INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE CENTRATOM TRIESTE

H4.SMR/452-56

ADRIATICO CONFERENCE ON FOURIER OPTICS AND HOLOGRAPHY

6 - 9 March 1990

SURFACE STRUCTURE INVESTIGATION

Prof. K. Leonhardt

Institut für Technische Optik

Stuttgart, F.R. Germany

SURFACE STRUCTURE INVESTIGATION

K.Leonhardt

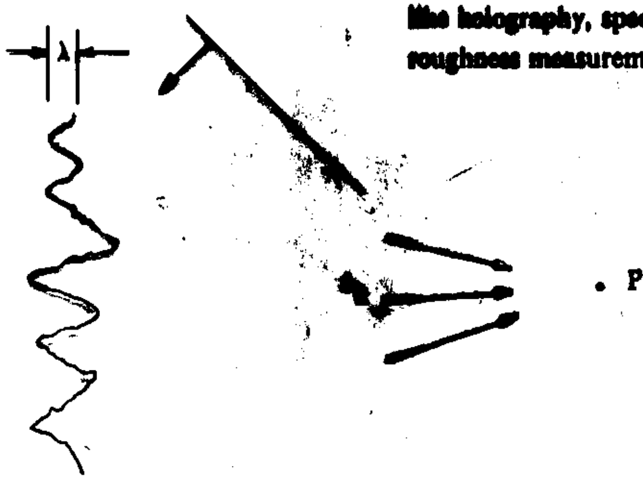
Institut für Technische Optik

Stuttgart

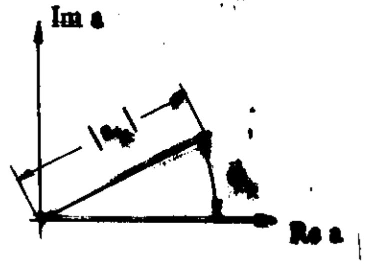
1. SURFACE AND SPECKLE
2. SURFACE DESCRIPTION
3. LIGHT ON ROUGH SURFACES
4. OPTICAL MEASURING METHODS
5. SURFACE ANALYSIS

SURFACE AND SPECKLE

Speckle phenomena: most surfaces of objects are optically rough; roughness is essential for many applications like holography, speckle metrology and optical roughness measurement.

