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WINTER COLLEGE ON OPTICS

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The Fundamentals of Speckles and their Applications

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The Fundamentals of Speckles and Their Applications

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Japan

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Reduction of speckles

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   - Chromatic speckles
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   - Fiber speckles
   - Bio-speckles
5. Stellar speckle interferometry
6. Applications :
   - Measurements of surface roughnes, velocity, and vibration
   - Measurements of blood flow

Development

Optics : Wave, Particle (photon) Duality
Electromagnetic wave

Spectroscopy
Interaction of light with matter
(atomic & molecular physics)

Precision mechanical Engineering

1940 Phase microscopy
(Principle of holography)

1950 Stellar intensity interferometry
(Astronomy)
Intensity correlation
Photon counting statistics

Statistical Optics

Coherence theory
Application of information theory to optics
(Concept of spatial frequency

1960 Maser, Laser
(Appearance of coherent light)

Holography, Speckle
Optical information processing

Quantum electronics
(Various lasers)

1970 Nonlinear optics

Optical fiber
Optical communication

1980 Quantum optics
(optical bistability
Optical chaos
optical squeezing)

Optical computing
Optical sensors

Present Future

Optical Physics

Optoelectronics
Optical Engineering

Photonics

(Information Tech.)

Development of Optics

A. Einstein (1921)

Photoelectric effect (1905)

Fluctuations of optical radiation (1909)

Stimulated emission (1916)

feeble light → photon

"For the rest of my life I want to reflect on what light is." (1916)

F. Zernike (1953)

Optical phase microscopy

Waves

"Activity in optics will proceed in waves."

D. Gabor (1971)

Holography

Information

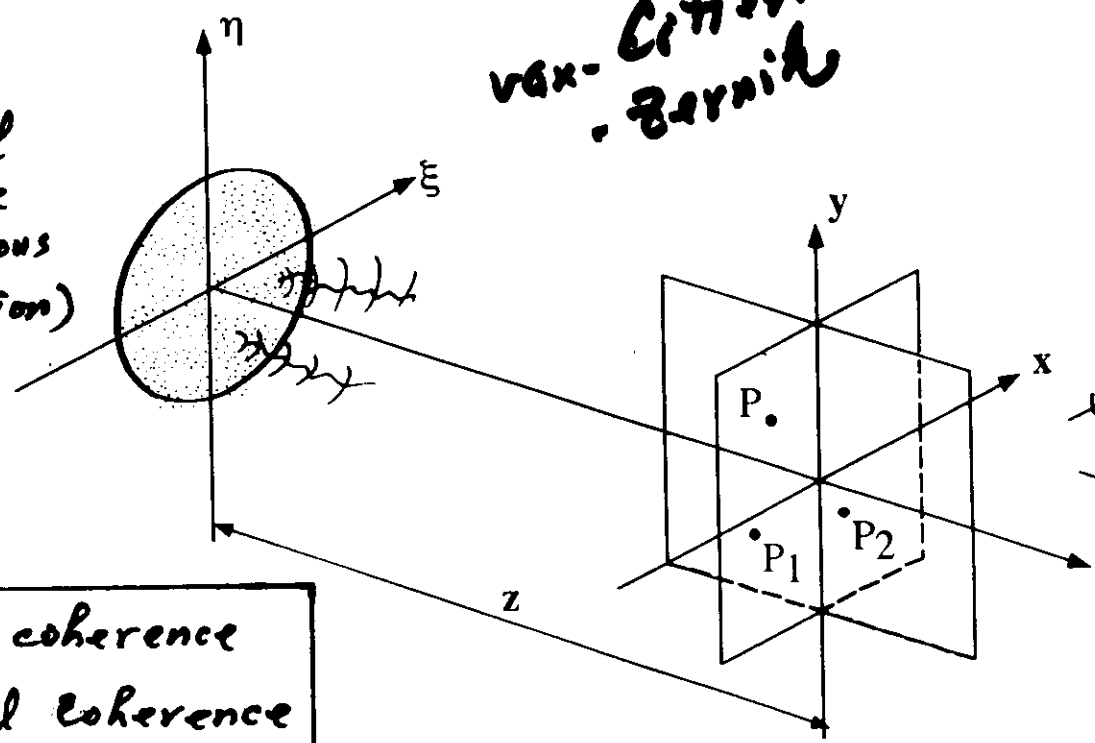
"What is Information?"

Coherence Phenomena

Coherent light
Partially coherent light
Incoherent light

Van-Cittert
Zernike

Thermal source (Spontaneous emission)



