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INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4.SMR/1058-16

# WINTER COLLEGE ON OPTICS

**9 - 27 February 1998**

***- Electronic Speckle Pattern Interferometry and Electronic Shearography***

***- Particle Sizing***

**A. Sona**

**CISE, Milano, Italy**

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# Winter College on Optics

## Laboratory session

**1)- Electronic Speckle Pattern Interferometry**

**For in plane and out of plane deformation measurements**

**2) - Electronic Shearography**

**For the measurement of deformations gradients or strains**

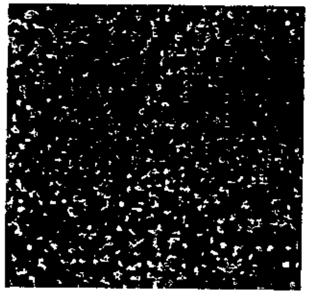
**by Michel HONLET**

**the equipment and the demo material was kindly provided by dr ETTEMEYER Gmbh &Co**

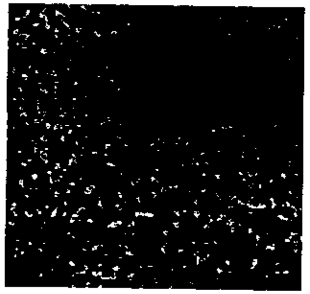
**Trieste, February 1998**

# Speckle-Interferometry

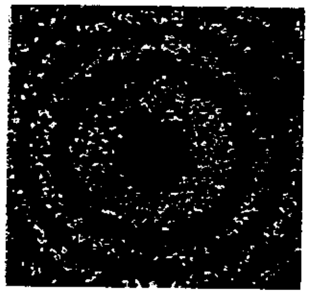
## Principle of speckle measuring techniques



Speckle pattern of the undeformed surface



Speckle pattern of the deformed surface



Difference of the two speckle patterns

The principle of speckle-interferometry uses the ability of laser light for interference. [illegible] is entirely [illegible] image [illegible] the object is recorded by a video camera. The lightwaves which are reflected by single points on the [illegible]'s surface interfere and produce a [illegible] speckle pattern. This represents the microstructure of the object's surface in combined form. [illegible] speckle pattern is superimposed [illegible] reference light, by a different measuring technique. The interference between the reference light and the speckle pattern produces a new speckle pattern which defines a position of interest on the

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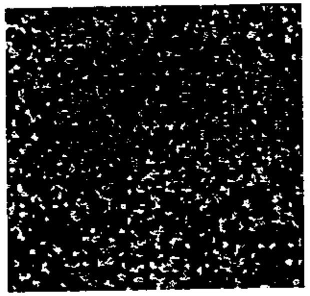
Technique

Exit | ESPI | Shearography | Dual Illumination

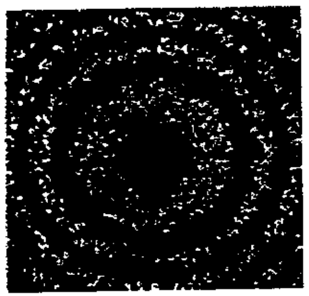
# Speckle-Interferometry

**Principle of speckle measuring techniques**



**Speckle pattern on the undeformed surface**

**Speckle pattern on the deformed surface**



**Difference between the two speckle patterns**

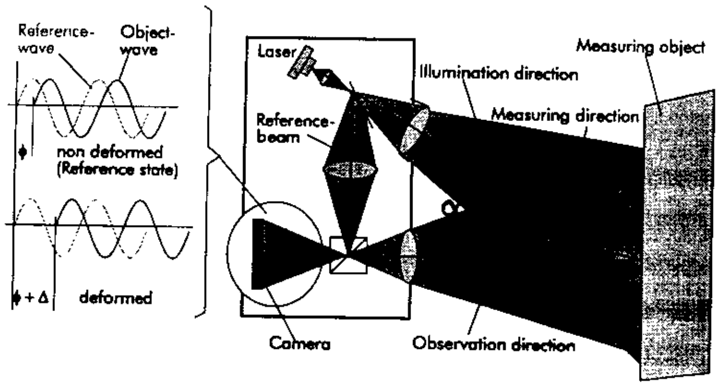
object's surface. This speckle pattern is stored in the image processing computer [illegible] reference [illegible] object [illegible] By comparison with the reference pattern, correlation fringes are produced which represent the displacement respectively deformation component of the object's surface in the measuring direction which is defined by the applied measuring technique. The evaluation software ISTRA for Windows, analyzes and counts these correlation fringes, and transforms them automatically into a quantitative set of deformations or strain data.

Technique | Sensors | Applications | Literature

# Speckle-Interferometry

**Principle of Electronic Speckle Pattern Interferometry (ESPI)**

OUT OF PLANE




The measuring sensitivity can be calculated by the following formula:

$$d = \frac{N \cdot \lambda}{2 \cdot \cos(\alpha/2)}$$

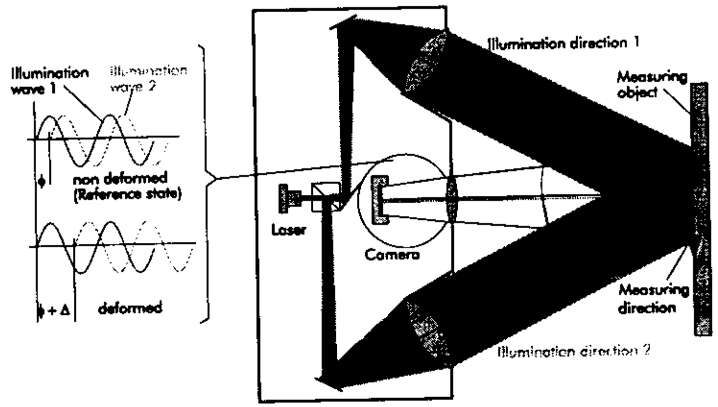
with

- d: deformation component of the object point in the measuring direction
- N: fringe order at the measuring point
- λ: wavelength of the used laser light
- α: angle between illumination and observation direction

# Speckle-Interferometry

**Principle of the dual illumination method**

IN PLANE




The measuring sensitivity can be calculated by the following formula:

$$d = \frac{N \cdot \lambda}{2 \cdot \sin(\alpha/2)}$$

with

- d: deformation component of the object point in the measuring direction
- N: fringe order at the measuring point
- λ: wavelength of the used laser light
- α: angle between the two illumination directions

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**Technique**

Exit | ESPI | Shearography | Dual Illumination

# Speckle-Interferometry

**The measuring sensitivity can be calculated by the following formula:**

$$\frac{d}{s} = \frac{N \cdot \lambda}{2 \cdot \cos(\alpha/2)}$$

with

- d: deformation component of the object point in the measuring direction
- s: shear distance
- N: fringe order at the measuring point
- λ: wavelength of the laser light
- α: angle between illumination and observation direction

The result represents the relative movement of the object, respectively the deformation gradient in the direction of the two sheared images. The shear distance (distance between the two superimposed object points) defines the sensitivity of this technique. The measuring direction is in the centerpoint between illumination and observation direction.

Technique | Sensors | Applications | Literature

# Speckle Pattern


- Speckle size due to the object:

  $\sigma_0 = 1.22\lambda \, L/D$ (in the far field) $\frac{\lambda}{a}$

  L - distance from the screen

  a - diffusing particles size

  D - illuminated area diameter

- Speckle size due to the lens:

  $\sigma = 1.22\lambda \, f/d = 1.22\lambda F$ (in the image plane)

  f - focal length

  d - aperture diameter

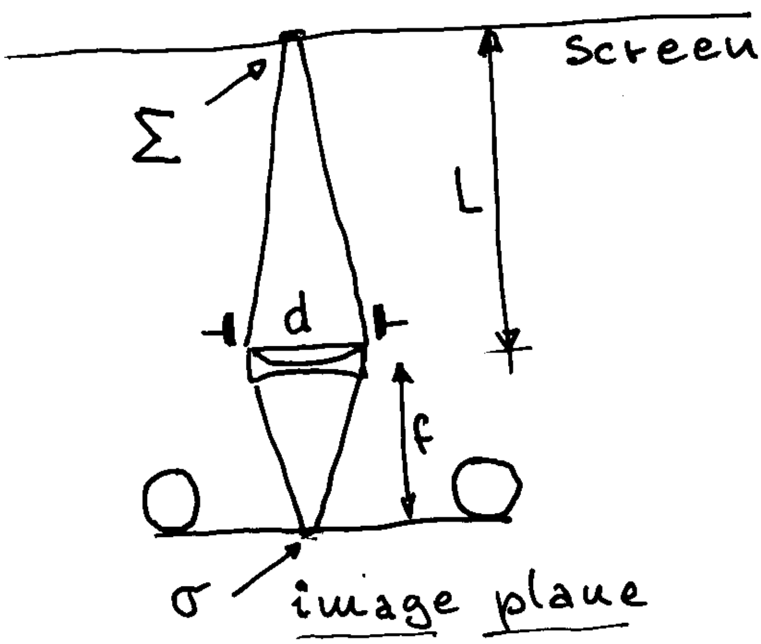
- Speckle size due to the lens:

  $\Sigma \simeq 1.22\lambda \frac{f}{d} \times \frac{L}{f} = 1.22\lambda F \cdot m$