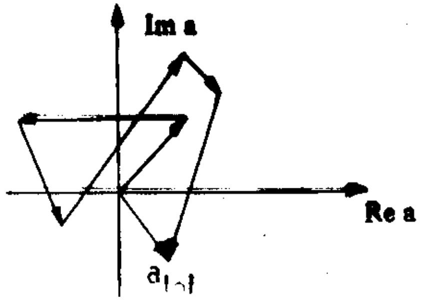


Component of the el. field in P: $a_k(x,y)$



$$a_k = |a_k| e^{i\phi_k}$$

Superposition of all contributions in P



$$a_{tot}(x,y) = \sum_{k=1}^{N} a_k(x,y)$$

Intensity in P: $I(x,y) = |a_{tot}(x,y)|^2$

$\phi_k = \frac{2\pi}{\lambda} 2h(x)$

mean Intensity $\langle I \rangle$

$\langle I \rangle$ large

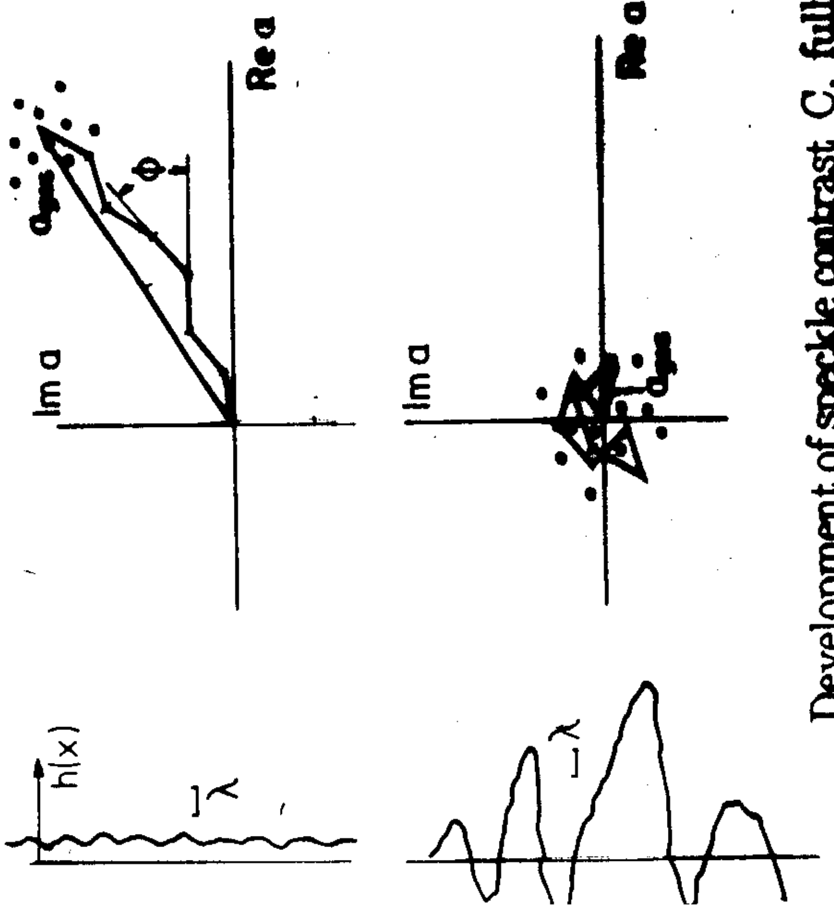
σ_I small

$C = \sigma_I / \langle I \rangle$

$\langle I \rangle$ = small

$\sigma_I \approx \langle I \rangle$

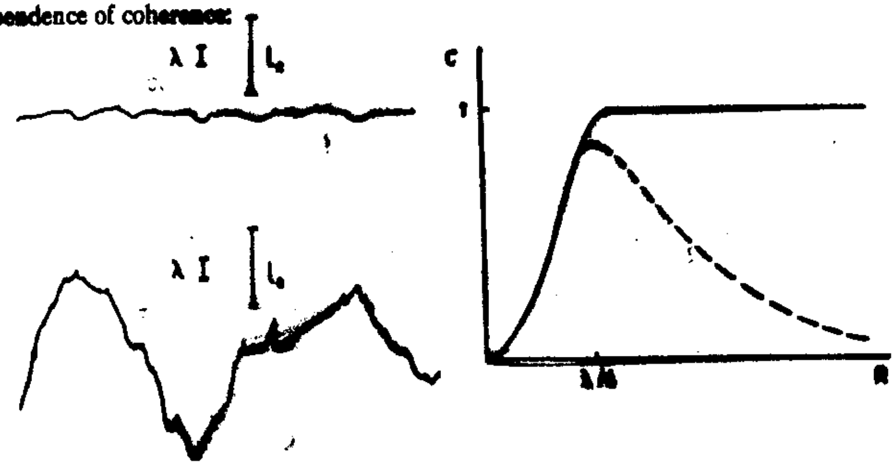
$C \rightarrow 1$



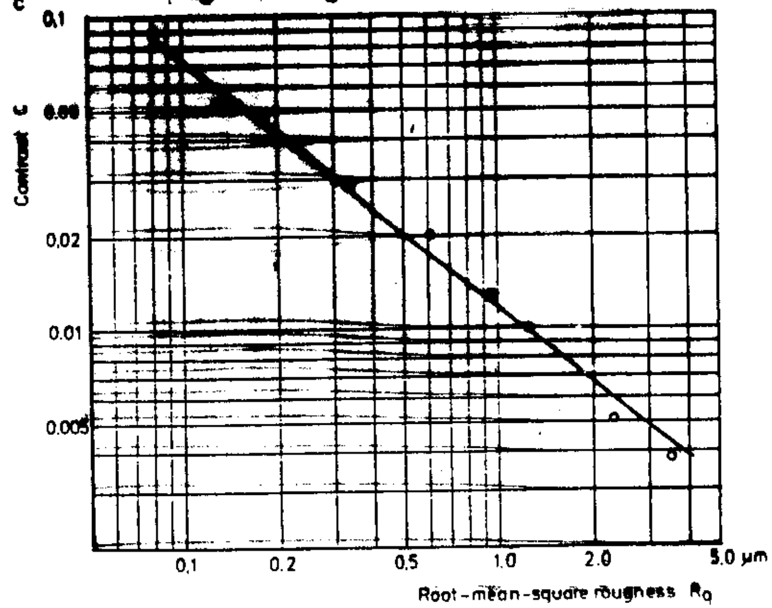
Development of speckle contrast C, fully coherent light

Light on rough surfaces

Dependence of coherence:

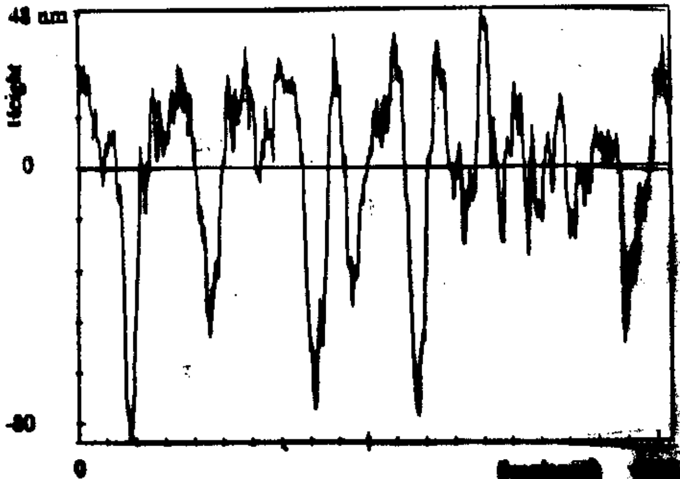


l_c = coherence length of the light



White light speckle contrast (K.Leonhardt and H.J.Tiziani Optica Acta 29 (1982) 493–499.)

Surface description



one dimensional scanning

detrended: a line, best fitted in the mean square sense is subtracted

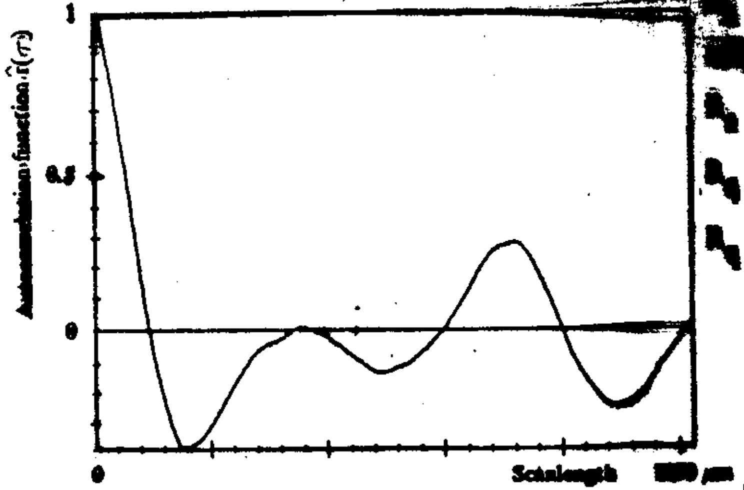
height h(x)
scanlength L
N discrete data

R_a (arithmetic) average roughness

$$R_a = \frac{1}{N}\sum_{i=1}^{N} |h_i|$$

$$R_q = \hat{\sigma}_h = rms =$$

$$R_q = \left(\frac{1}{N}\sum_{i=1}^{N} h_i^2\right)^{0.5}$$



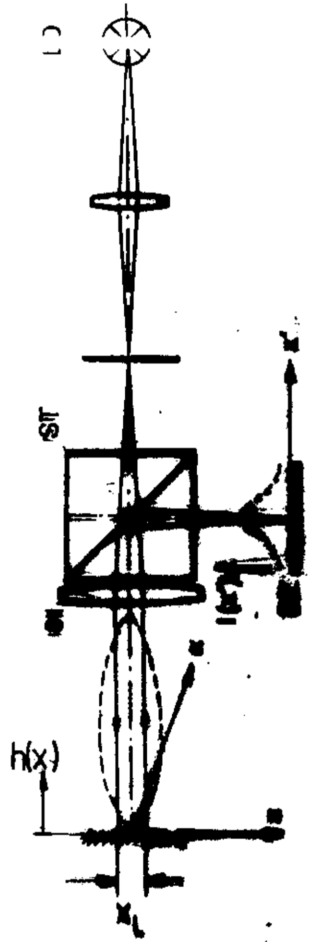
Autocorrelation $r(\tau_x)$ of the heights h(x):

$$r(\tau) = \frac{1}{\sigma_h^2}\int_{-\infty}^{+\infty} h(x)\, h(x+\tau)\, dx$$

with N discrete data we get the estimate:

$$\hat{r}_k = \frac{1}{N-k}\sum_{i=1}^{N-k} h_i\, h_{i+k} \qquad \text{with } \tau_x = k\,\Delta x$$

more descriptors: ... Surface Analysis



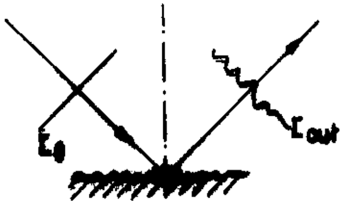
x_L small: distinct speckle pattern

x_L large: scattered light Indicatrix

Halo on array

backscattered light:

$$a(x) = a_0\, \underbrace{rect\left(\frac{x}{x_L}\right)}_{spot}\, \underbrace{\exp\left\{i\, 2\pi \frac{2\, h(x)}{\lambda}\right\}}_{phase\ screen}$$



$$\text{in } x': \quad a(x') = \int_{-\infty}^{+\infty} a(x)\; e^{i 2\pi R x}\, dx$$

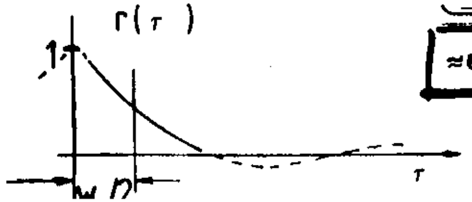
$$\text{with } R = \frac{-x'}{\lambda\, f'}$$

Intensity $I = a^* a$

$$I(x') = \int_{x_1=x_2=-x_L/2}^{+x_L/2}\int \exp\left\{i 2k\left[\left(h(x_2) - h(x_1)\right)\right]\right\} \exp\left\{i 2\pi R(x_2 - x_1)\right\} dx_1\, dx_2$$

