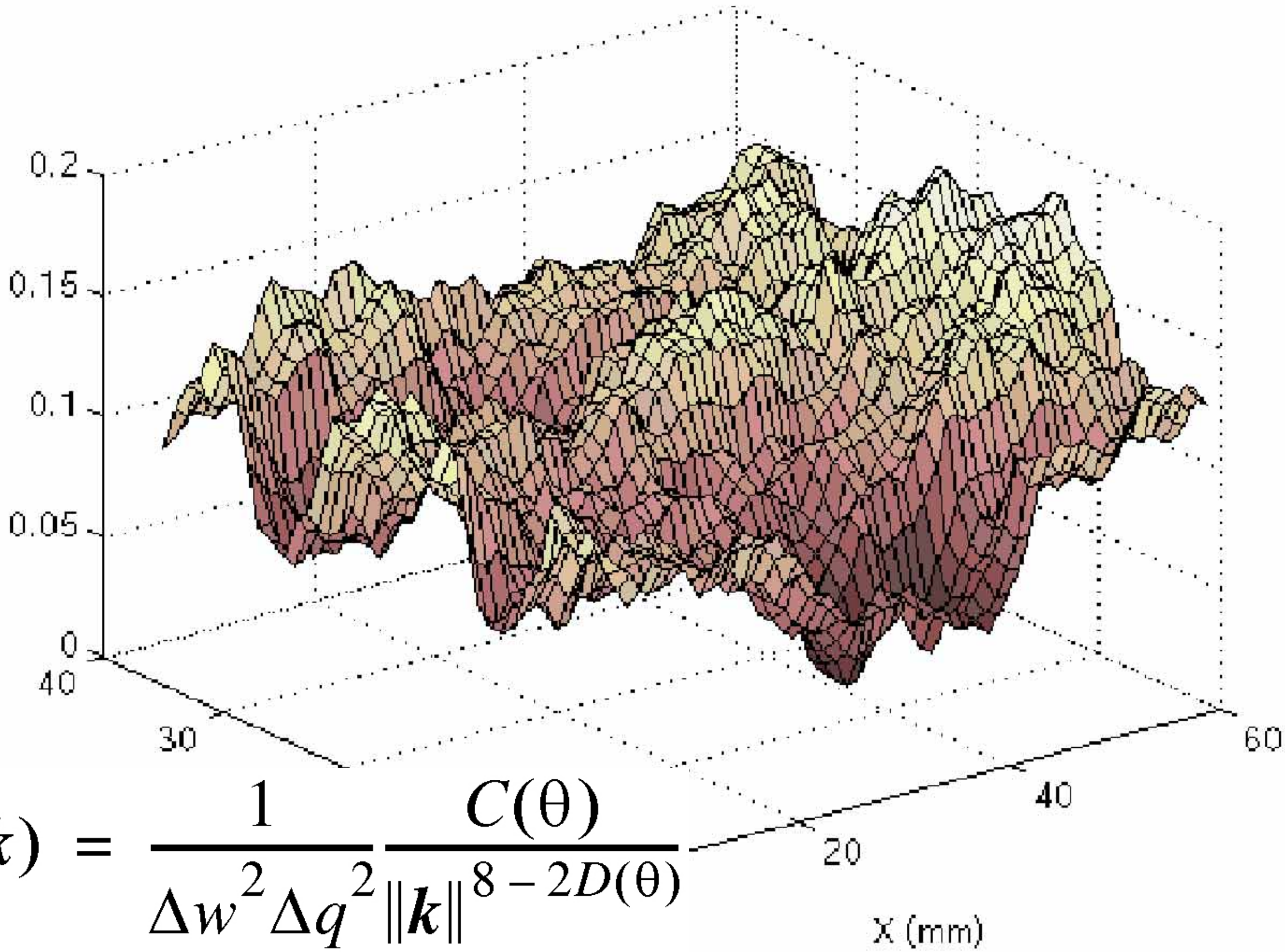
Surfaces

Example amplitude Coefficient Plot

- Resampled surface Amplitude Coefficients within 10% of original values
- Resampled Fractal Dimension ±0.6% of original value.