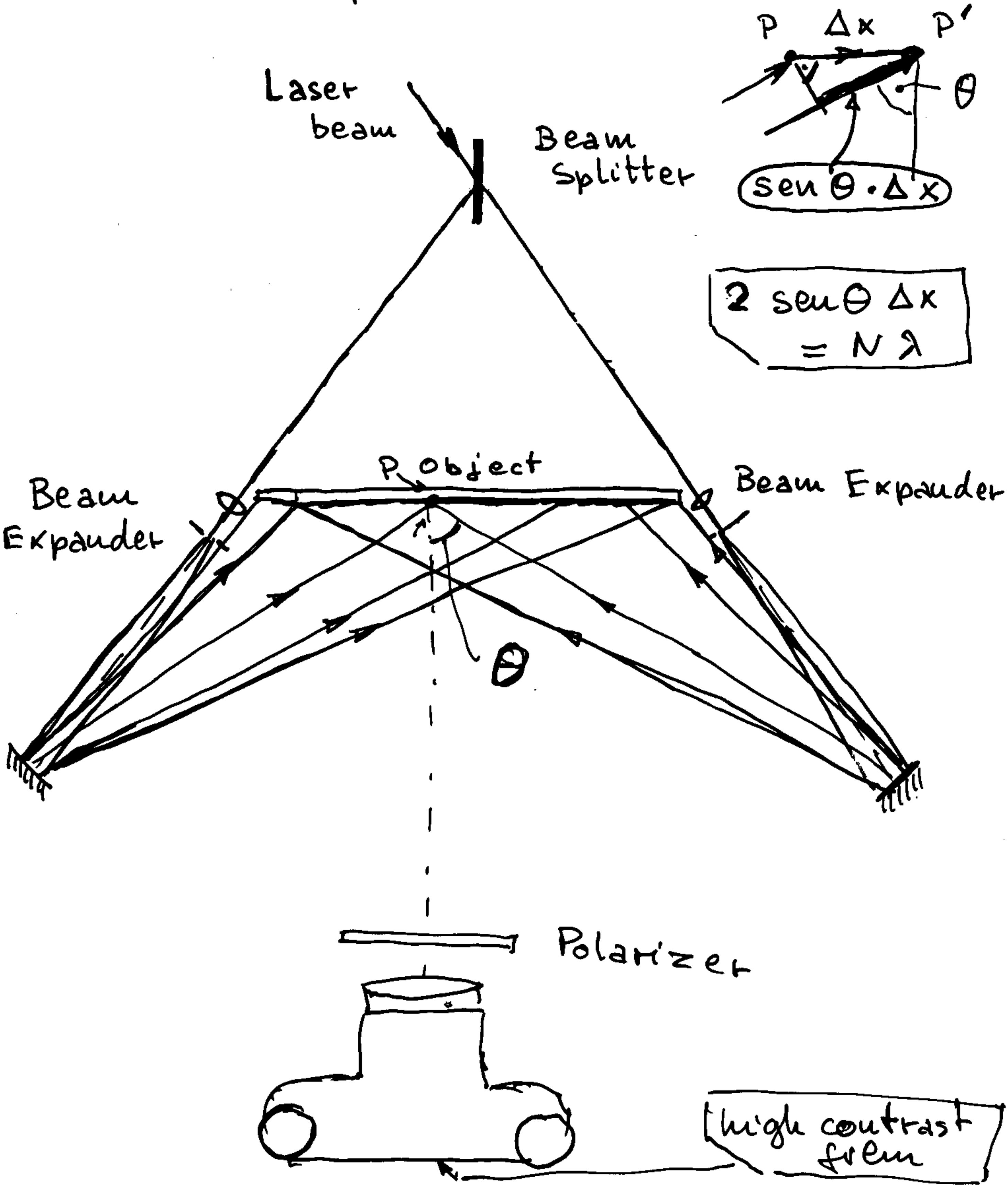
  (in the plane of the screen)

  (in the magnification ratio

  $-\ m = L/f$



# Double-exposure speckle recording of "in-plane" displacement




$$2 \operatorname{sen}\theta \, \Delta x = N\lambda$$

(From E. ARCHBOLD et al. Optica Acta 17 883 1970)

$- \cos\theta \cos\phi + \text{sen}\,\theta\, \text{sen}\,\phi$

$+ \cos\theta \cos\phi + \text{sen}\,\theta\, \text{sen}\,\phi$

$2\, \text{sen}\,\theta\, \text{sen}\,\phi$



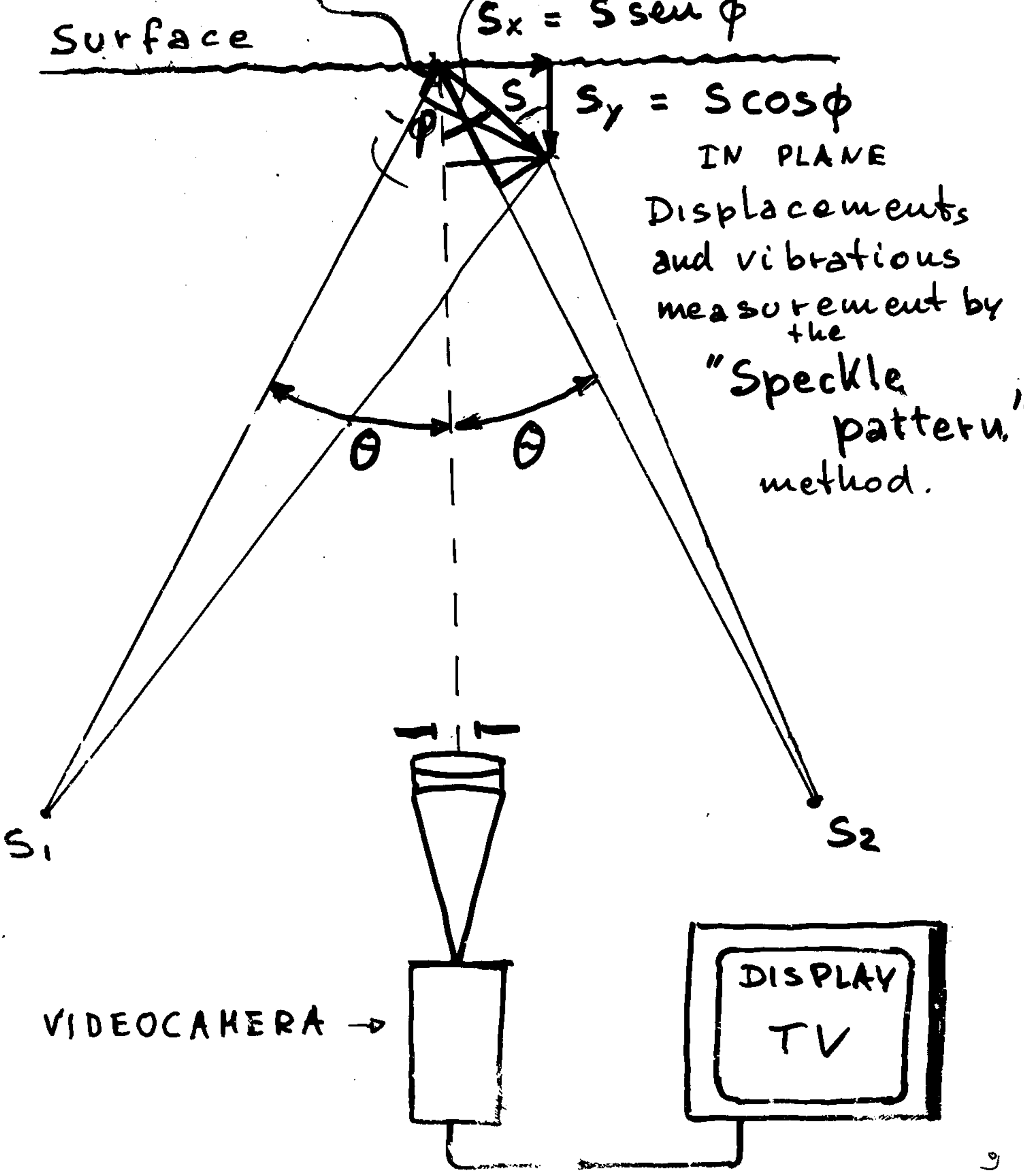
$$\Delta L = -S\cos(\theta+\phi) + S\cos(\phi-\theta) = \underline{2 s_x \,\text{sen}\,\theta}$$

$S_x = S\,\text{sen}\,\phi$

$S_y = S\cos\phi$

IN PLANE

Displacements and vibrations measurement by the "Speckle pattern" method.



# "In plane" displacement measurement by double exposure (correlation fringes) due to N.L. recording

- A displacement $\Delta x$ $\longrightarrow$ $\boxed{N = 2 \frac{\Delta x}{\lambda} \sin\theta}$ Fringes

The maximum measurable displacement is of the order of $\Sigma$ ; $\Delta x_{max} \lesssim \Sigma = m \cdot \sigma$

$$N_{MAX} = 2 \frac{\Delta x_{MAX}}{\lambda} \sin\theta \simeq 2 \frac{\Sigma}{\lambda} \sin\theta = 2.44\, m F \sin\theta$$

For $\Delta x > \Sigma$ the correlation fringes visibility drops below 1/3 of the $\Delta x = 0$ value.