Expected value :

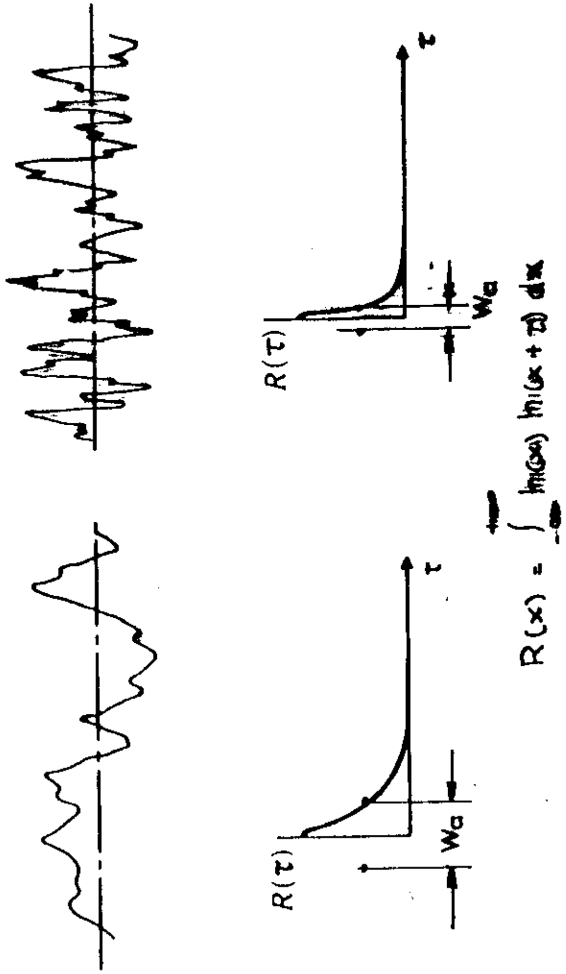
$$E\left\{I(x')\right\} = \int_{x_1=x_2=-x_L/2}^{+x_L/2}\int E\left\{\exp\left[i 2k\left(h(x_2) - h(x_1)\right)\right]\right\} \exp\left\{i 2\pi R(x_2 - x_1)\right\} dx_1\, dx_2$$

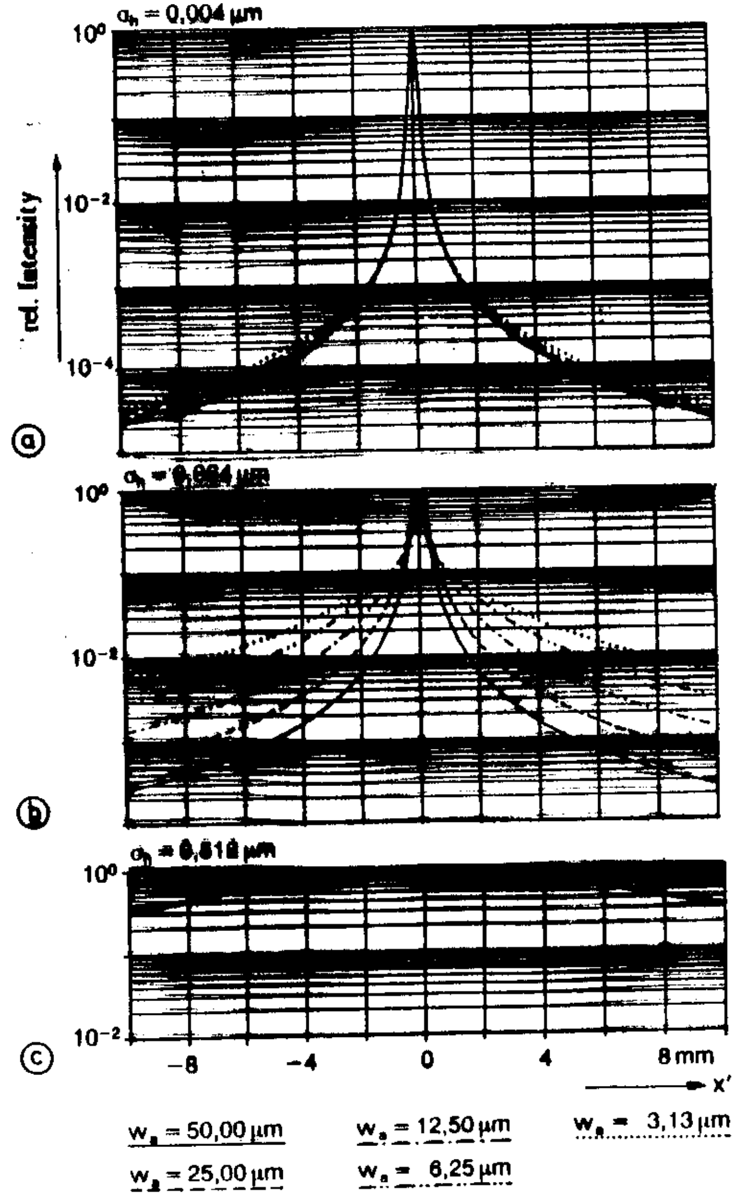


$$\approx \exp\left\{-4 k^2 \sigma_h^2 \left(1 - r(\tau)\right)\right\}$$

with $\sigma_h^2 = R_q^2$ = variance of h(x)

$r(\tau)$ = autocorrelation function of h(x)


R(τ)
τ
Wa
R(x) = ∫ h(x) h(x + τ) dx


σh = 0,004 µm
10⁰
10⁻²
10⁻⁴
rel. Intensity
a
b
c
-8
-4
0
4
8 mm
x'
wa = 50,00 µm
wa = 25,00 µm
wa = 12,50 µm
wa = 6,25 µm
wa = 3,13 µm

Optical methods of measuring rough surfaces

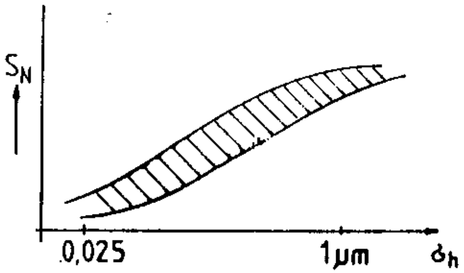
Scattering by evaluation of the radius of gyration (Rodenstock RM 400)

$S_N = \text{const}\ \Sigma (x_i - \bar{x}_i)^2\ I_i^2$

I_i = intensity on the i th diode

x_i = distance of the i th diode from center

$\bar{x}$ = distance of the center of gravity



in reality

$S_N = f(\sigma_h, w_a, \ldots)$

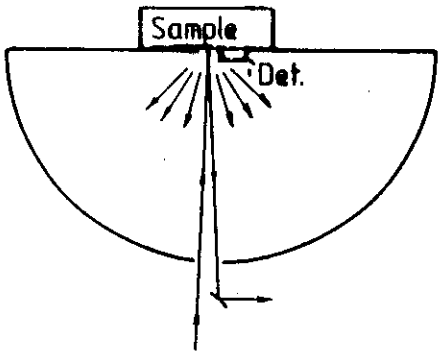
applications:

control of finish process

in mass-production

(comparative value)