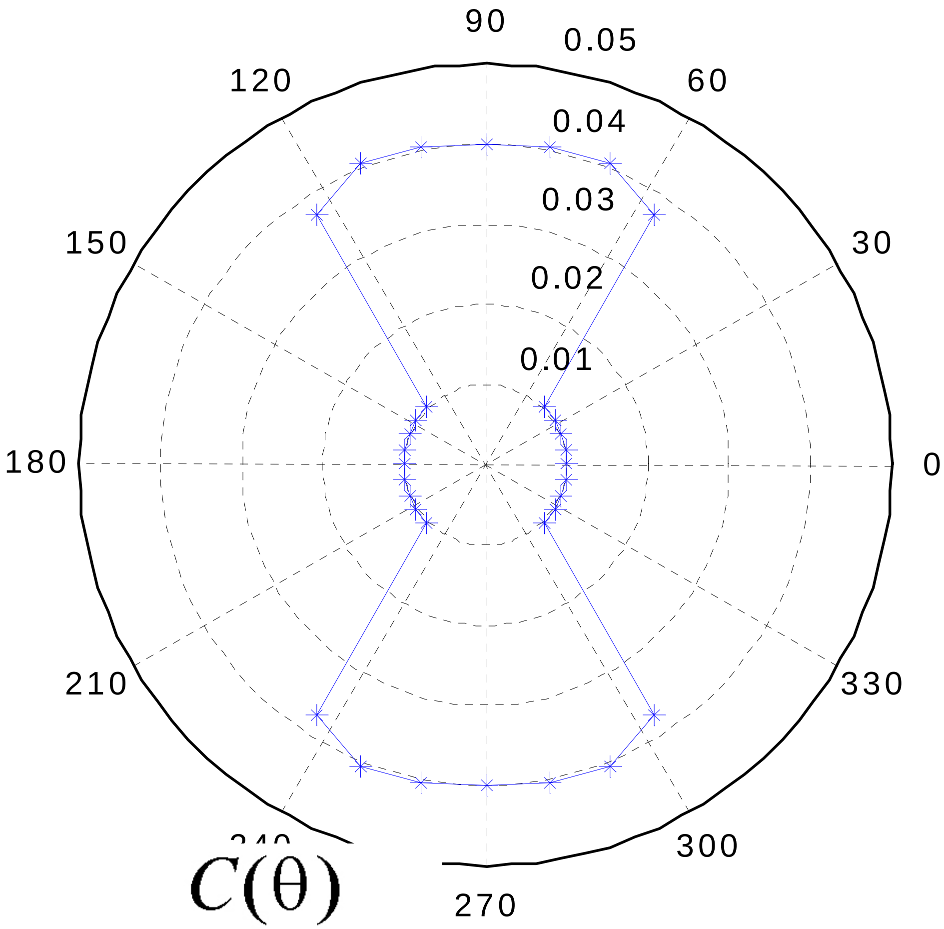
Anisotropic Surface



$$P(\boldsymbol{k}) = \frac{1}{\Delta w^2 \Delta q^2} \frac{C(\theta)}{\|\boldsymbol{k}\|^{8-2D(\theta)}}$$

Anisotropic Surface

Amplitude Coefficient Rose Plot



$$P(\boldsymbol{k}) = \frac{1}{\Delta w^2 \Delta q^2} \frac{C(\theta)}{\|\boldsymbol{k}\|^{8-2D(\theta)}}$$