x
Spatial fluctuation

τ
Temporal fluctuation

Spatial coherence
Temporal coherence

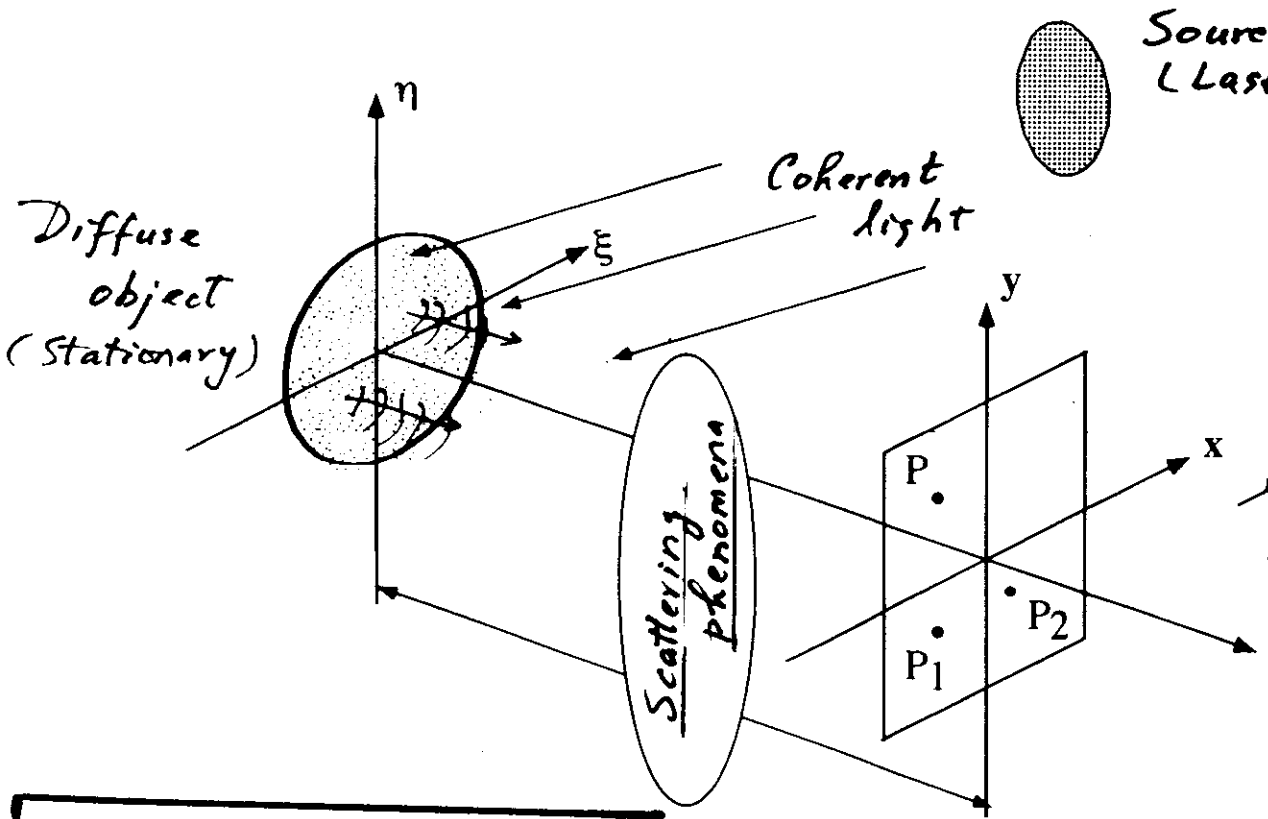
Non-observable

Fundamental physical quantity

$$\Gamma_{12}(\tau) = \left\langle u(P_1, t+\tau) u^*(P_2, t) \right\rangle$$

Time-average

Speckle Phenomena



Statistical quantity

x

Scattering field
= **Speckle field**

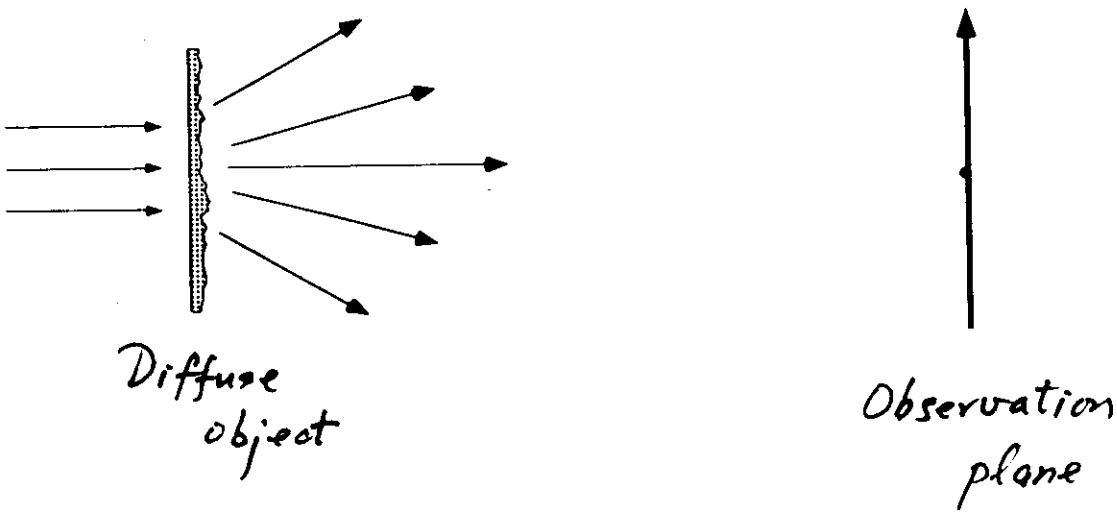
Observable

Diffraction speckle
Image speckle

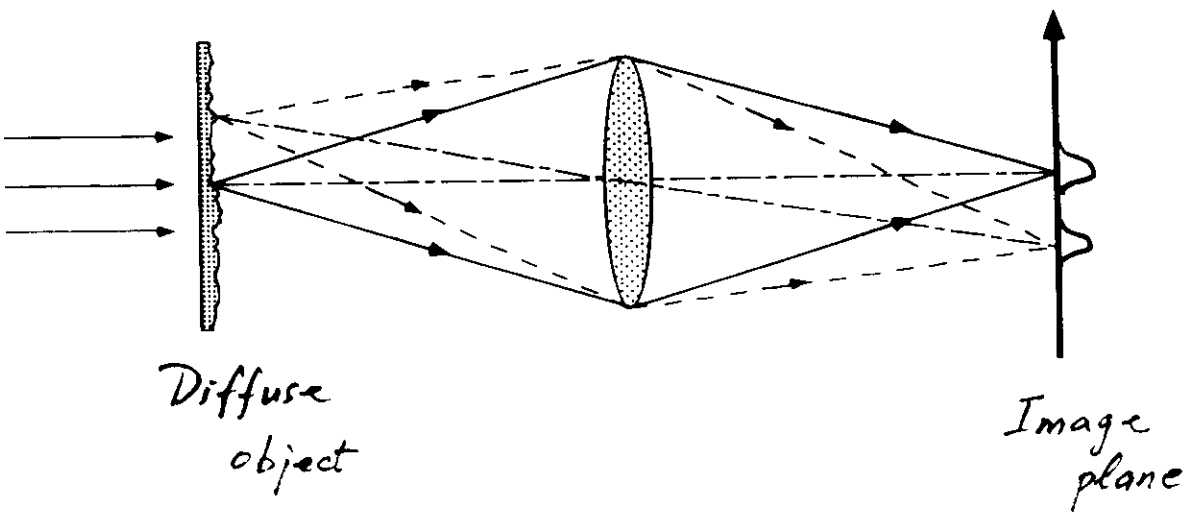
Static speckle
Dynamic speckle

Formation of Speckle

- Diffraction speckle



- Image speckle



Fluctuations of Light

Coherence . Speckle