- A strain $\beta = \Delta x / \ell$ gives rise to

$$\boxed{n_0 = \frac{N}{\ell} = 2\beta \frac{\sin\theta}{\lambda}}$$

fringes/unit length at the <u>object plane</u>

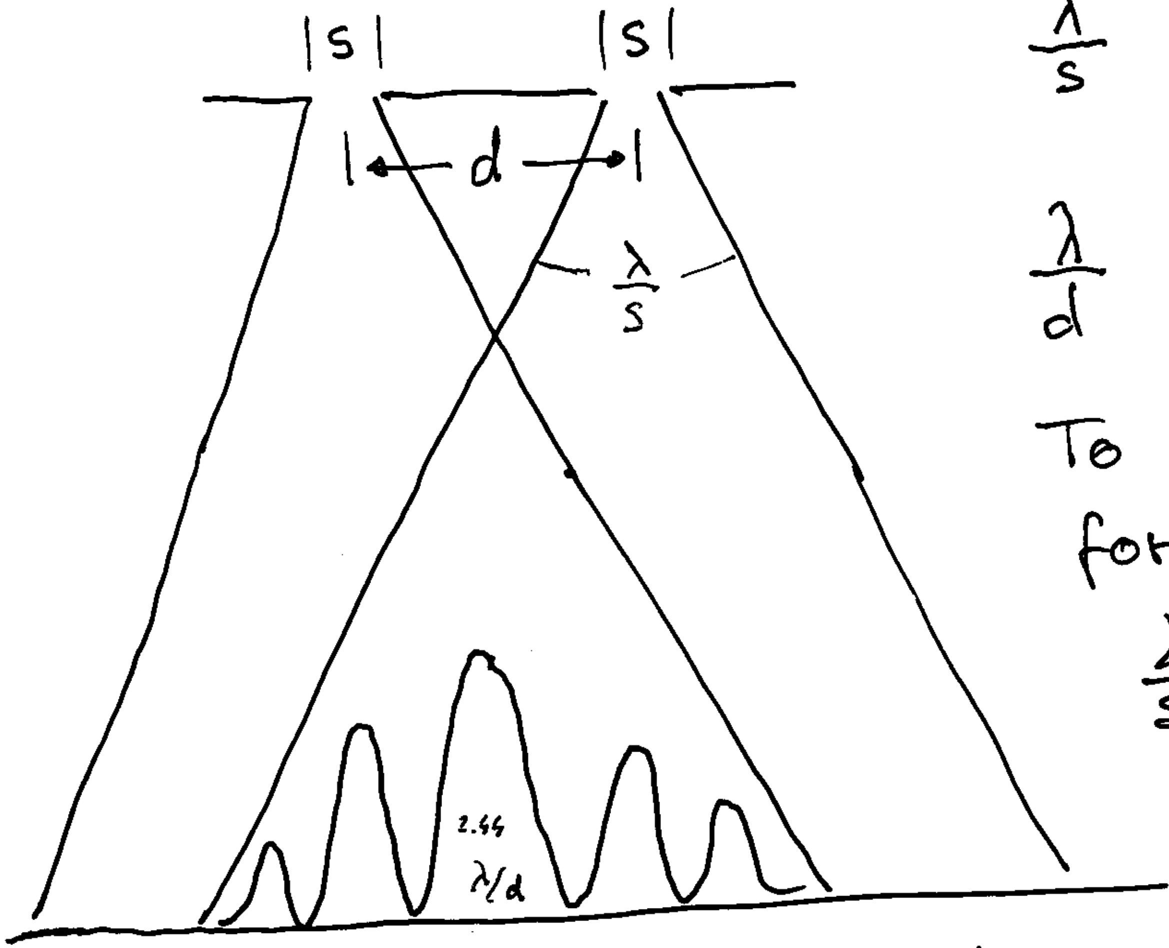
and on the film a fringe system with a pitch:

$$D = \frac{1}{m} \cdot \frac{1}{n_0} = \frac{1}{m} \frac{\lambda}{2\beta \sin\theta}$$

The signal to noise ratio is $\frac{D}{\sigma} = \frac{1}{2.4\, m \beta F \sin\theta}$

Ex. $m = 10$ ; $\beta = 10^{-3}$ ; $F = 2$ ; $\sin\theta = \sqrt{2}/2$ ; $D/\sigma =$ [illegible]

# Young interferometer




$\frac{\lambda}{s}$ diffraction angle of the slit

$\frac{\lambda}{d}$ angle between two minima

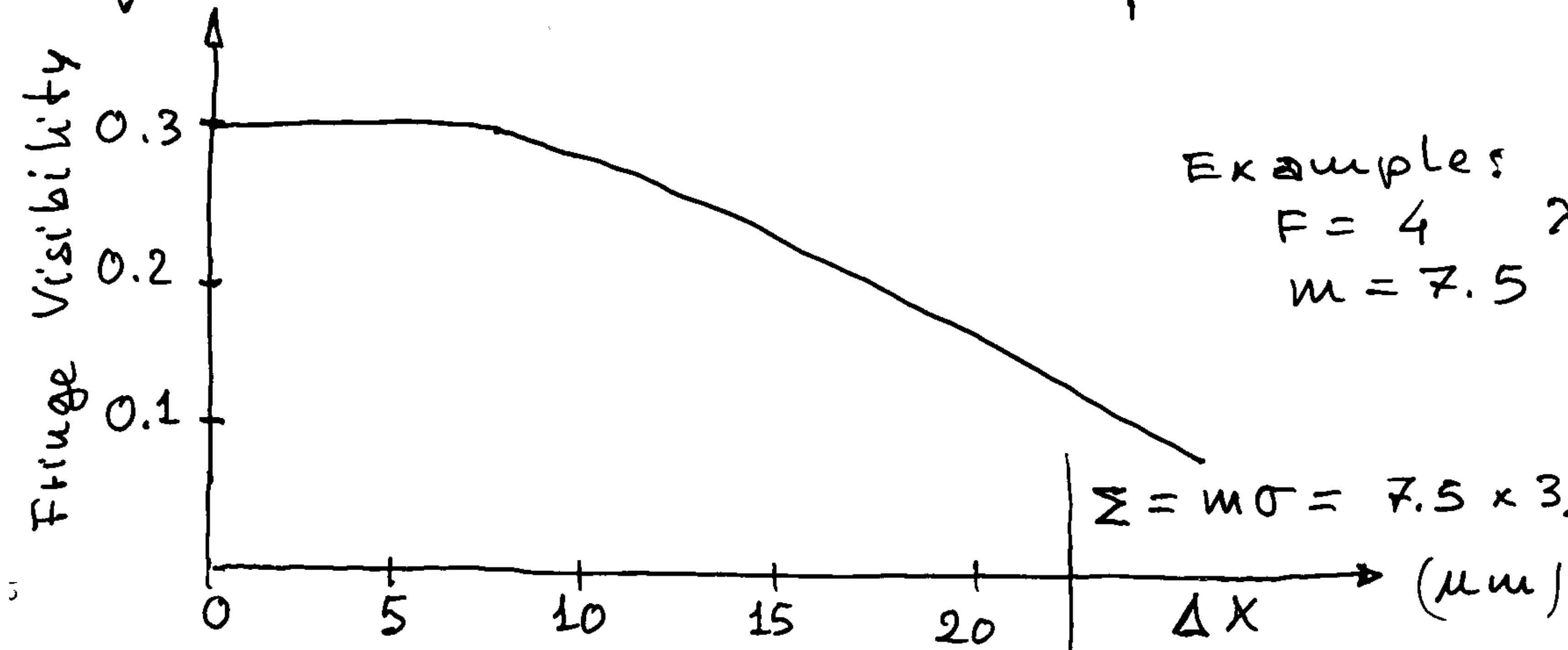
To allow for fringe formation

$$\frac{\lambda}{s} > \frac{\lambda}{d} \quad \text{i.e.:}$$

$$\boxed{d > s}$$

The photographic speckle pattern method with Fourier analysis of the film (optical transform) can be used for $\Delta x > \Sigma$ only
It perfectly <u>complements</u> the correlation fringes method.

Correlation fringes method (fringes on the film) | Optical trasform method (fringes in the far field)



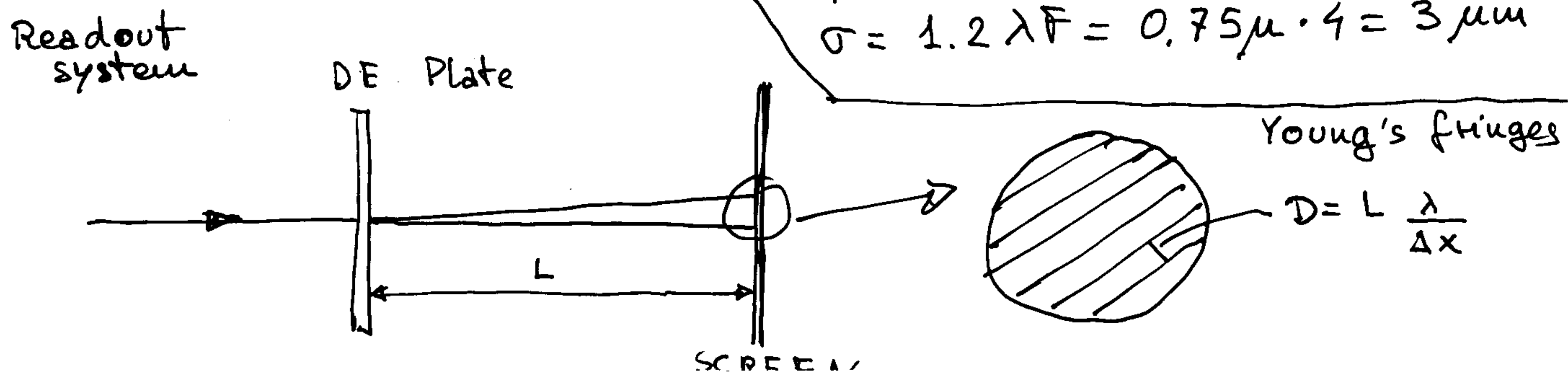

Examples:

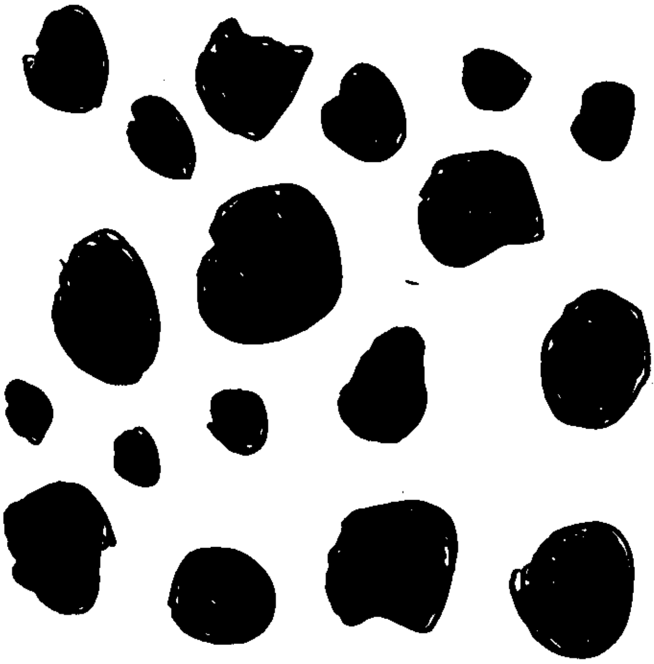
$F = 4$ $\lambda = 0{,}63\ \mu m$

$m = 7.5$

$\Sigma = m\sigma = 7.5 \times 3\ \mu m = 22.5\ \mu m$

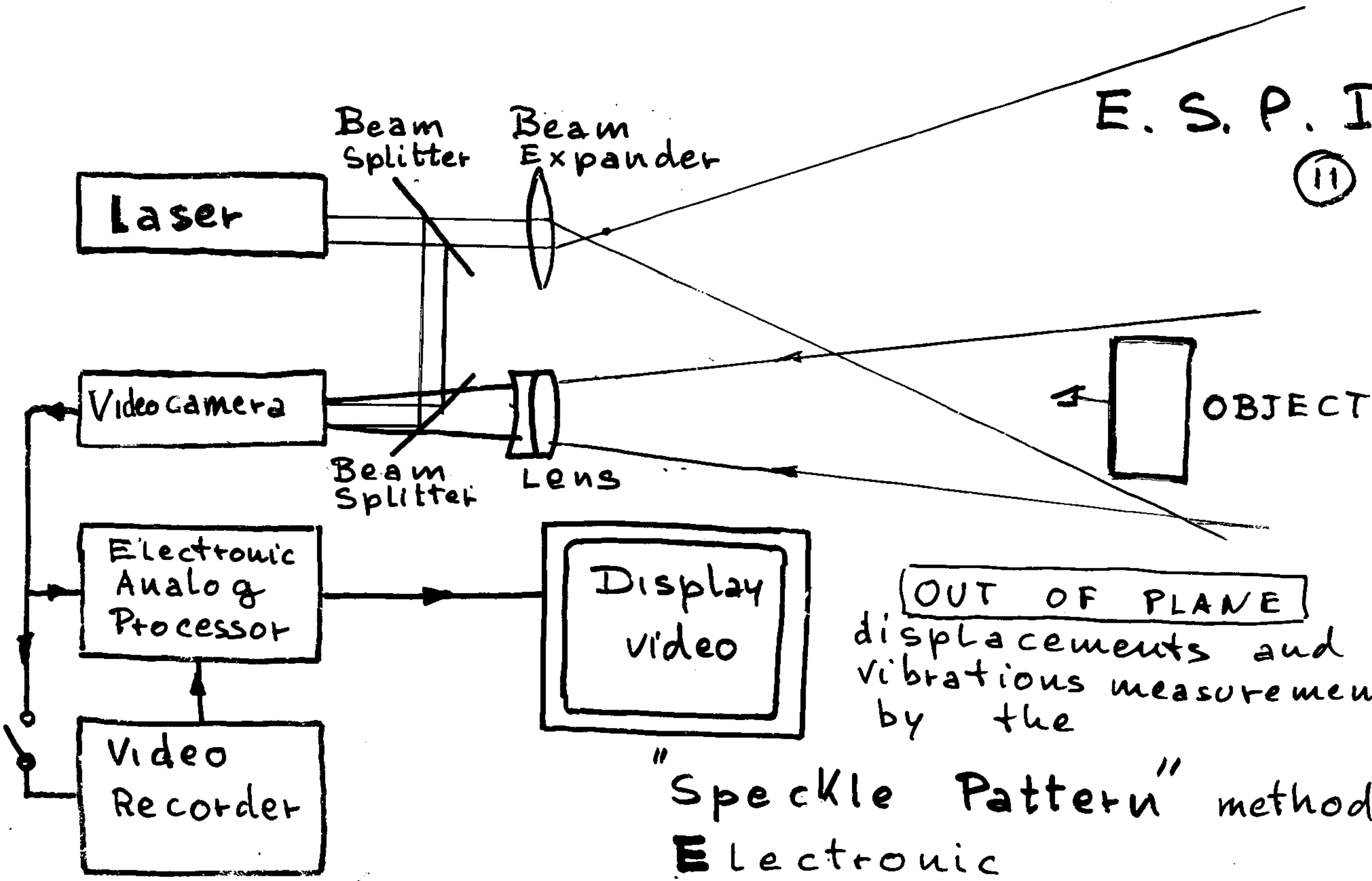
$\sigma = 1.2\lambda F = 0{,}75\mu \cdot 4 = 3\ \mu m$





# E. S. P. I.

(11)

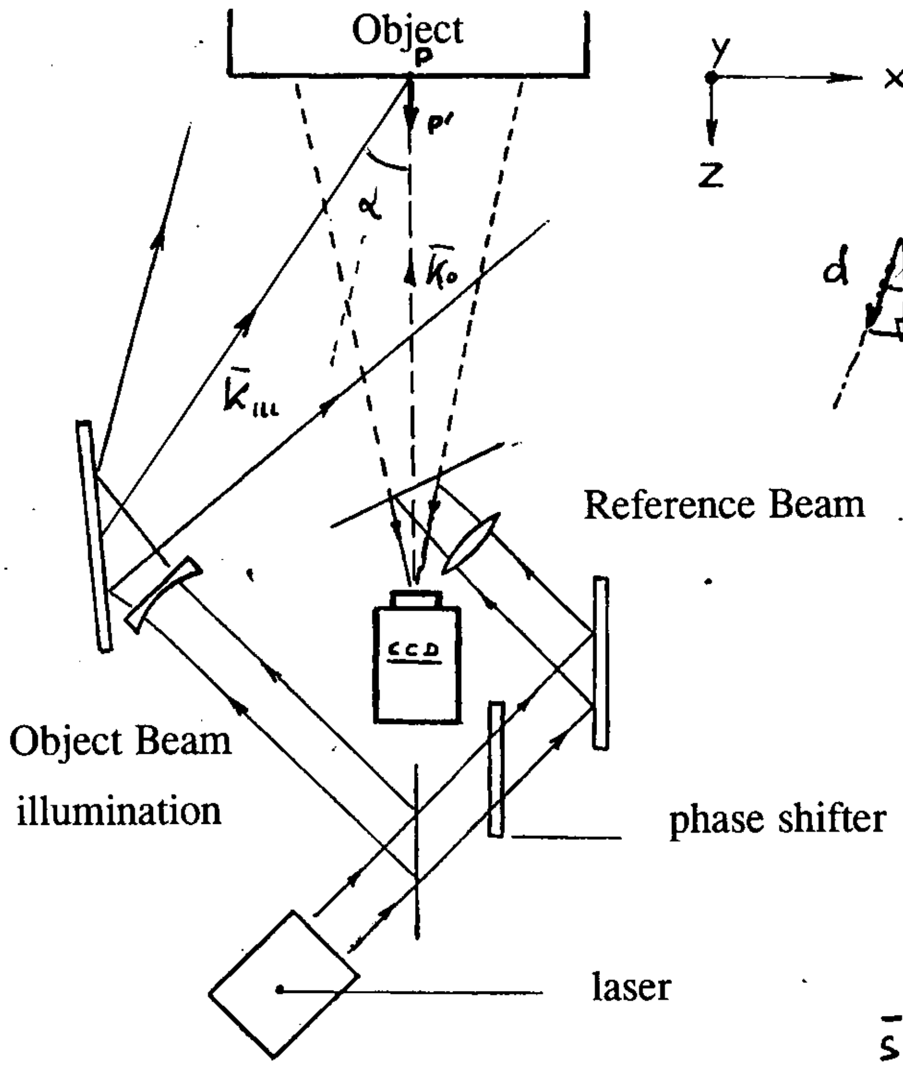


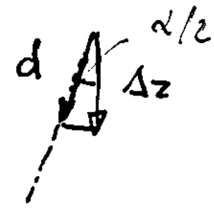

OUT OF PLANE displacements and vibrations measurements by the "Speckle Pattern" method

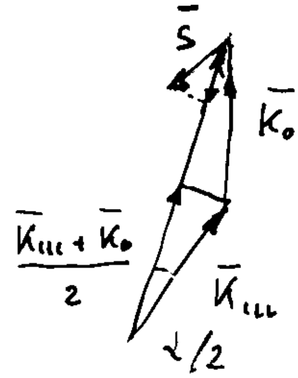
**E**lectronic
**S**peckle
**P**attern
**I**nterferometry