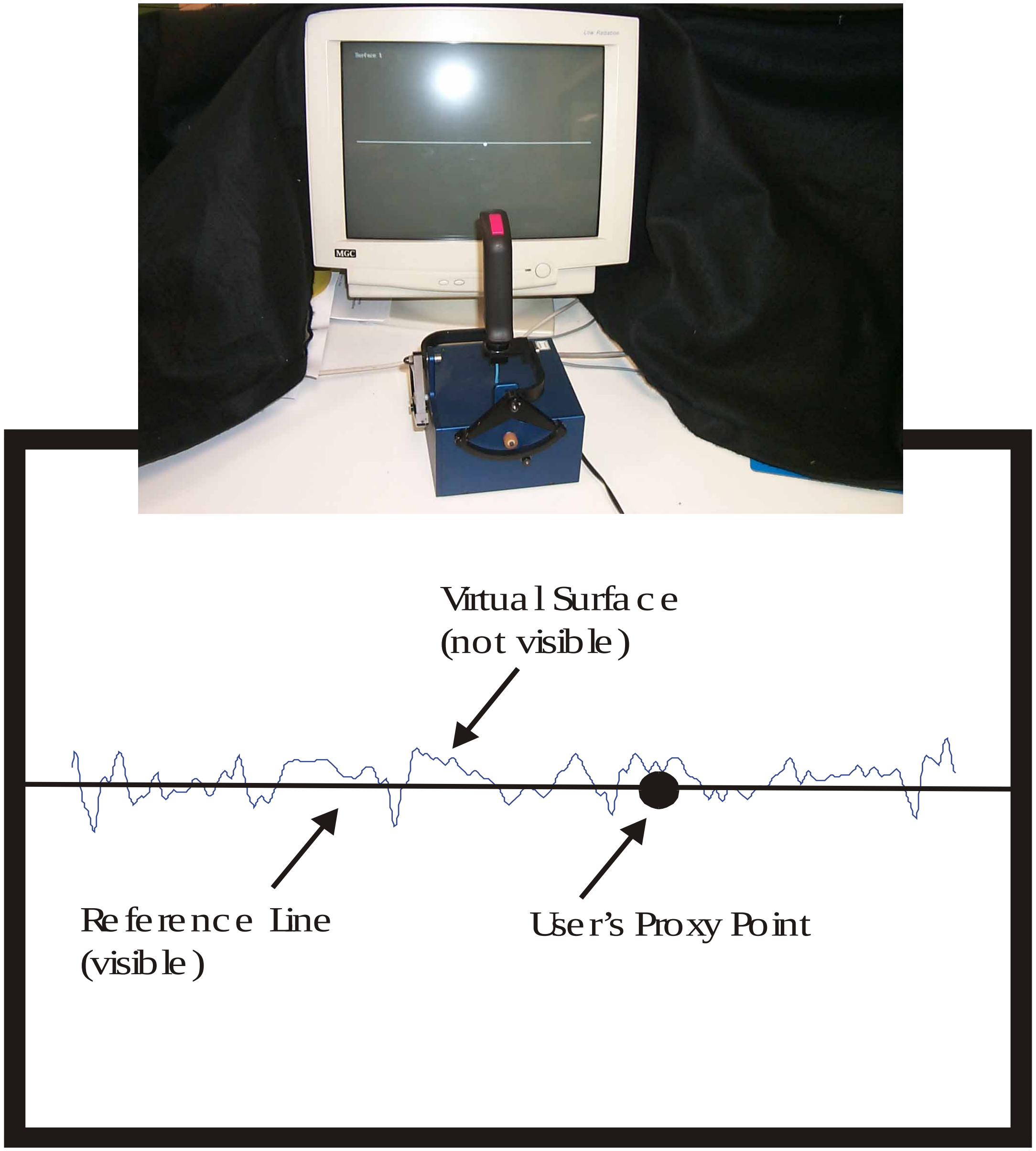
Surfaces

Perception Application

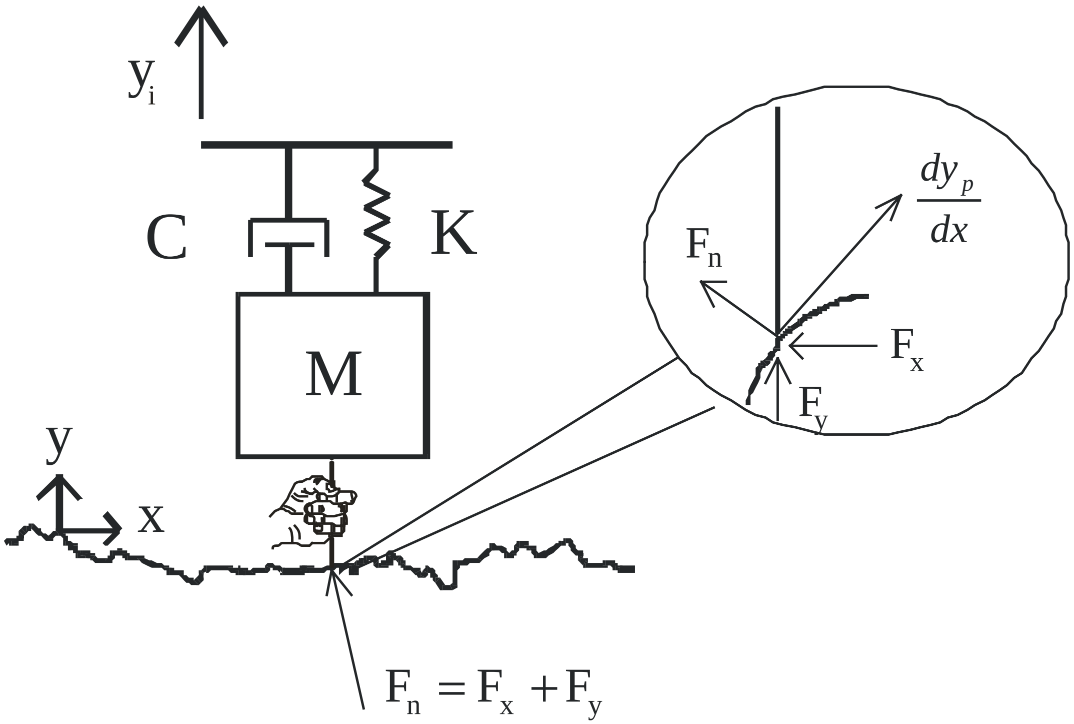
- Conduct a Roughness Perception Experiment with Virtual Profiles
  - Use Force Feedback Joystick to Display Fractal Surfaces
  - Synthesize Surfaces With Designed Fractal Parameters

Experiment Equipment