Coherence (Classic)

Verdet (1869), van Laue (1907)
van Cittert (1934), Zernike (1938)
H.H. Hopkins (1951), Blanc-Lapierre,
Dumontet (1955)
Wolf (1955) ....

Speckle (Scattering phenomena)

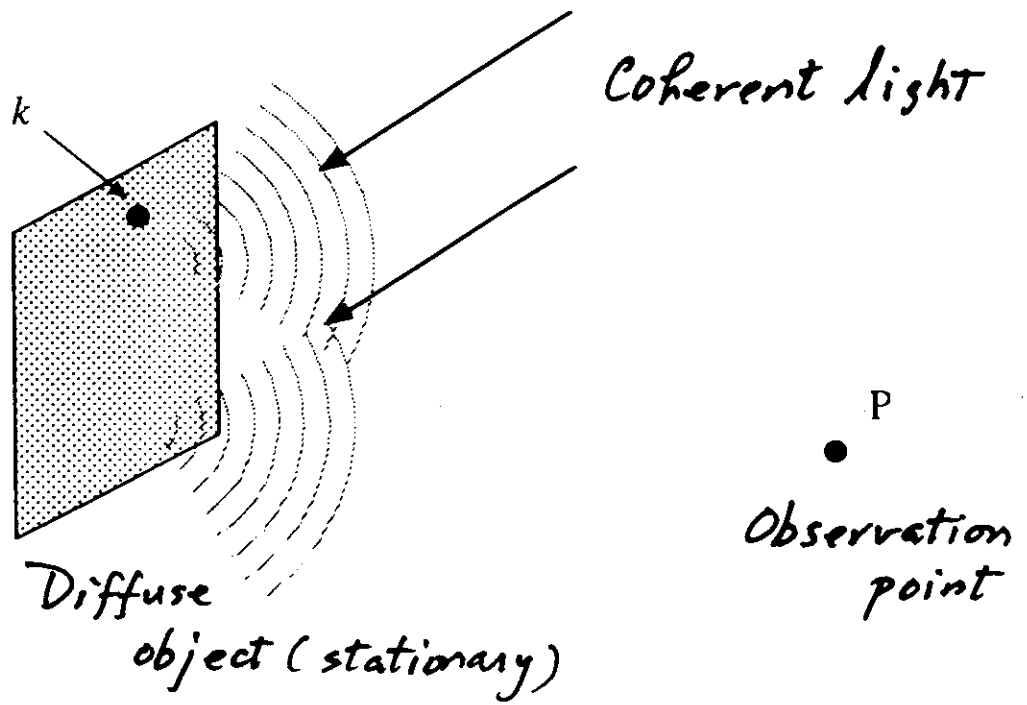
Newton, Exner (1877), von Laue
de Haas (1913), Goodman, Dainty
Asakura

Speckle

$$u(\mathrm{P},t) = U(\mathrm{P})\exp\left[-i2\pi\bar{\upsilon}t\right]$$

$$U(\mathrm{P}) = |U(\mathrm{P})|\exp\left[i\theta(\mathrm{P})\right]$$

$$= \sum_{k=1}^{N} |a_k(\mathrm{P})|\exp\left[i\phi_k(\mathrm{P})\right]$$



Strong diffuse object

① Amplitude and phase of the scattering cells are statistically independent.