ESPI OUT OF PLANE

**Sensitive to out of plane displacements** Z



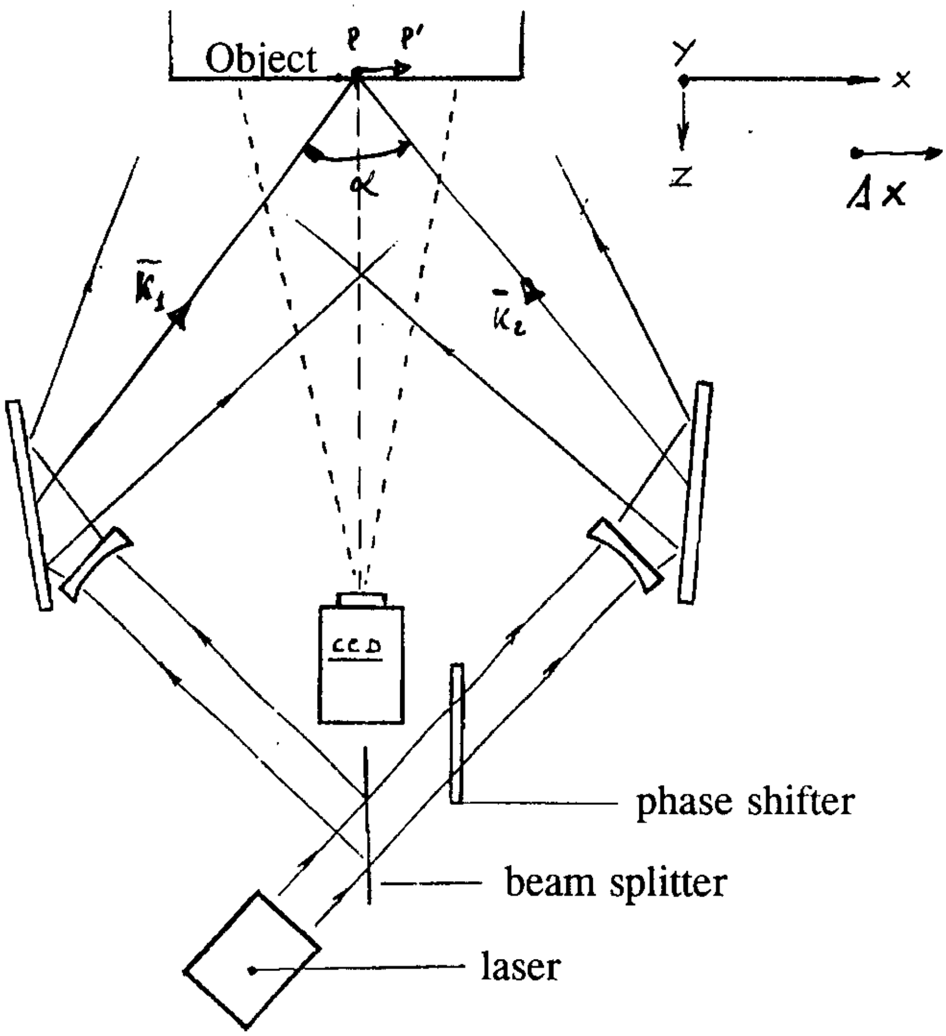



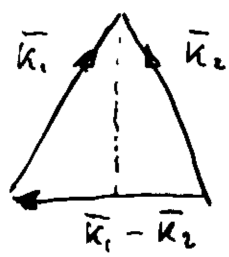

$$d = \frac{N\lambda}{2\cos\alpha/2}$$

$$2\bar{S}\cdot\left(\frac{\bar{K}_{ill}+\bar{K}_o}{2}\right) = 2N\pi$$

ESPI IN PLANE

## Sensitivity to x (or y) displacements



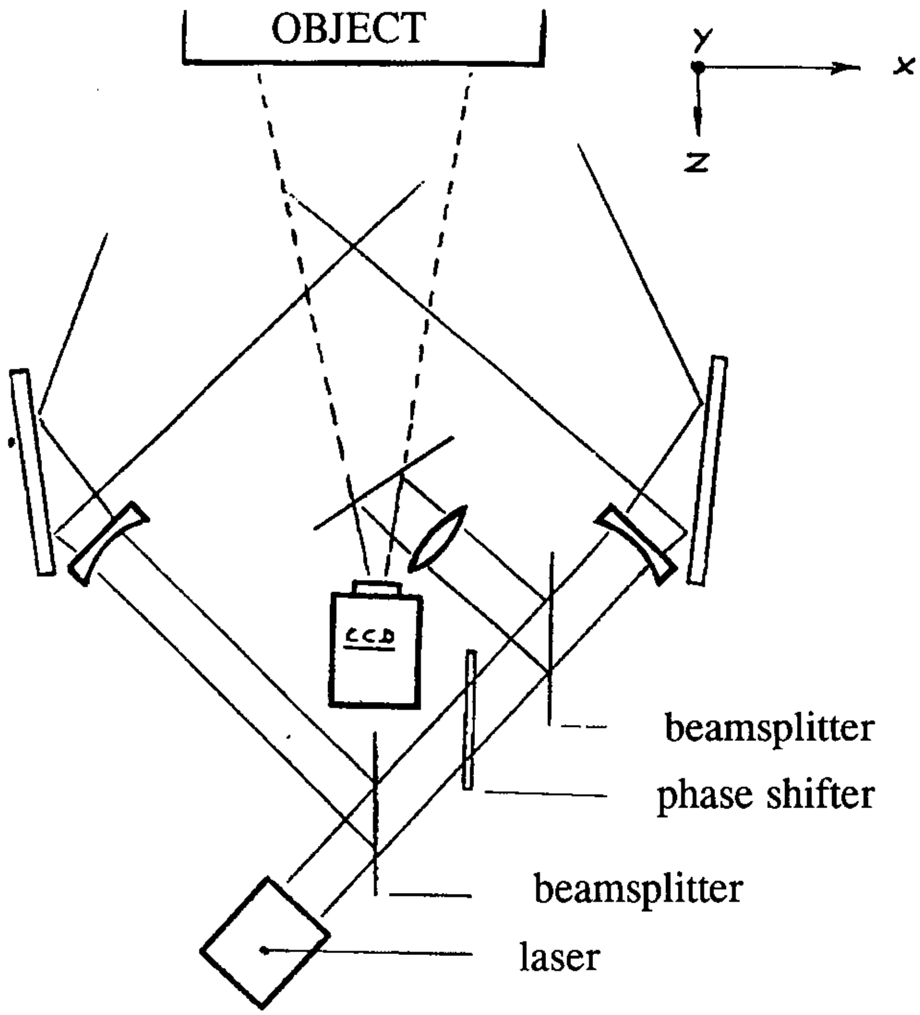

$$\boxed{\Delta x = \frac{N\lambda}{2 \sin \alpha/2}}$$

$$2\,\Delta x \cdot \frac{2\pi}{\lambda} \sin\frac{\alpha}{2} = 2N\pi \qquad 2\,\bar{S}\cdot\left(\bar{K}_1 - \bar{K}_2\right) = 2N\pi$$

$$\vec{S} = \vec{\Delta x}$$

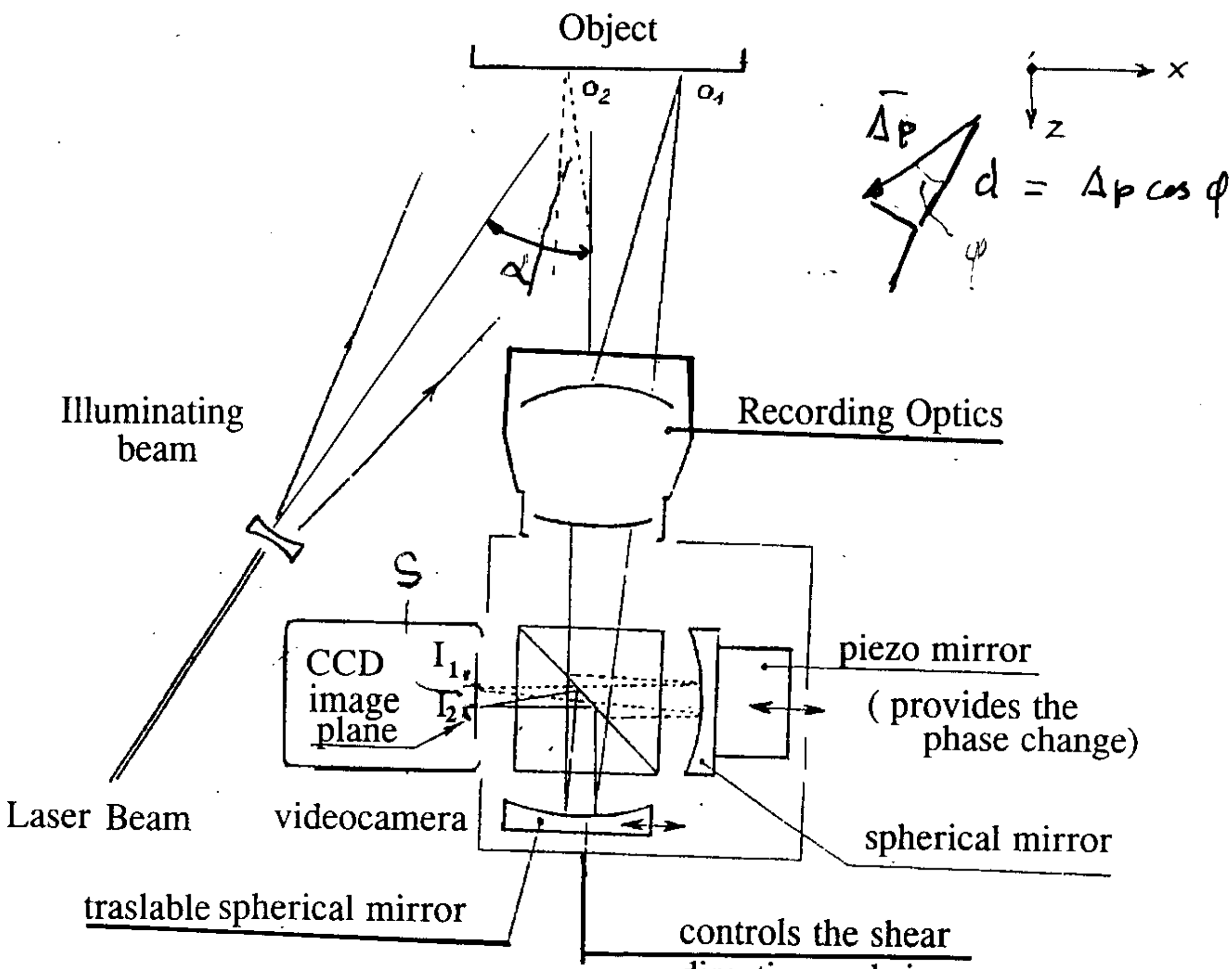
ESPI IN PLANE AND OUT OF PLANE

**Sensitive to x ,y, z displacements**



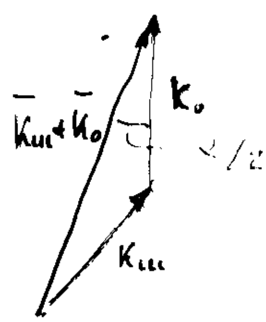
SHEAROGRAPHY

# Sensitive to deformations gradients i.e. strains




S - shear

$$\boxed{\frac{d}{S} = \frac{N\lambda}{2\cos\alpha/2}}$$




$$\frac{\overline{\Delta p}}{S} \cdot \left(\overline{K_{ill}} + \overline{K_o}\right) = 2\pi N$$

I

# Winter College on Optics

## - Laboratory session -

PARTICLE SIZING
Ex. of Applications

# Granulometric characterization of solid particles suspended in a liquid by means of both a diffraction based optical particle sizer and a multi-wavelength extinction technique.

by

S. Musazzi and E. Paganini

CISE Tecnologie Innovative
via Reggio Emilia 39 - 20090 Segrate (MI)

Trieste, February 1998

## 1 Title of the experimental activity

Measurements with a diffraction based optical particle sizer for the granulometric characterization of solid particles suspended in a liquid.

## 2 Scope of the experimental activity

The experimental activity is aimed to describe the working principles of one optical particle sizer and to get familiar with its mode of operation. It will be possible to carry out typical operations like the preparation of the sample, the collection and the analysis of the scattering data as well as the handling of the experimental results.