Total integrated scatter TIS



$$TIS = \frac{I_{R,diffuse}}{I_{R,total}}$$

$$= 1 - e^{-4k^2\sigma_h^2}$$

$(w_a \to 0)$

$$\boxed{\approx 4k^2\sigma_h^2}$$

for $\sigma_h \ll \lambda$

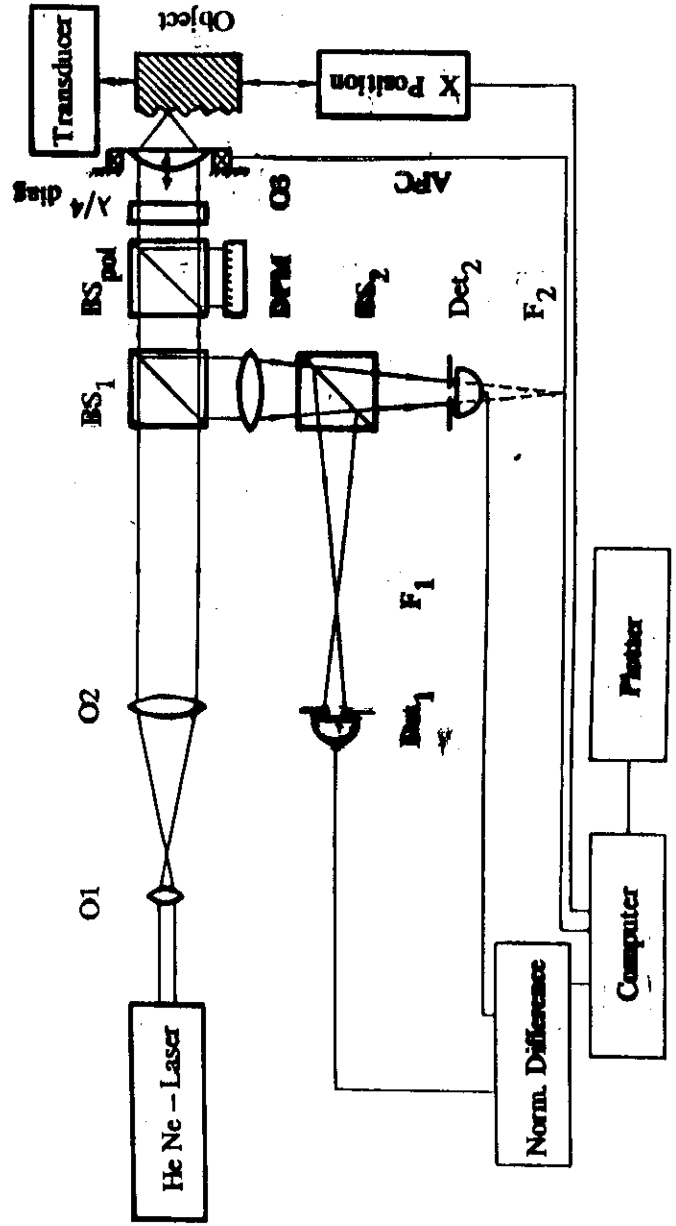
at $\lambda \approx 600$nm

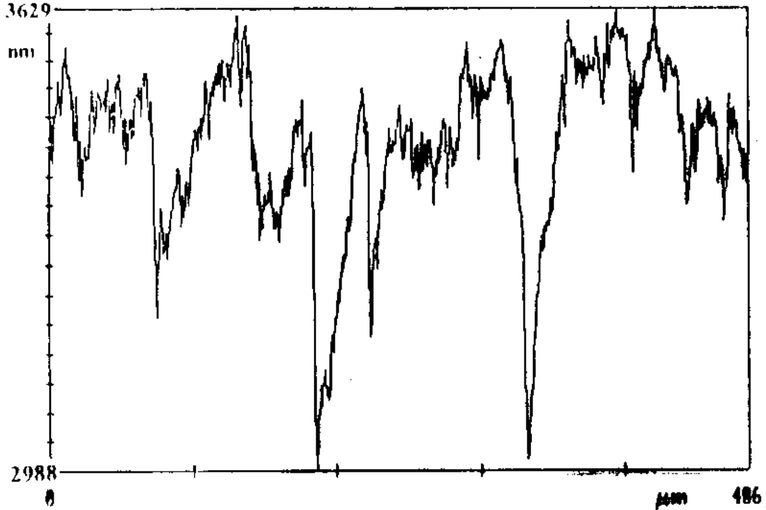
$\sigma_h \leq 20$ nm

application : polished

and superpolisched surfaces

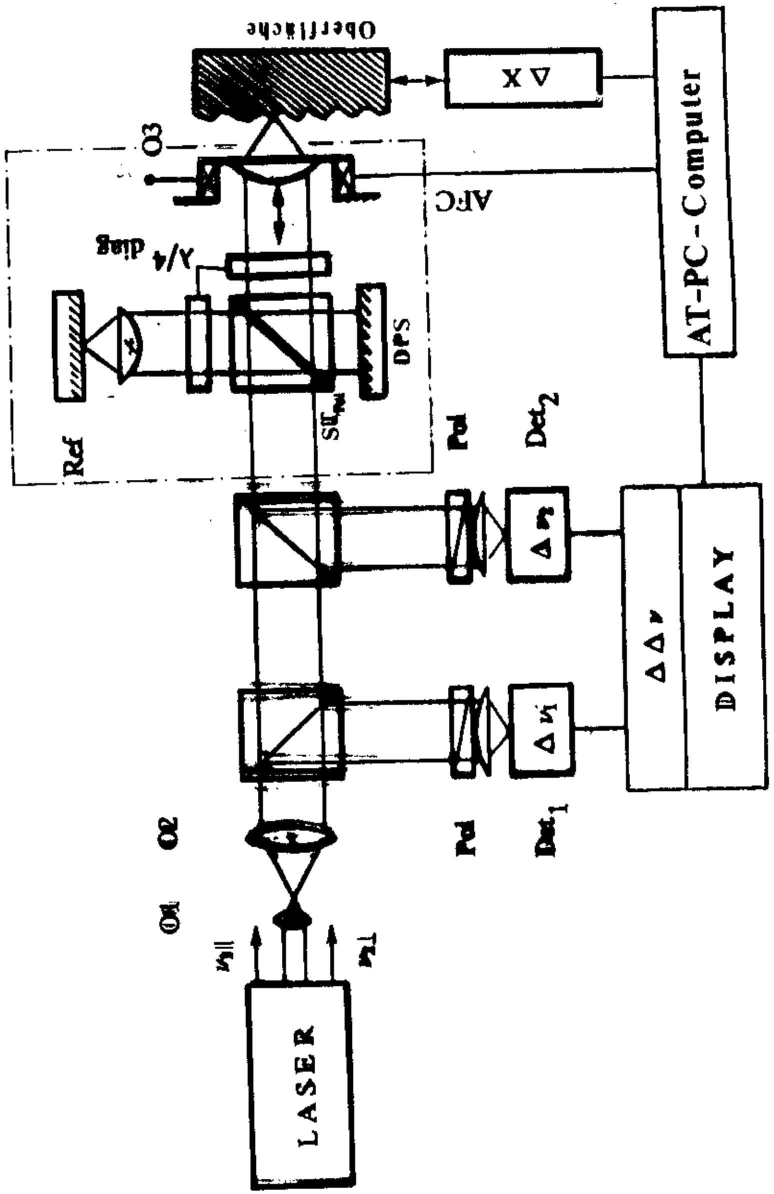
in reality $TIS = f(\sigma_h, w_a, \ldots)$