② Phases of the scattering cells are equally likely to lie anywhere in the interval $(-\pi, \pi)$.

③ N is large.

Speckle statistics

$$p(U_r, U_i) = \frac{1}{2\pi\sigma^2} \exp\left[-\frac{U_r^2 + U_i^2}{2\sigma^2} \right] \quad ; \quad \sigma^2 = \sigma_r^2 = \sigma_i^2$$

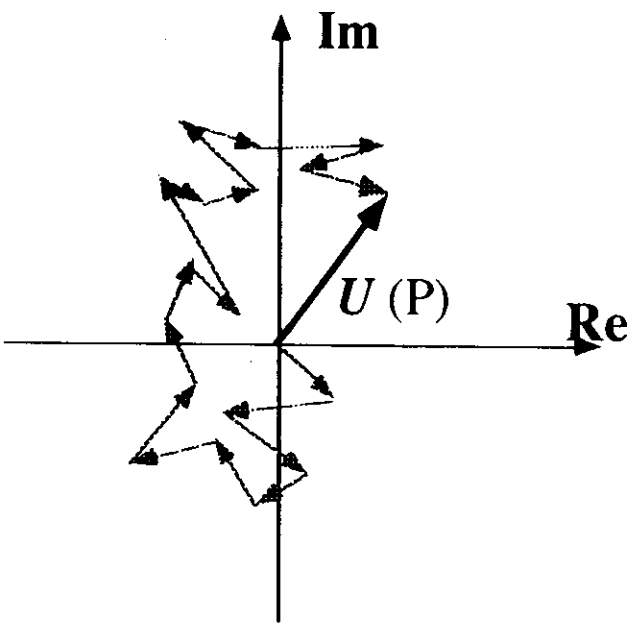
$\sigma_r = \sqrt{\langle U_r^2 \rangle - \langle U_r \rangle^2}$