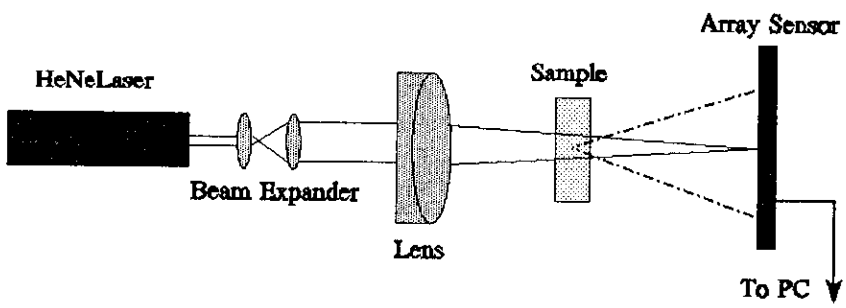
## 3 Description of the activity

The activity will be carried out according to the following scheme:

- Brief presentation dealing with the principle of operation of the diffraction based optical particle sizers and their optical, mechanical and electronic configuration
- Description of the instrument to be used for the experimental activity (measuring head, circulating unit and software)
- Utilization of the instrument to carry out measurements on different samples of solid particles. The following activities will be performed:
  - preparation of the sample
  - recording of the background and the scattered intensity distributions
  - analysis of the recorded scattering data by means of the inversion algorithm
  - graphical presentation of the measured particle size distribution
- Analysis of the experimental results
- Discussion on open points

## 4 Experimental apparatus

The instrument utilized for the experimental activity is a particle sizer developed at CISE Laboratories and now manufactured by a german company (Fritsch model "Analysette 22")

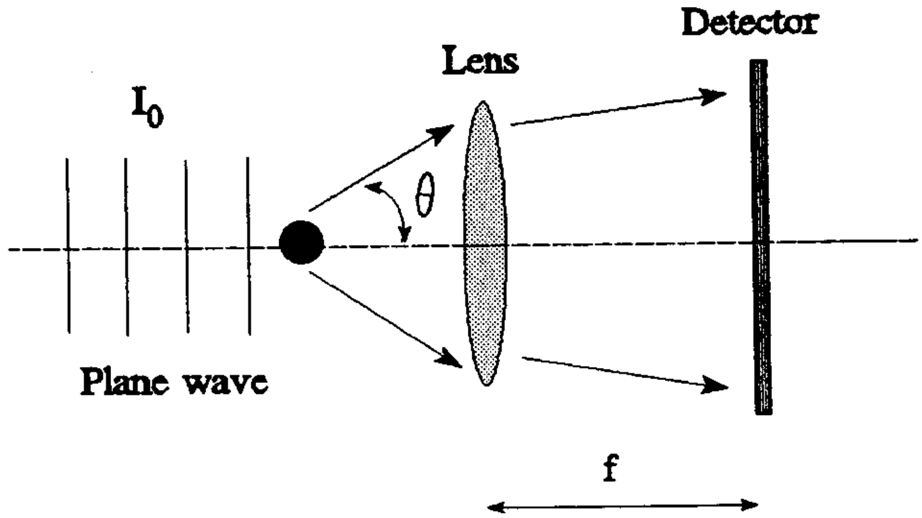



**Optical scheme of the particle sizer developed at CISE Labs.**

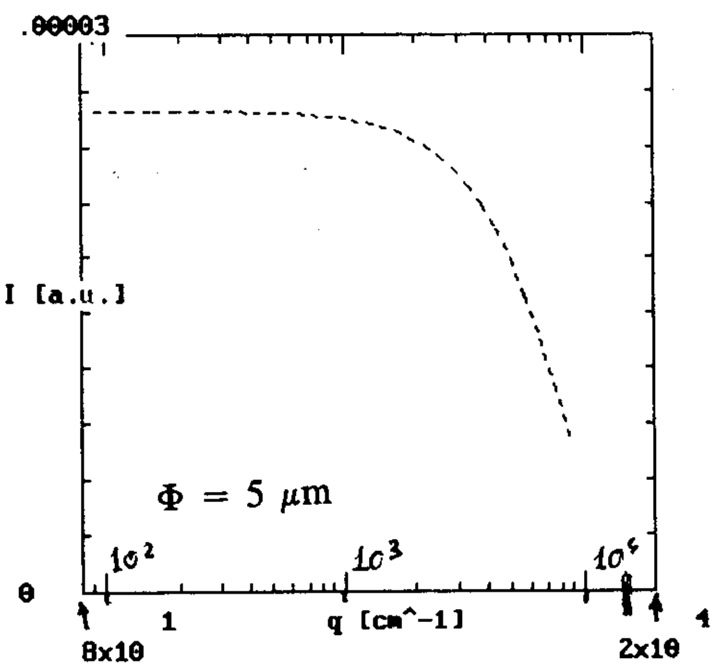
# DIFFRACTION BASED OPTICAL PARTICLE SIZERS

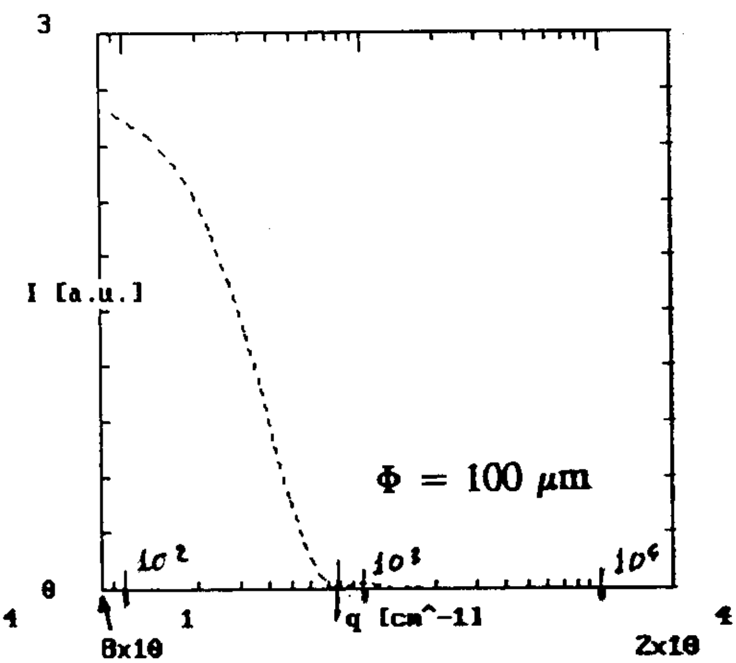
## - Principle of operation -

- Single spherical particle with diameter $2a > \lambda$




- The intensity distribution in the detector plane is the well known Airy function $q = 2\pi \frac{\sin\theta}{\lambda}$




$q = 15280$ $q = 764$ $1^{st}$ zero $q = 3.82$

# DIFFRACTION BASED OPTICAL PARTICLE SIZERS

- Principle of operation -

- Monodisperse sample (i.e. a sample made by N particles with the same diameter)

$$I(\theta) = NcI_0 \frac{\pi^2 a^4}{\lambda^2} \left[ \frac{2J_1(\frac{2\pi a\theta}{\lambda})}{(\frac{2\pi a\theta}{\lambda})} \right]^2$$

Where:

| | | |
|---|---|---|
| $J_1$ | = | First-order Bessel function of first kind |
| c | = | Proportionality constant |
| N | = | Number of particles |
| $I_0$ | = | Intensity of the illuminating wave |
| a | = | Particle radius |
| $\lambda$ | = | Illuminating wavelength |
| $\theta$ | = | Scattering angle |

- The intensity distribution in the detector plane is simply N times the intensity distribution scattered by a single particle

# DIFFRACTION BASED OPTICAL PARTICLE SIZERS

## - Principle of operation -

- Polydisperse sample (i.e. a sample made by particles with different diameter)

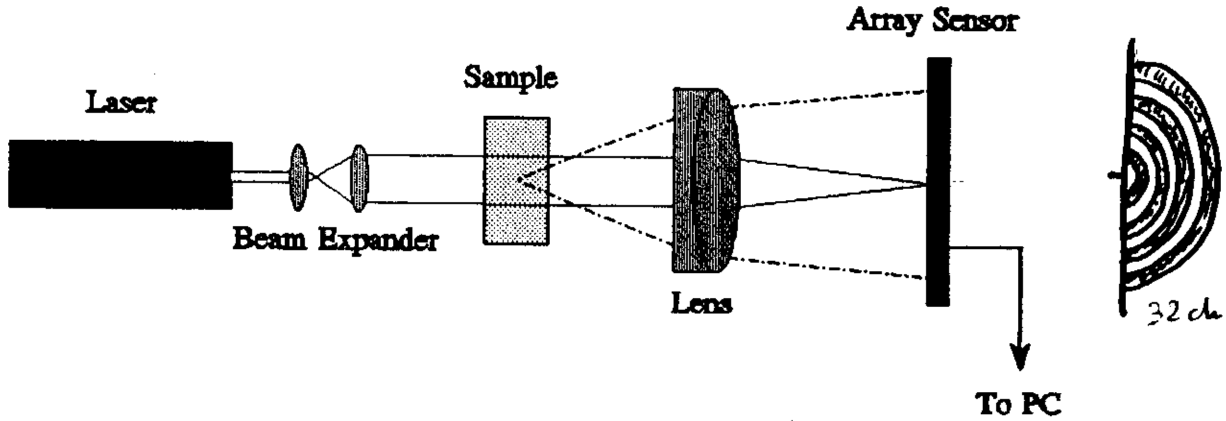
$$I(\theta) = \int_{a_{min}}^{a_{max}} c I_0 \frac{\pi^2 a^4}{\lambda^2} \left[ \frac{2 J_1 \left( \frac{2\pi a \theta}{\lambda} \right)}{\left( \frac{2\pi a \theta}{\lambda} \right)} \right]^2 N(a)\, da$$

Where:

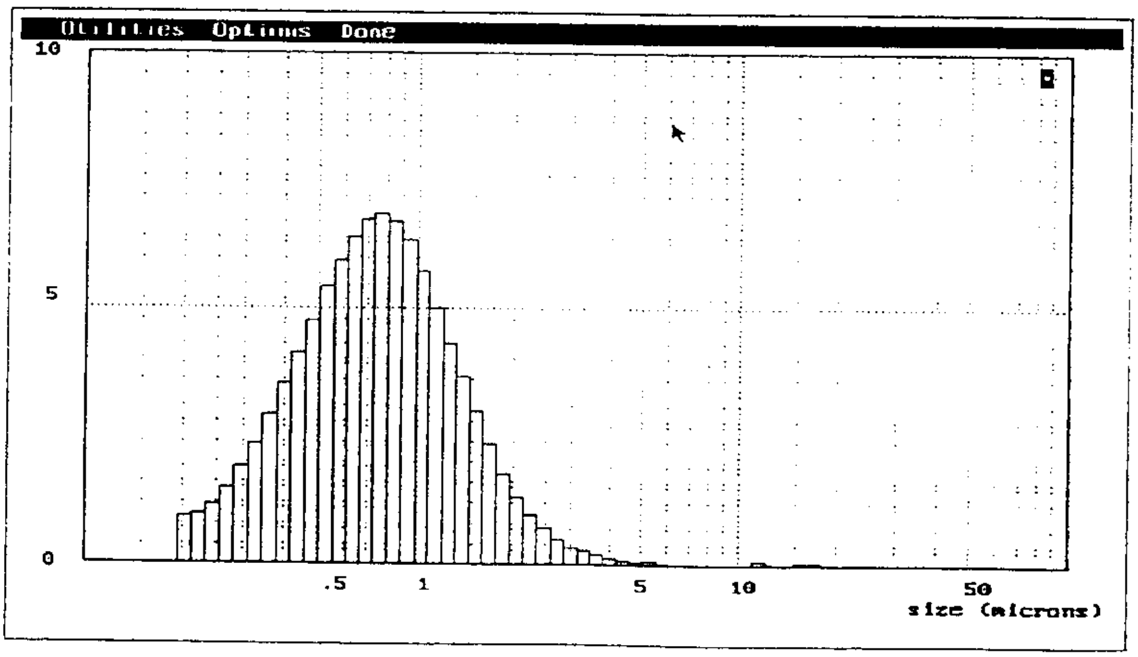
N(a)da = number of particles with radius between (a, a+da)

# DIFFRACTION BASED OPTICAL PARTICLE SIZERS

## - Experimental apparatus -

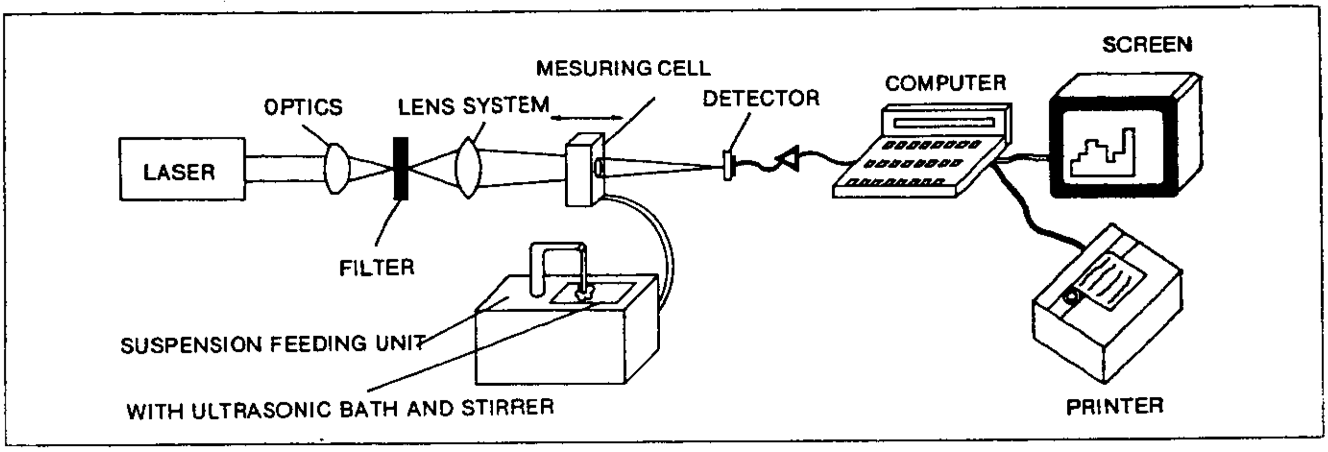


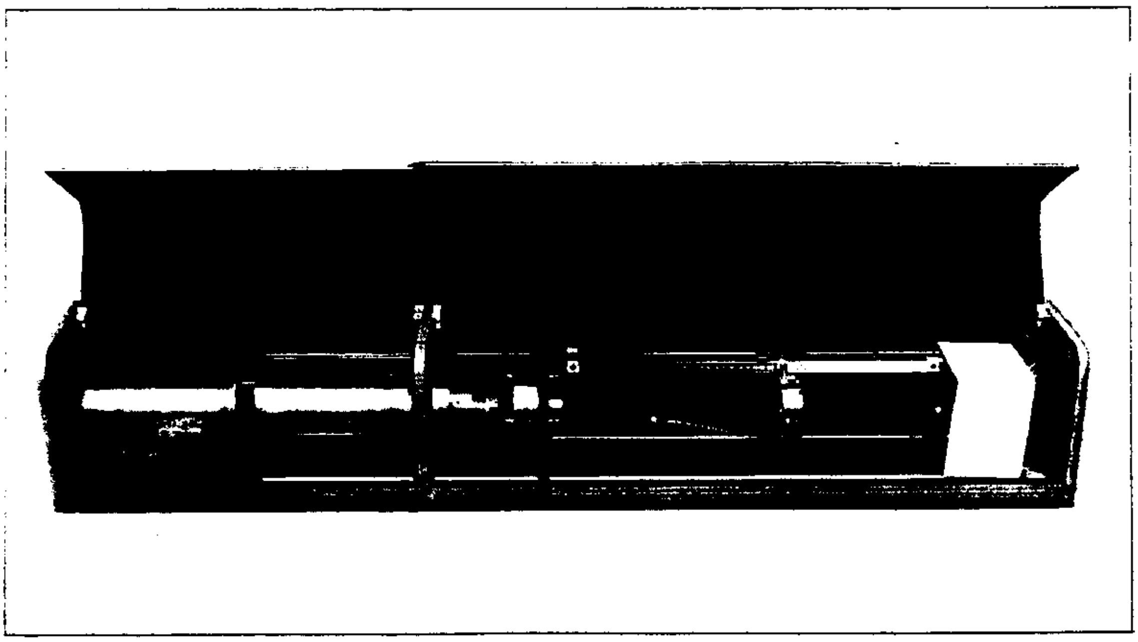

- Typical particle size distribution



# DIFFRACTION BASED OPTICAL PARTICLE SIZERS

## - Instrument layout -



1 **Title of the experimental activity**

Multispectral extinction measurements on solid particles suspended in a liquid and utilization of the extinction spectra for particle sizing.

2 **Scope of the experimental activity**

Main purpose of the experimental activity is to get familiar with:
a) a typical laboratory set-up for extinction measurement.
b) measurement procedures and spectra exinction data handling.

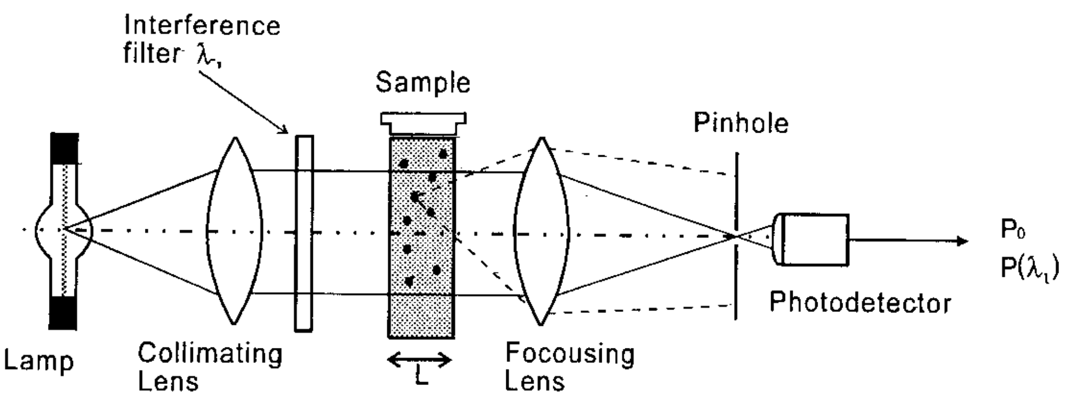
3 **Description of the activity**

The activity will be carried out according to the following scheme:

- Brief presentation dealing with the principle of operation of extinction based optical particle sizers.
- Description of the set-up to be used for the experimental activity
- Utilization of the instrument to carry out measurements on different samples of solid particles. The following activities will be performed:
    - preparation of the sample
    - measurement of the extinction at different wavelenghts
    - analysis of the recorded data by means of the inversion algorithm
- Analysis of the experimental results
- Discussion on open points

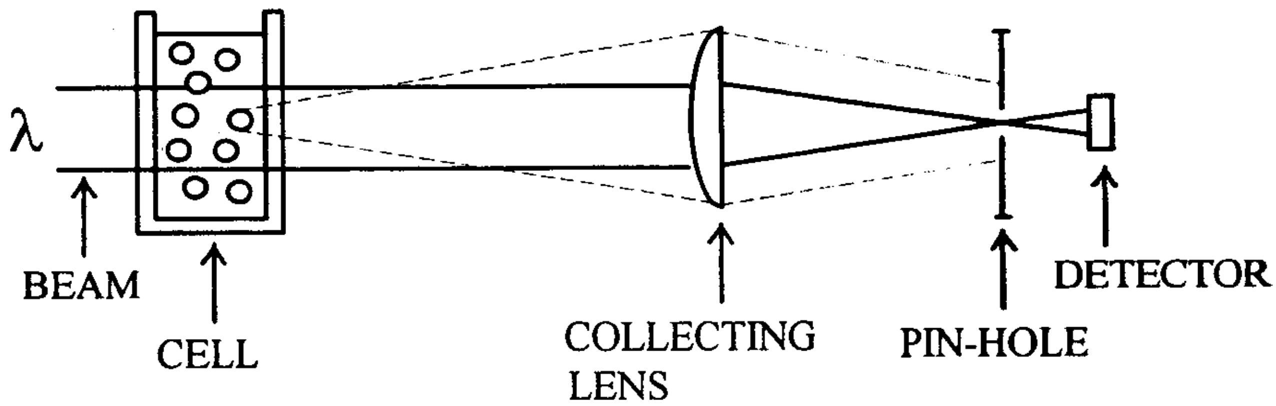
4 **Experimental apparatus**

The experimental set-up is made by commercial componets assembled on an optical bench.\