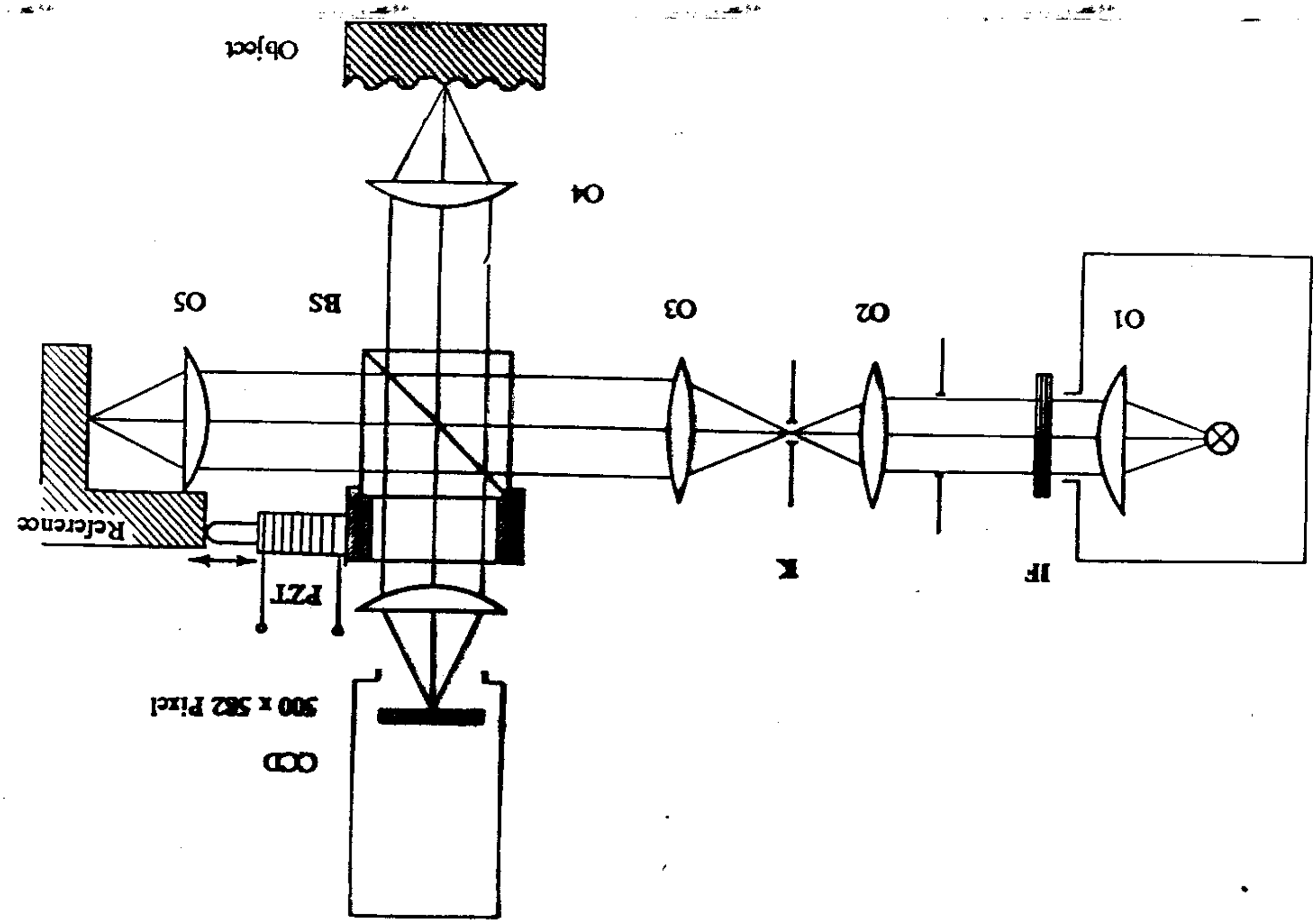


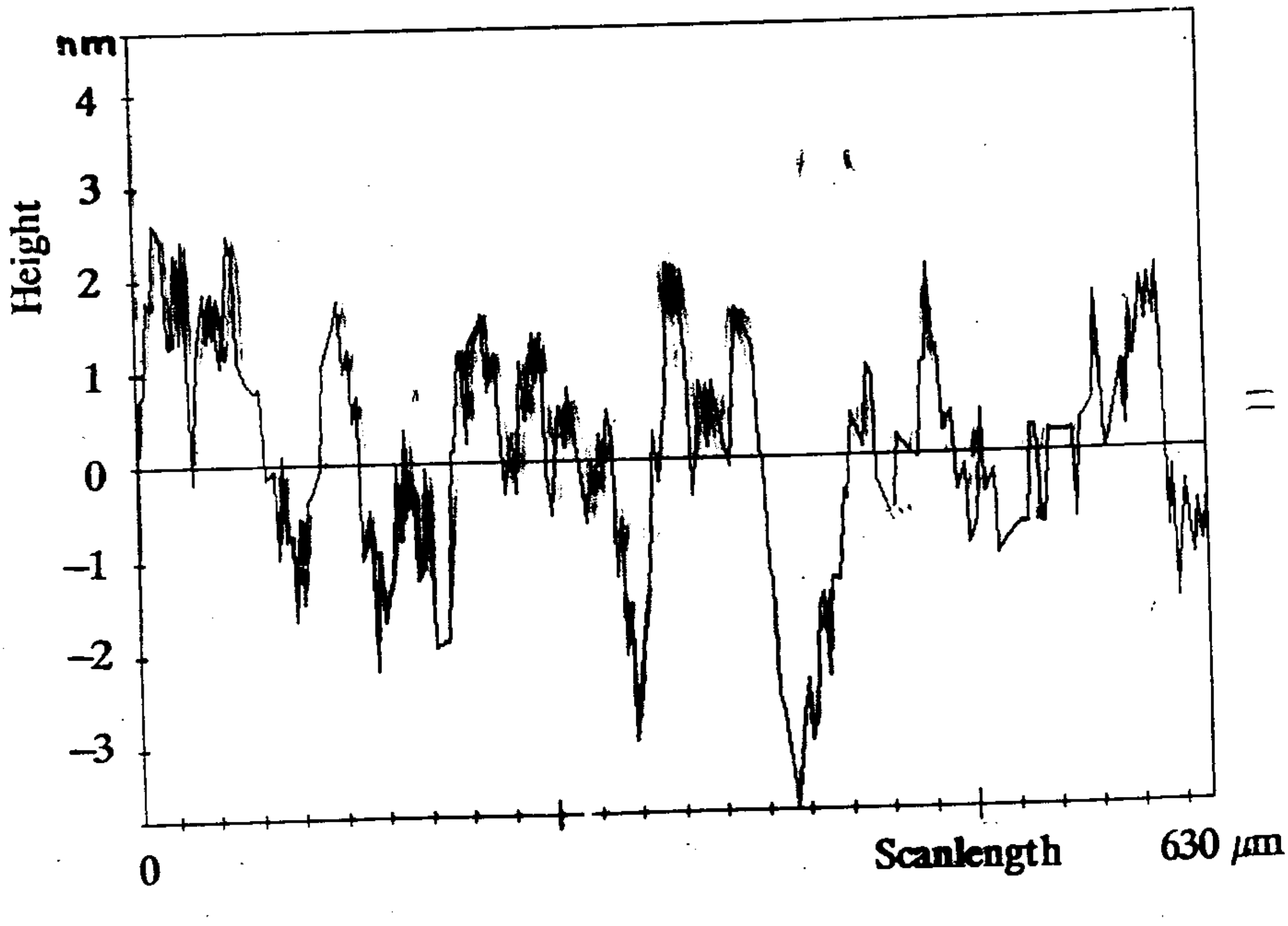


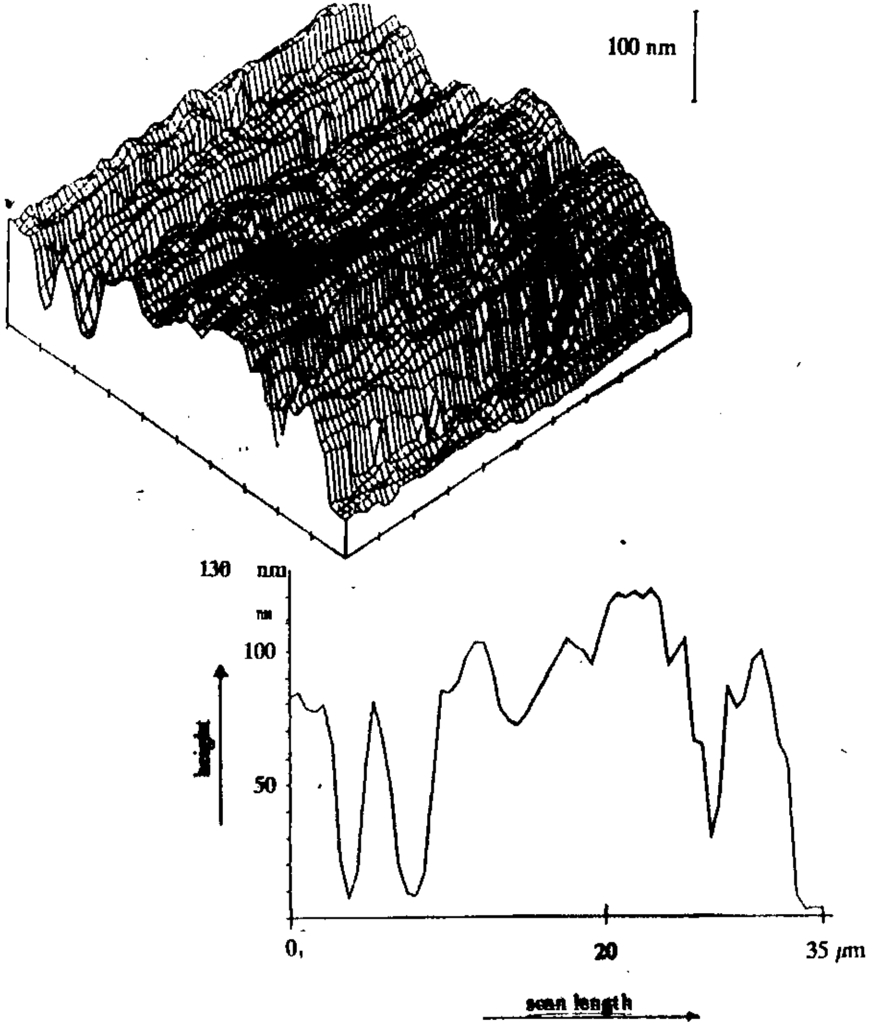
Anzahl der Messpunkte : 1024

CERAMIC GASKET RING
PHOTOMETRIC PROFILOMETER, DOUBLE-PASS



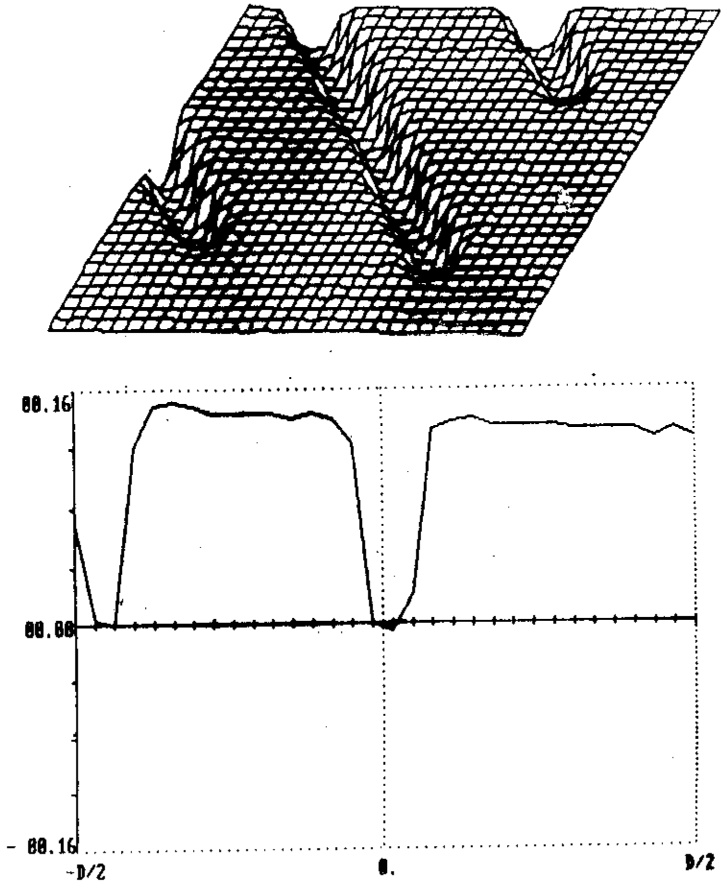

Object
O4
O5
BS
O3
O2
O1
Reference