$\sigma_i = \sqrt{\langle U_i^2 \rangle - \langle U_i$

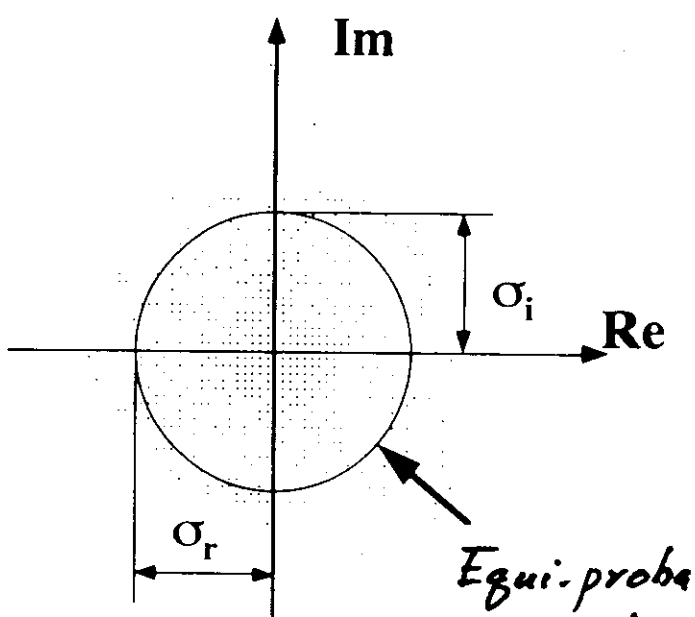
standard devia

of the ampli

Gaussian distribution → **Gaussian speckle**



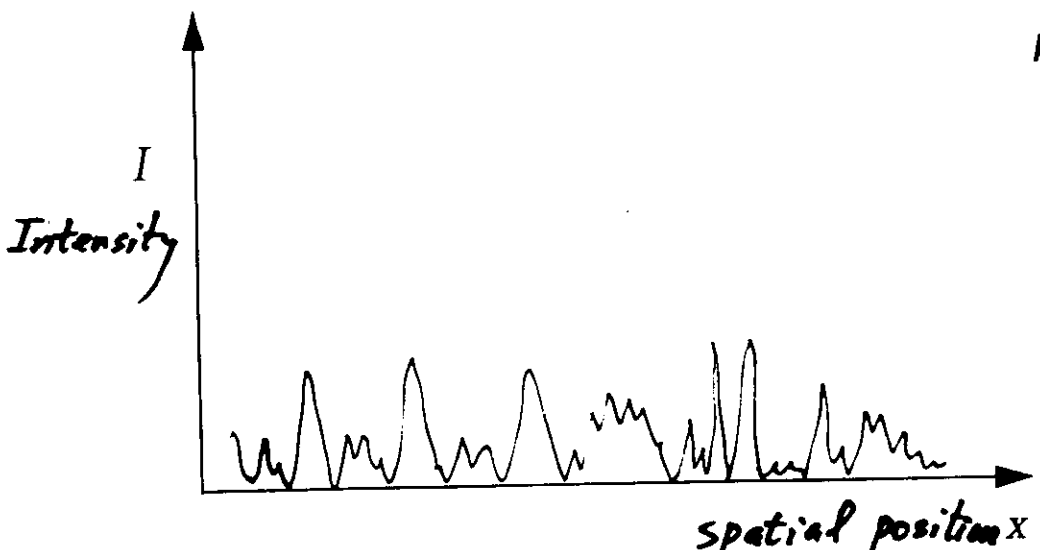
Random walk problem

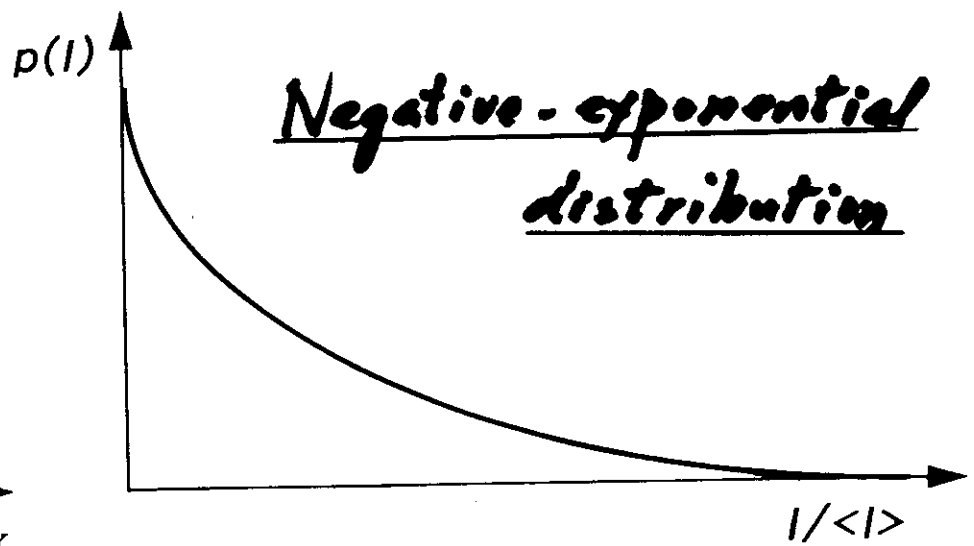


Circular statistics

Probability density function of intensity

$$p(I) = \frac{1}{\langle I \rangle} \exp\left[-\frac{I}{\langle I \rangle}\right] \quad ; \quad I = |U(\mathrm{P})|^2$$