- Impulse Engine Force Feedback Joystick
  - Force - 8.9 N
  - Bandwidth - 120Hz
  - Position Resolution - .0309mm
  - Achievable Spatial Resolution
    - 20mm/s Exploration Speed
    - 0.1667 mm/sample
    - Spatial Frequency - 6 Hz



Haptic Interaction Model



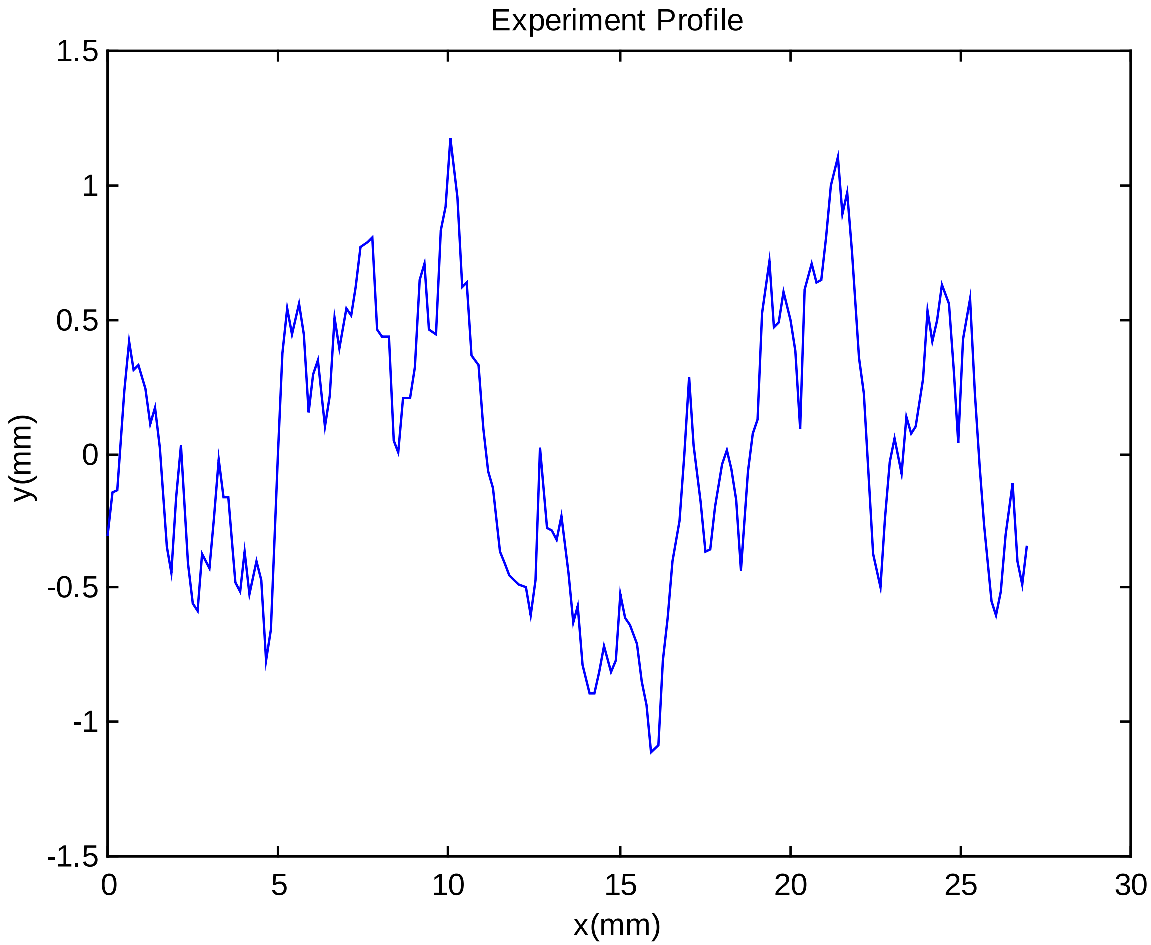
K=1.28 N/mm
M=1.85x10^{-6}g
C=4.6x10^{-5} N/(mm/s)