PZT
K
IF
500 x 582 Pixel
CCD


nm
4
3
2
1
0
–1
–2
–3
Height
0
Scanlength
630 μm

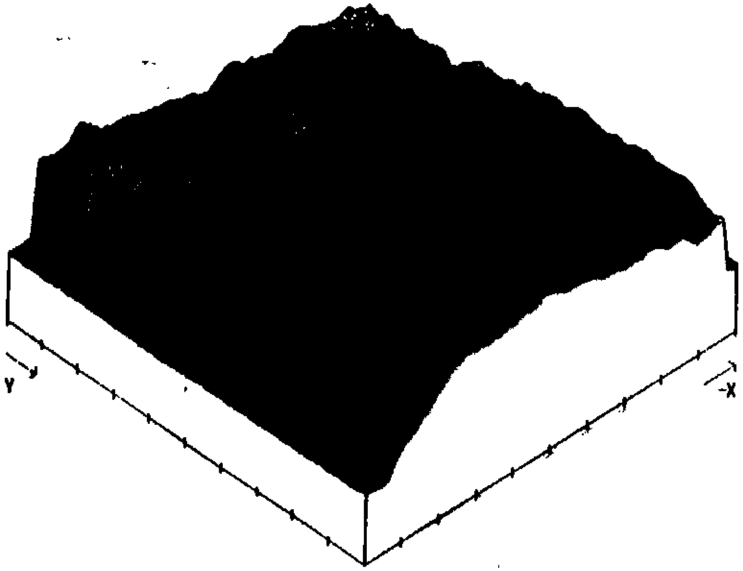


Wavelengths	: 618.6 nm / 550 nm
No. of values	: 64 x 64
measured height	: 150 nm

Institut für Technische Optik	Rough surface 2 wavelengths method	K.Leonhardt S. Al Fakir