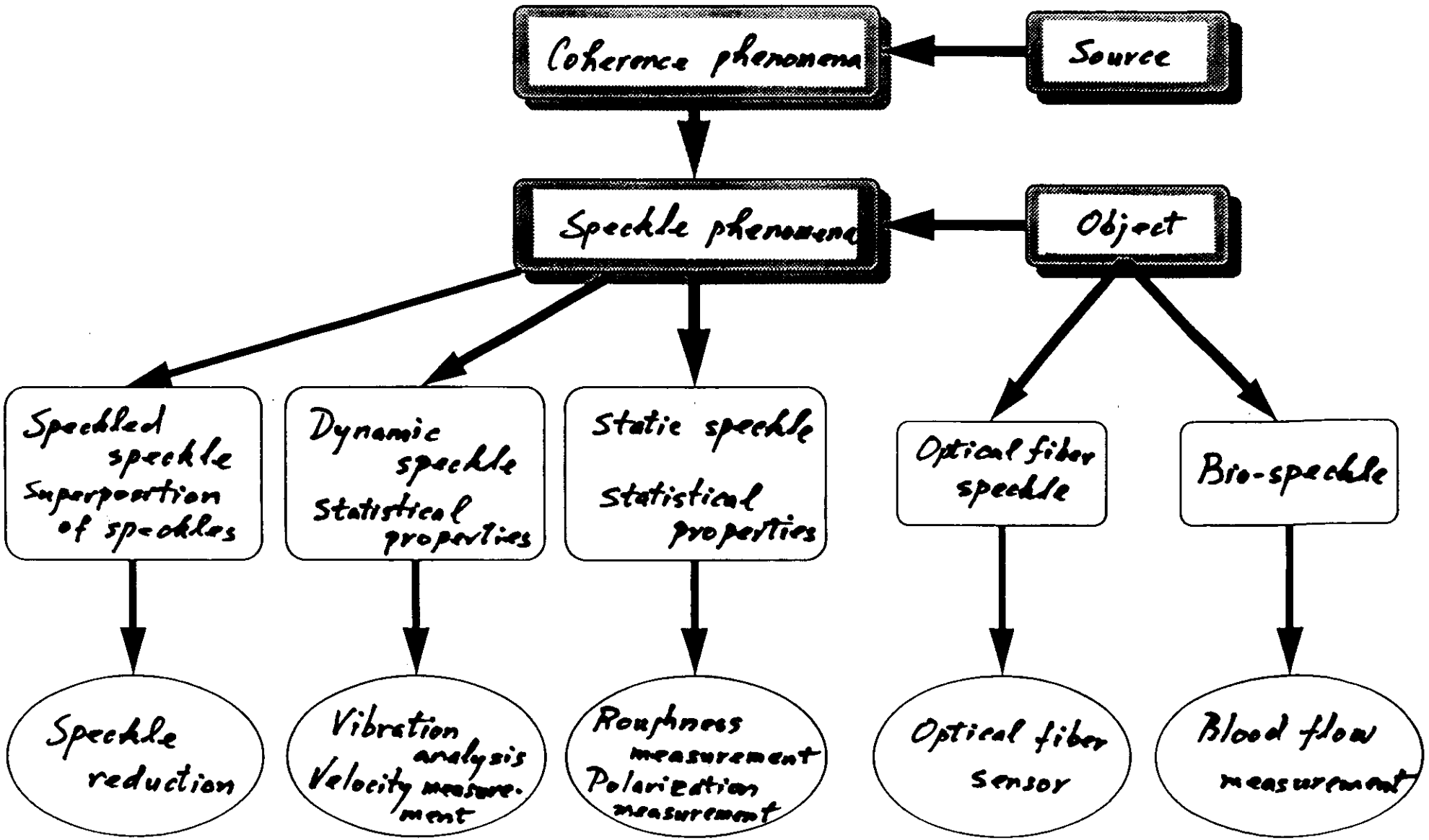


Negative-exponential distribution

Average contrast

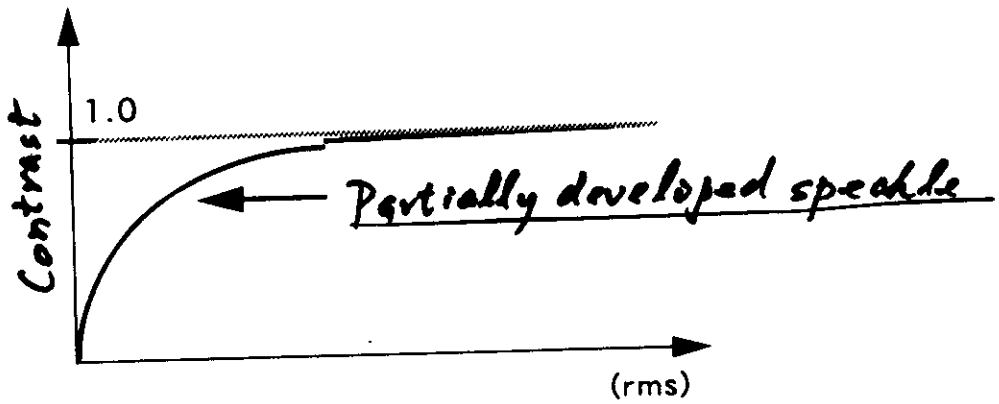
$$C = \frac{\sigma_I}{\langle I \rangle} = \frac{\sqrt{\langle I^2 \rangle - \langle I \rangle^2}}{\langle I \rangle} = 1 \longrightarrow$$

Fully developed speckle

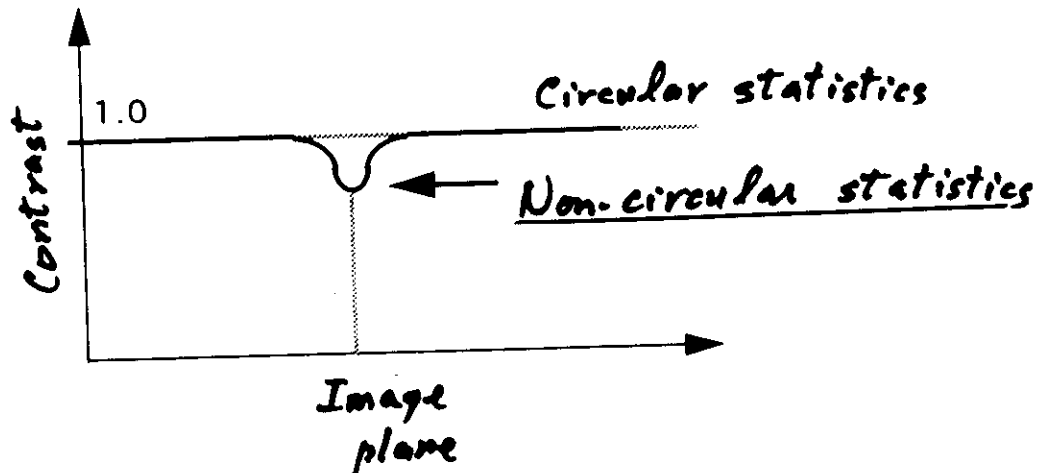

Coherence phenomena
Source
Speckle phenomena
Object
Speckled speckle
Superposition of speckles
Dynamic speckle
Statistical properties
Static speckle
Statistical properties
Optical fiber speckle
Bio-speckle
Speckle reduction
Vibration analysis
Velocity measurement
Roughness measurement
Polarization measurement
Optical fiber sensor
Blood flow measurement