$$M\ddot{y}_p = K(y_i - y_p(x)) + C(\dot{y}_i - \dot{y}_p(x, t)) + F_y$$

$$F_n = \vec{F}_x + \vec{F}_y$$

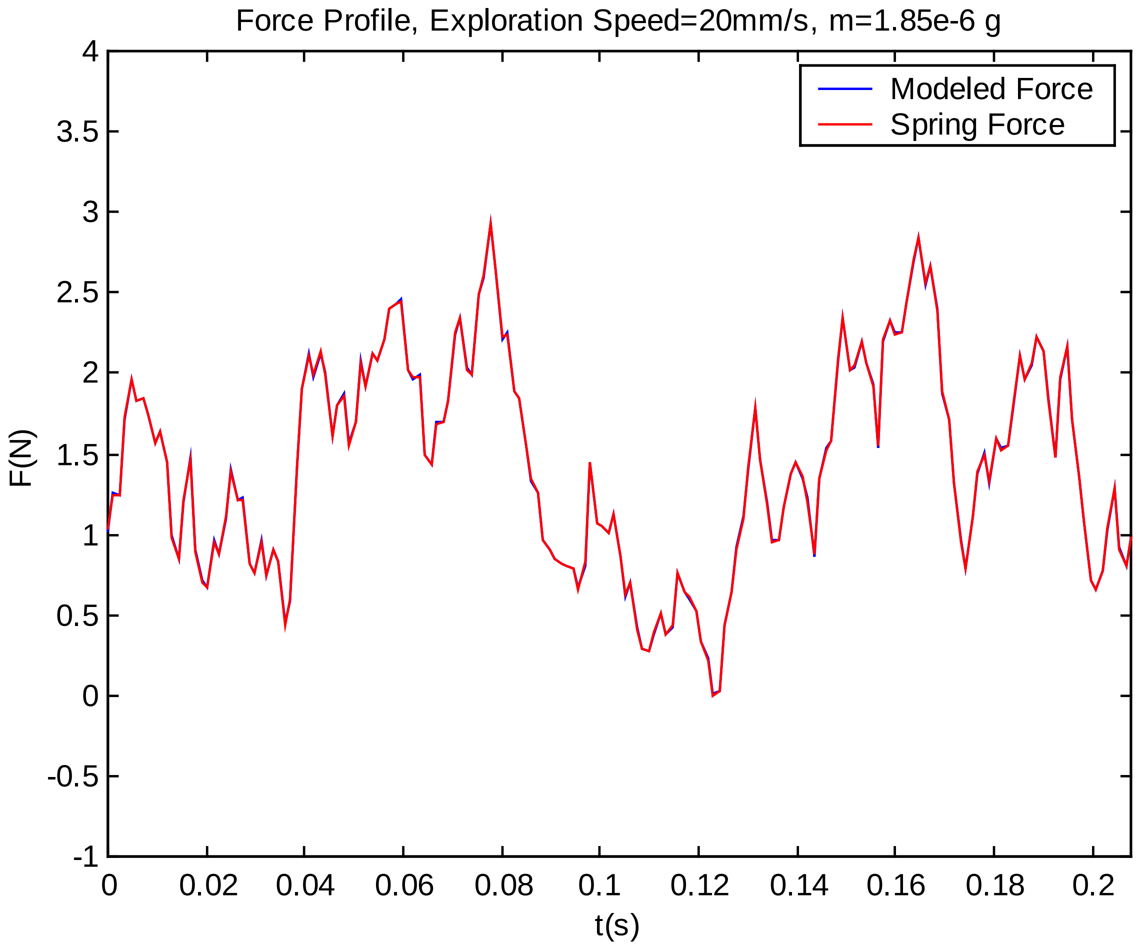
$$F_x = F_y\left(\frac{dy_p}{dx}\right)$$