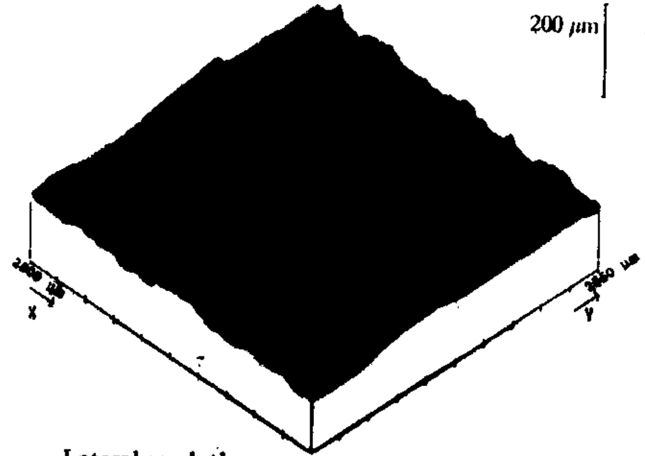


SI-PLATE: ELECTRON-BEAM LITHOGRAPHY
W ≈ 1 μM ; H ≈ 0.15 μM



Deep–drawing steel surface
with oil film supporting structure

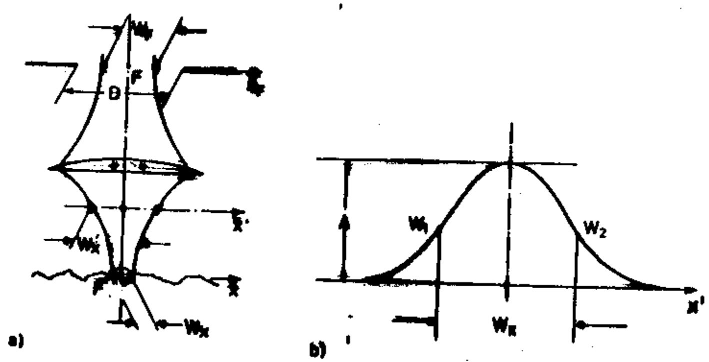
Surface Analysis



3–D Topography on a
2–D scanning raster

End milled surface,
grooves in form of
crossing arcs

Lateral resolution:



$w_x = \frac{\lambda\ f'}{w_F}$

$(w_x < D)$

num. aperture

$NA = D/(2 f')$

lateral res. is
a function of

$V = D/w_F$

Aperture ratio

$Dx_{lat} = \frac{\lambda\ V}{2\ NA}$

Deconvolution:

$h_{meas.} = P(x) * h(x) + noise$

with P(x) point spread function of the measuring system

$$h(x,y) \xrightarrow{2DFFT} \tilde{h}(f_x,f_y)$$

$$h(f_x,f_y) \cdot \tilde{P}_{inv}(f_x,f_y) = \tilde{h}_{dec}(f_x,f_y)$$

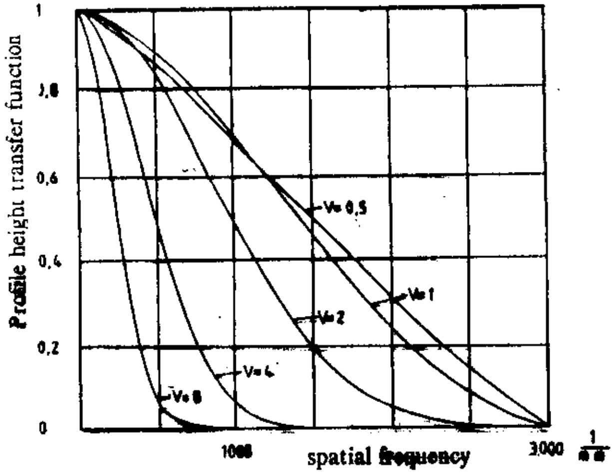
$$\tilde{h}_{dec}(f_x,f_y) \xrightarrow{inv2DFFT} h_{dec}(x,y)$$

with $\tilde{P}_{inverse}(f_x,f_y) = 1/\ \tilde{P}(f_x,f_y)$ for P real and symmetric

if noise cannot be neclected: Wiener filter.

Profile height transfer function $P(f_x)$

of the ITO Stuttgart heterodyne profilometer (theoretical curves)



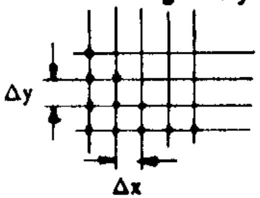
$\lambda = 633nm$
num. aperture
NA = 0.95

diffraction limited

large area detector

Aperture ratio $V = D/w_F$ w_F beam waist

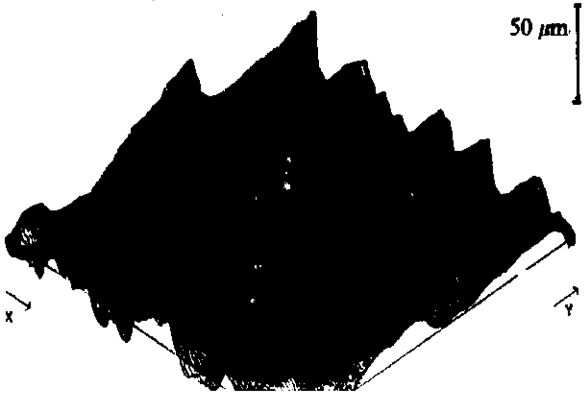
aliasing for $f_g > f_{Ny}$, $F_{Ny} = \frac{1}{\Delta x \cdot 2}$



sampling points on object

for convolution:

$$P'_{invers} = \begin{cases} P_{invers}(f_x, f_y) & \text{for } |f_x|,|f_y| < 2 f_{Ny} - f_g \\ 0 & \text{otherwise} \end{cases}$$



"detrended" topography a plane, best fitted in the mean square sense is substracted

Autocorrelation and spectral representation of the suface

Spectral analysis:

- comparing results of different measuring techniques
- modelling typical spectra
- understanding the finishing process (vibrations)

$h(x,y)$ deconv. random truncated $\xleftrightarrow{\text{2DFFT}}$ $h(f_x,f_y)$ random truncated not very usefull