Three experiments leading to new discoveries

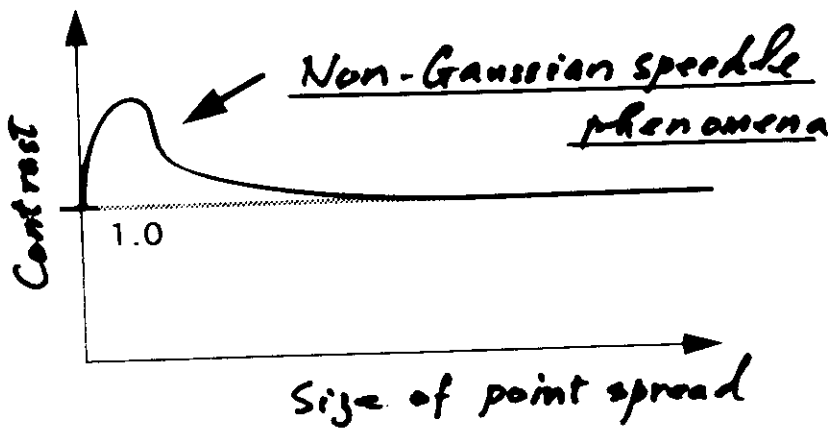
① Dependence of speckle on surface roughness



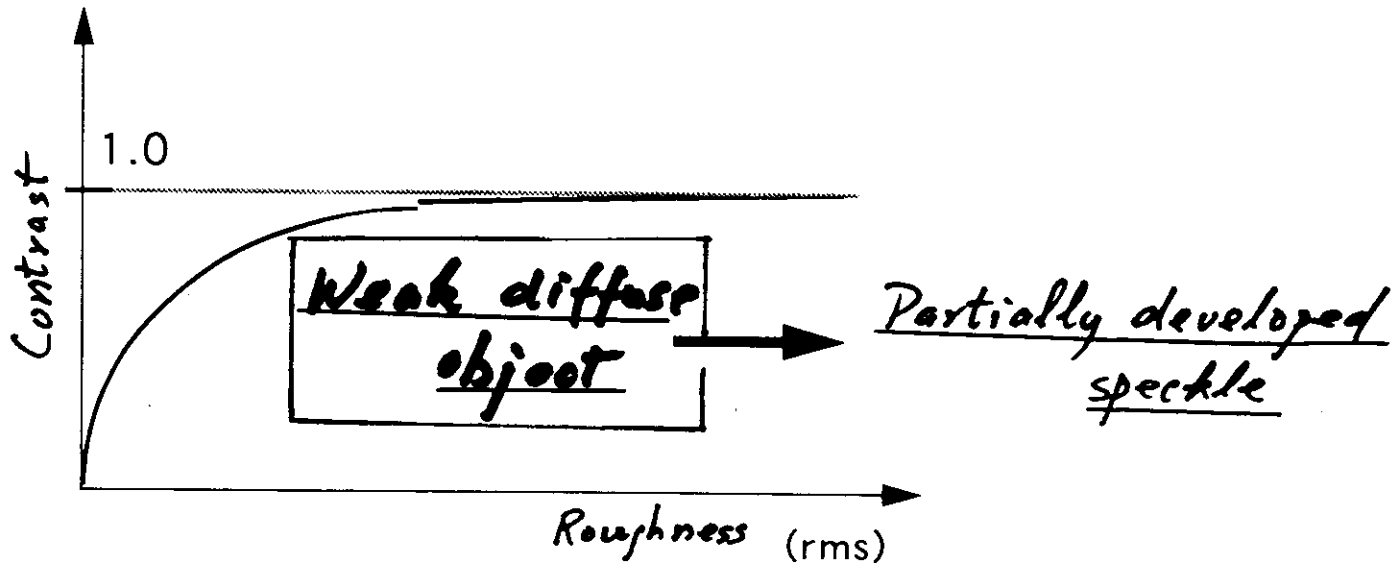
② Circular statistics, non-circular statistics