# SPECTRAL EXTINCTION
## principle of operation

- Extinction = Absorption + Scattering




- Two measurements:

  $P_0$ = light power without particles

  $P$ = light power with particles

- Lambert-Beer law:

  $\alpha(\lambda)$ = Extinction coefficient

  $L$ = Cell length

$$P = P_0 e^{-\alpha(\lambda)L}$$

$$\alpha(\lambda) = \frac{1}{L} \ln \frac{P_0}{P}$$

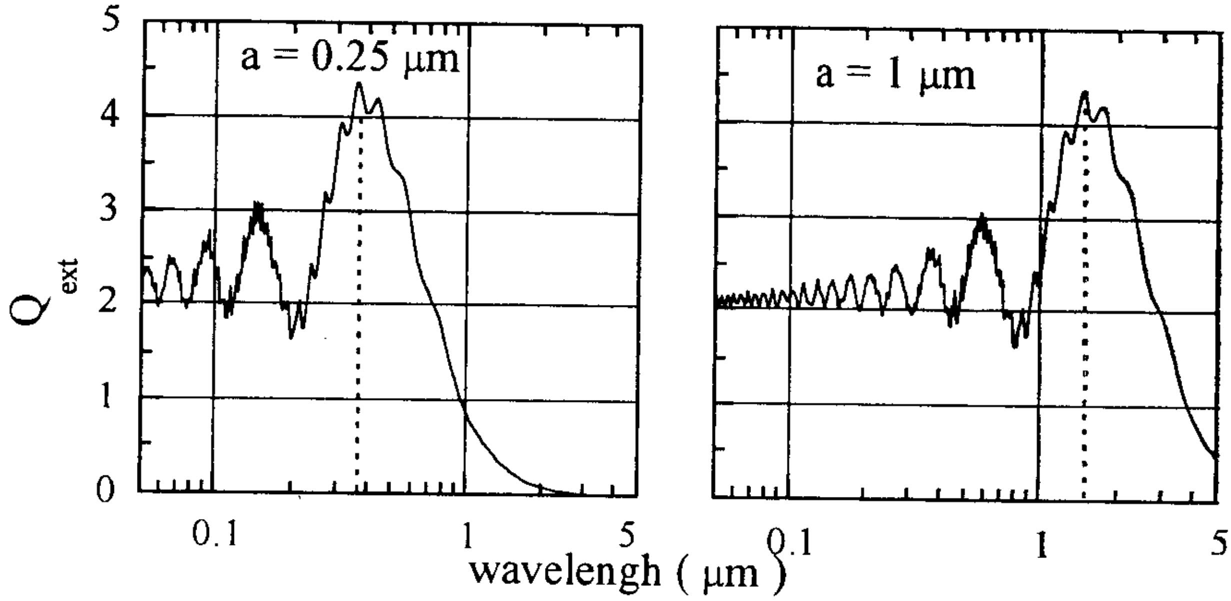
# SPECTRAL EXTINCTION

## principle of operation

For a monodisperse distribution:

m = relative refraction index
n = number concentration ($cm^{-3}$)
$Q_{ext}$ = extinction efficiency
a = particle radius

$$\alpha(\lambda) = \pi a^2 Q_{ext}(a, \lambda, m) \ \ n$$




The position of the maximum is a function of the particle radius

⬇

Particle Sizing is feasible

# SPECTRAL EXTINCTION

principle of operation

For a polydisperse sample :

- homogeneous suspension of non-interacting particles of different sizes
- n(a)da is the concentration of particle [$cm^{-3}$] with radii between a and a+da

$$\alpha(\lambda) = \int_{a_{\min}}^{a_{\max}} \underline{\pi a^2 Q_{ext}(a,\lambda,m)}\, n(a)\, da$$

| Extinction coeff. Measured function | Kernel Known from Mie Theory | Number distribution Unknown function |
|---|---|---|

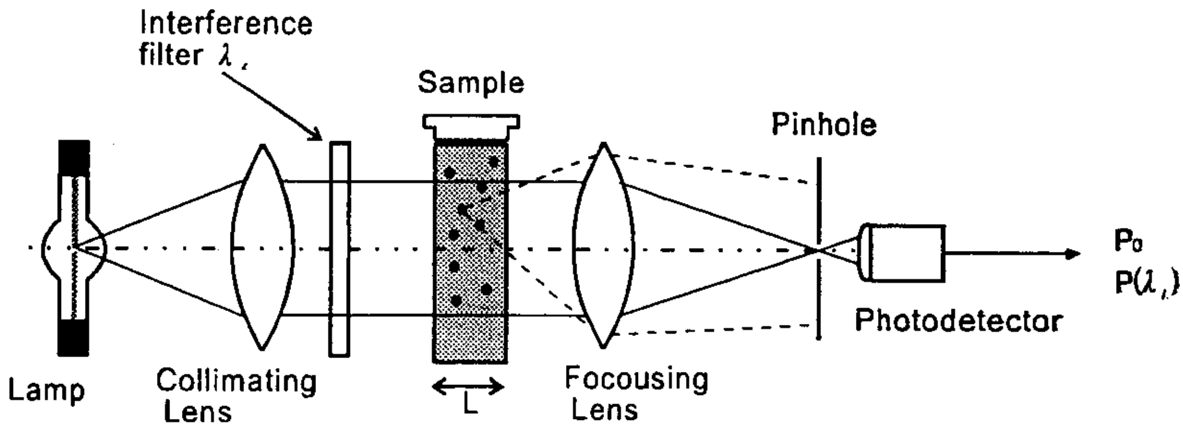
We have to recover n(a)

ILL-POSED PROBLEM ➡ INVERSION IS NOT TRIVIAL!!

The algorithm must be { Efficient & Accurate; Reliable & Stable }

# SPECTRAL EXTINCTION

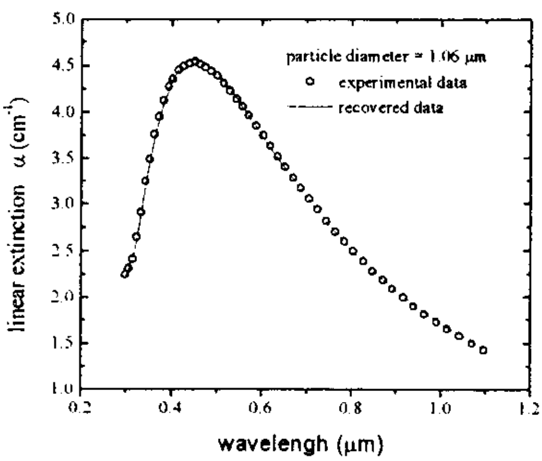
## Experimental set-up

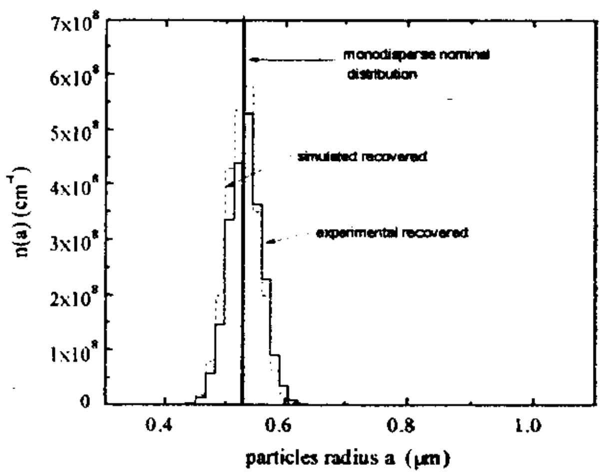



## Experimental results

Sample: latex, particle radius 0.530 µm

Recovered distribution class width = 3% of the mean radius



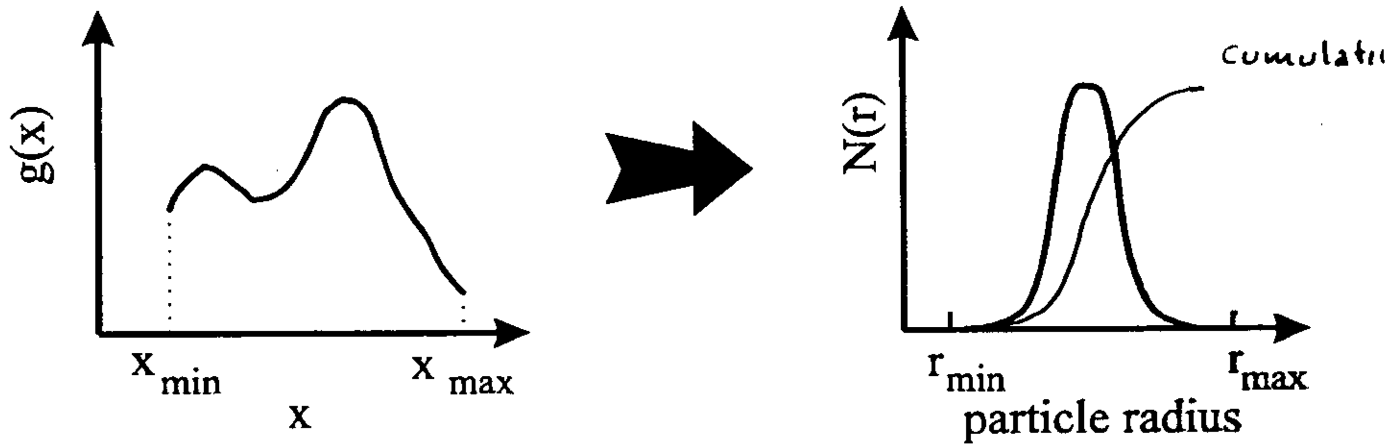

Resolution: 2 class HWHM ( 6% )

Accuracy: Mean diameter ± 5 %

Concentration ± 5 %

INV

# INVERSION OF EXPERIMENTAL DATA




Low angle ligth scattering ➡ { g(x) = scattered intensity; x = scattering angle }

Multiwavelengh extinction ➡ { x = wavelengh; g(x) = linear extinction α }

$$g(x) = \int_{r_{min}}^{r_{max}} N(r)\ K(x,r)\ dr$$

Fredholm Equation of the first kind

Utilized inversion algorithm : Chahine iterative algorithm

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