Fractal Profile



Perception

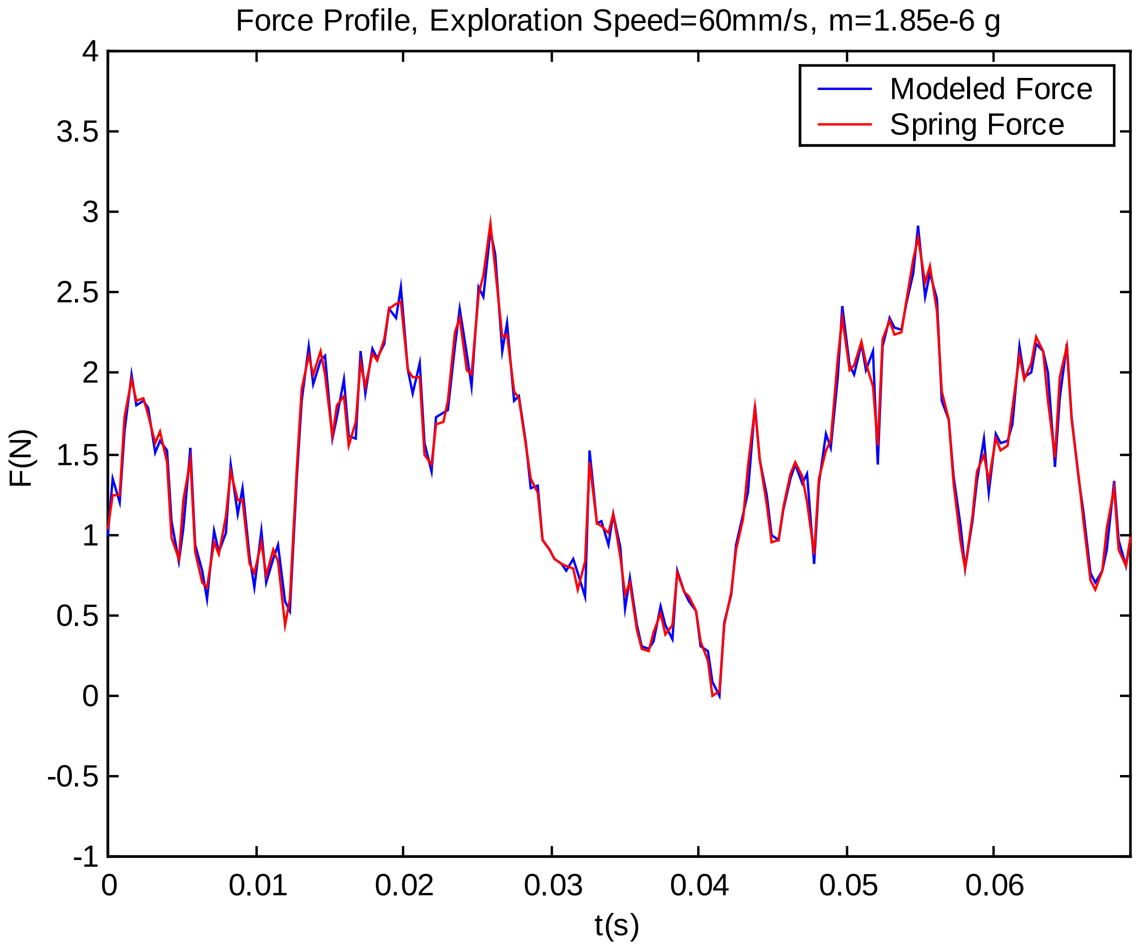
Force Profiles



V=20mm/s, M=1.85x10^{-6}g

Perception

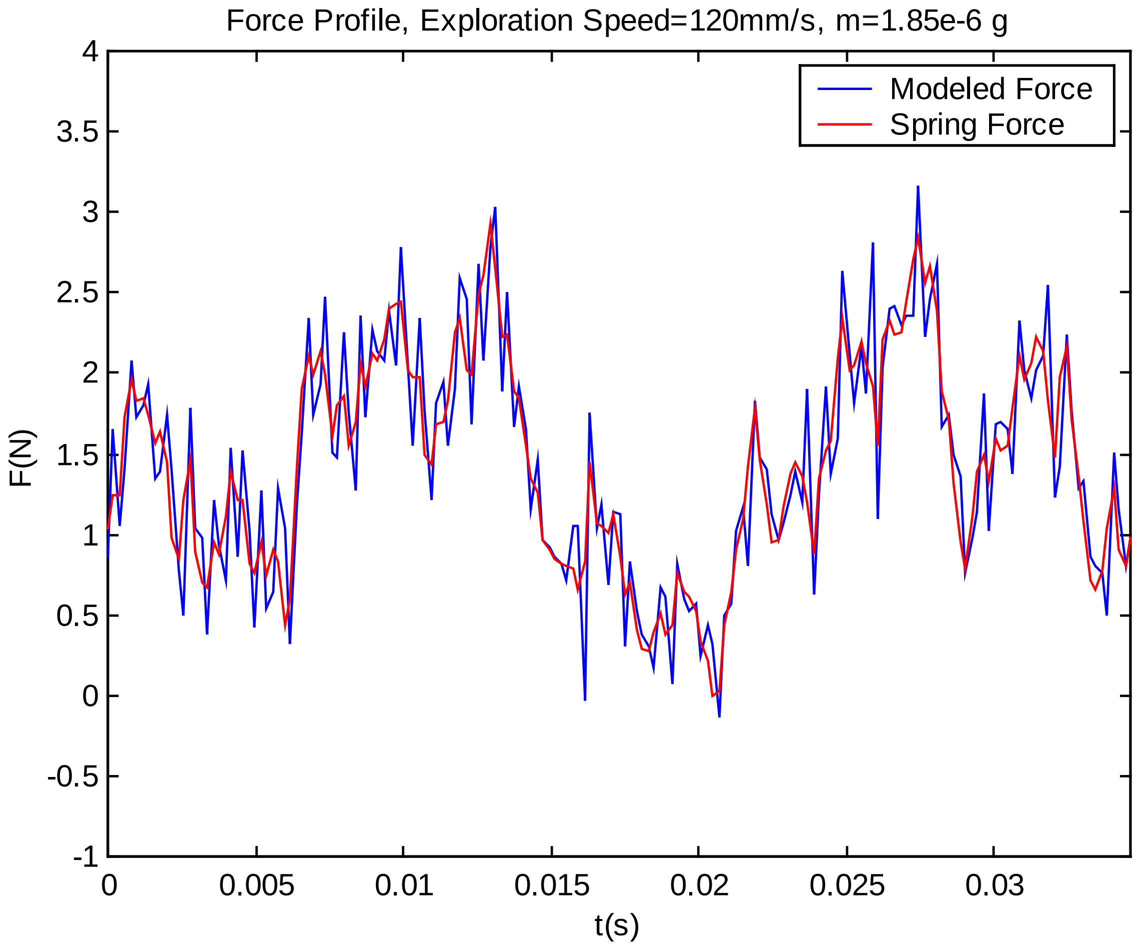
Force Profiles



V=60mm/s, M=1.85×10^{-6}g

Perception

Force Profiles



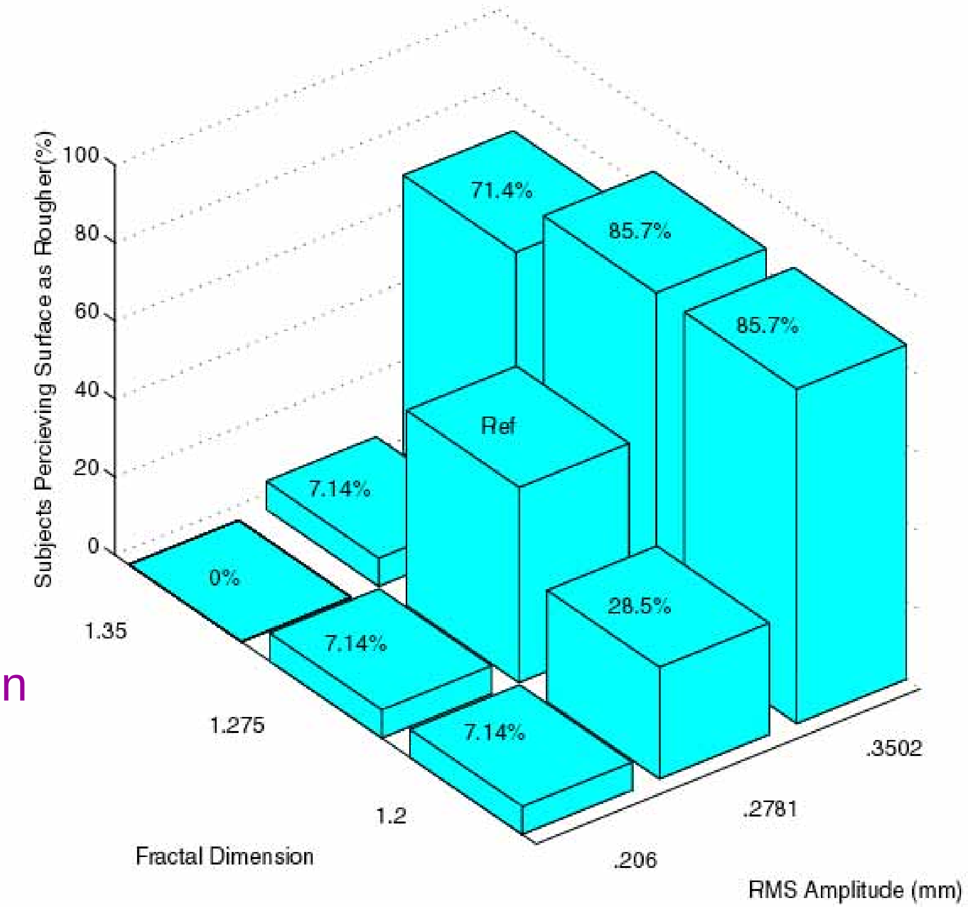
V=120mm/s, M=1.85x10^{-6}g

Perception

Related work: texture perception

- Roughness Perception of Metal Gratings
  - Lederman, 1974
  - Taylor & Lederman, 1975
- Using a Probe to Encode Vibration Information
  - Klatzky & Lederman,1998
  - Klatzky & Lederman, 1999.
- Fourier Series for Surface Identifying Characteristics
  - Wall & Harwin, 1999.

Perceived Roughness, Set 1 - Lower Dimensions and Amplitudes



Logistic Regression

- Wald Test
  $W = \beta_i / (SE(\beta_i))$
- p-values of *W*
  - Chi-Square Distribution
  - Significance α=.05
  - p-value W_{RMS}=7.8e-6
  - p-value W_D=.0128

Perception

Experiment Conclusions

- Factors Affecting Roughness Perception of Fractal Surfaces
  - RMS Amplitude most Important
  - For Dimensions 1.2-1.35 weak negative correlation with fractal dimension
    - Agreement with Other Perception Studies
- Way to Characterize Natural Rough Surfaces
  - Can generate random surfaces that mimic nature with quantifiable parameters