↓ Correlation ↓ $|h|^2$

$C'_2(\tau_x,\tau_y)$ $\xleftrightarrow{\text{2DFFT}}$ $S'(f_x,f_y)$

↓ Averaging ↓ Averagimg

$\hat{C}_2(\tau_x,\tau_y)$ $\xleftrightarrow{\text{2DFFT}}$ $\hat{S}(f_x,f_y)$

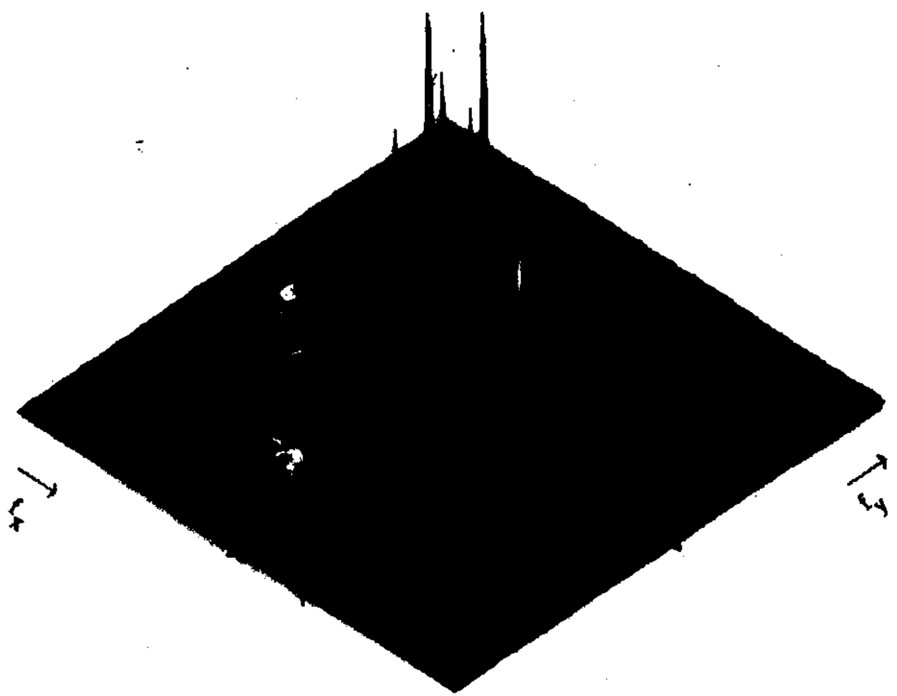
Estimate of the Correlation function

Estimate of the Power spectral density

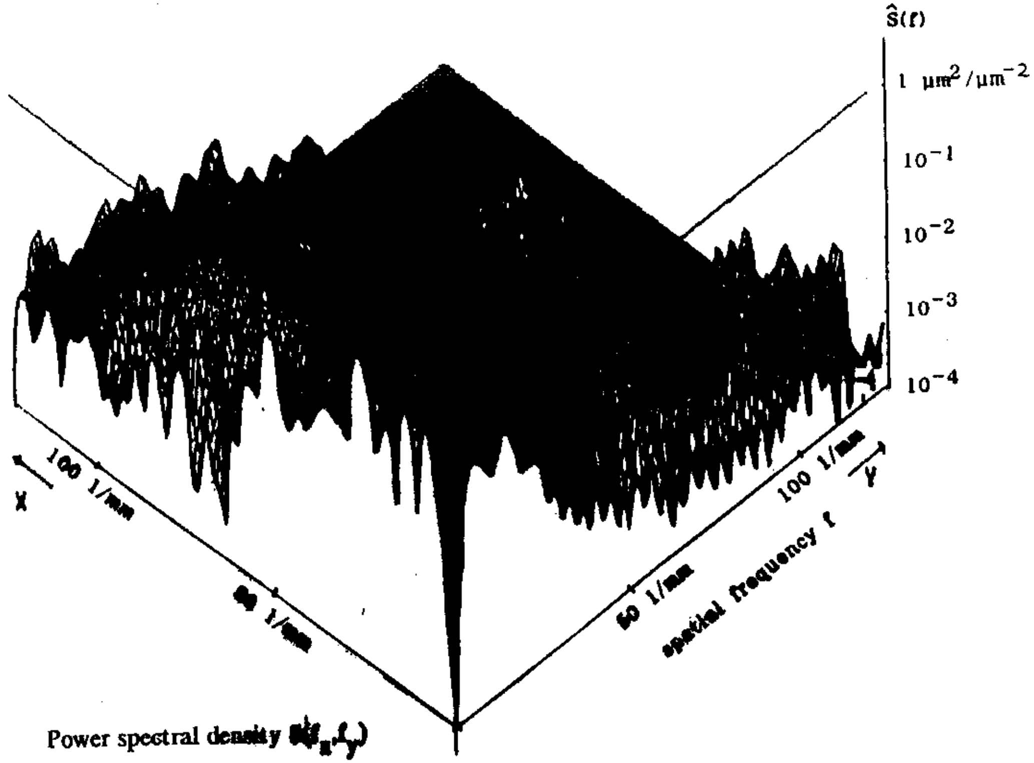
↓

$$\frac{C_2(\tau_x,\tau_y)}{C_2(0,0)} = r(\tau_x,\tau_y)$$

Autocorrelation



Power spectal density - schematic representation



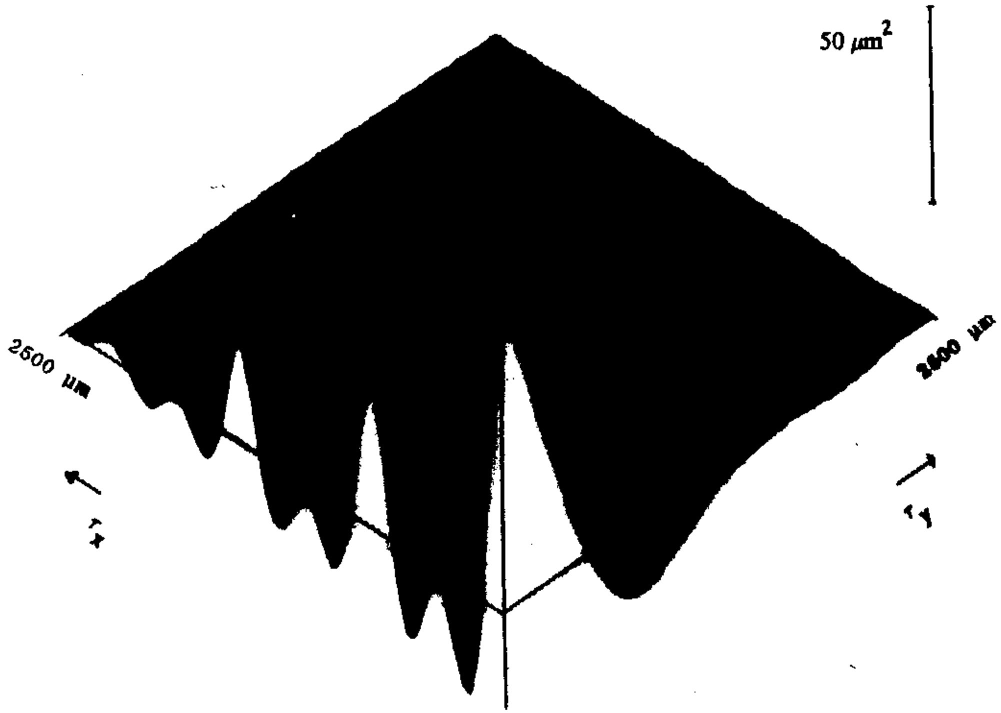
Power spectral density $S(f_x,f_y)$

–finding and measuring **weak periodicities** { **spatial frequency**, **direction**, **(magnitude)**

ripple marks
waviness

– on optical surfaces: **high spatial frequencies contribute to straylight**
low spatial frequencies contribute to wavefront deformations (aberrations).

Intensity in the Fourier plane:
for $\sigma_h < \lambda/20 \quad I(f_x,f_y) = \mathrm{const} \cdot S'(f_x,f_y)$



Autocovariance function or
Correlation function $C_2'(\tau_x, \tau_y)$

even function with

$C_2(\tau_x = 0, \tau_y = 0) = \sigma_h^2 = R_q^2 = (rms)^2$ = max. of C_2

periodic components appear with their original period

$V_A = w_{ay} / w_{ax}$

$V_a \rightarrow V_a max$ with the scan–raster oriented exactly perpendicular and parallel to the lay of the structure

$V_a max$: measure of anisotropy.