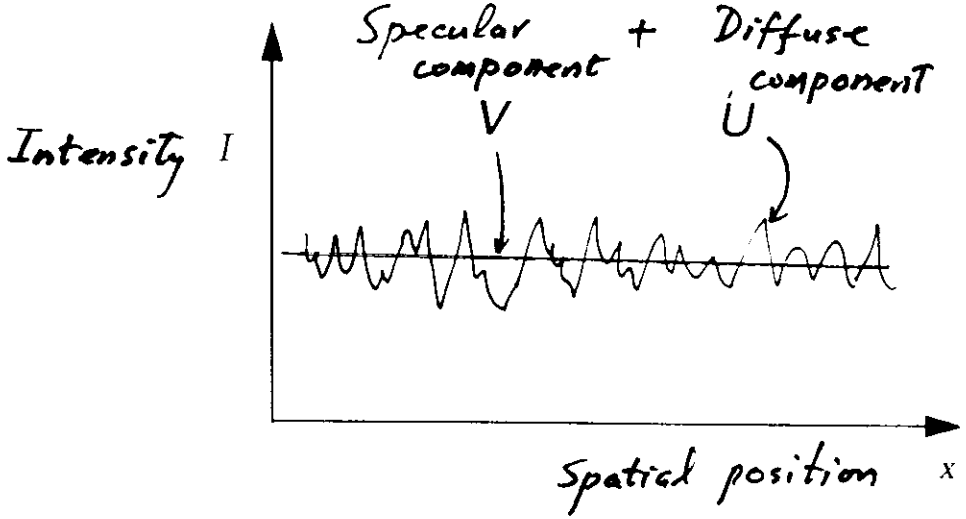


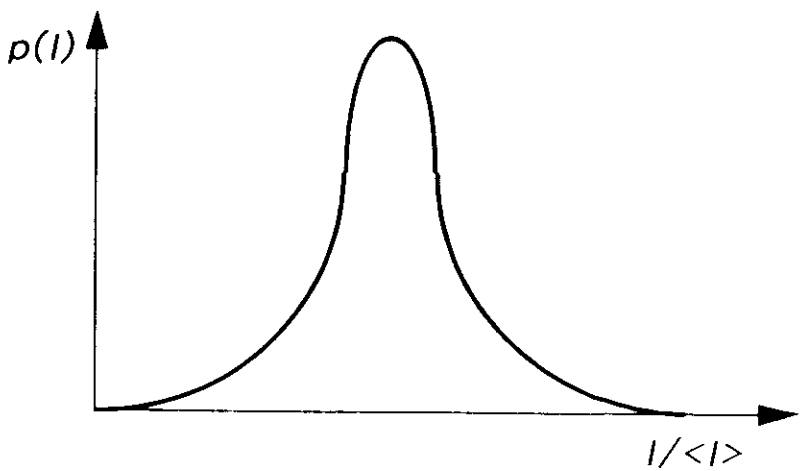
③ Gaussian speckle, non-Gaussian speckle



Dependence of speckle on surface roughness



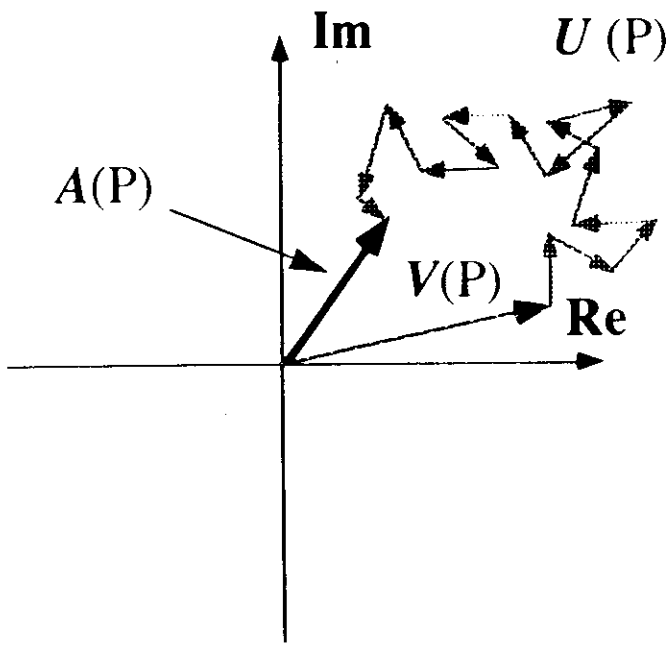


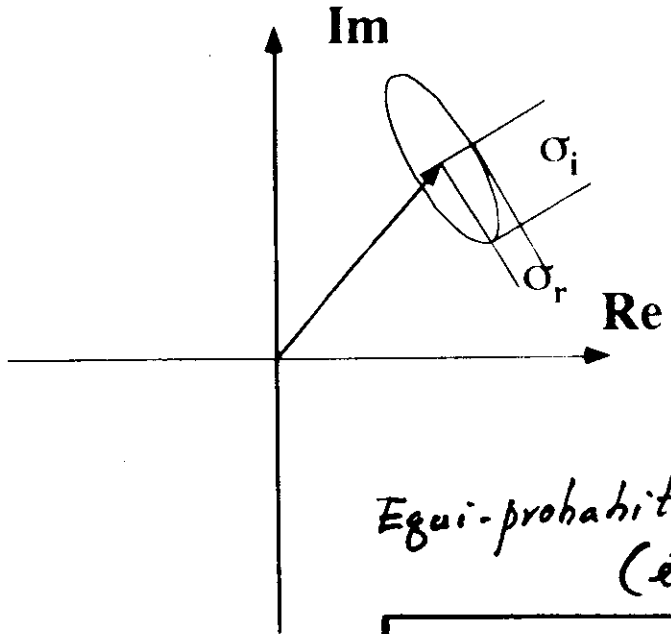


Amplitude probability density function of partially developed speckle

$$A(\mathrm{P}) = U(\mathrm{P}) + V(\mathrm{P}) = \left\{U_r(\mathrm{P}) + i\,U_i(\mathrm{P})\right\} + \left\{V_r(\mathrm{P}) + i\,V_i(\mathrm{P})\right\}$$
$$= A_r(\mathrm{P}) + i\,A_i(\mathrm{P})$$
$$U(\mathrm{P}) = \sum_{k=1}^{N} |u_k(\mathrm{P})| \exp\left[-i\varphi_k\right]$$

$$p(A_r, A_i) = \frac{1}{2\pi\sigma_r\sigma_i\sqrt{1-\rho^2}} \times \exp\left[-\frac{1}{2(1-\rho^2)}\left(\frac{\Delta A_r^{\,2}}{\sigma_r^{\,2}} - \frac{2\rho\,\Delta A_r\,\Delta A_i}{\sigma_r\sigma_i} + \frac{\Delta A_i^{\,2}}{\sigma_i^{\,2}}\right)\right]$$



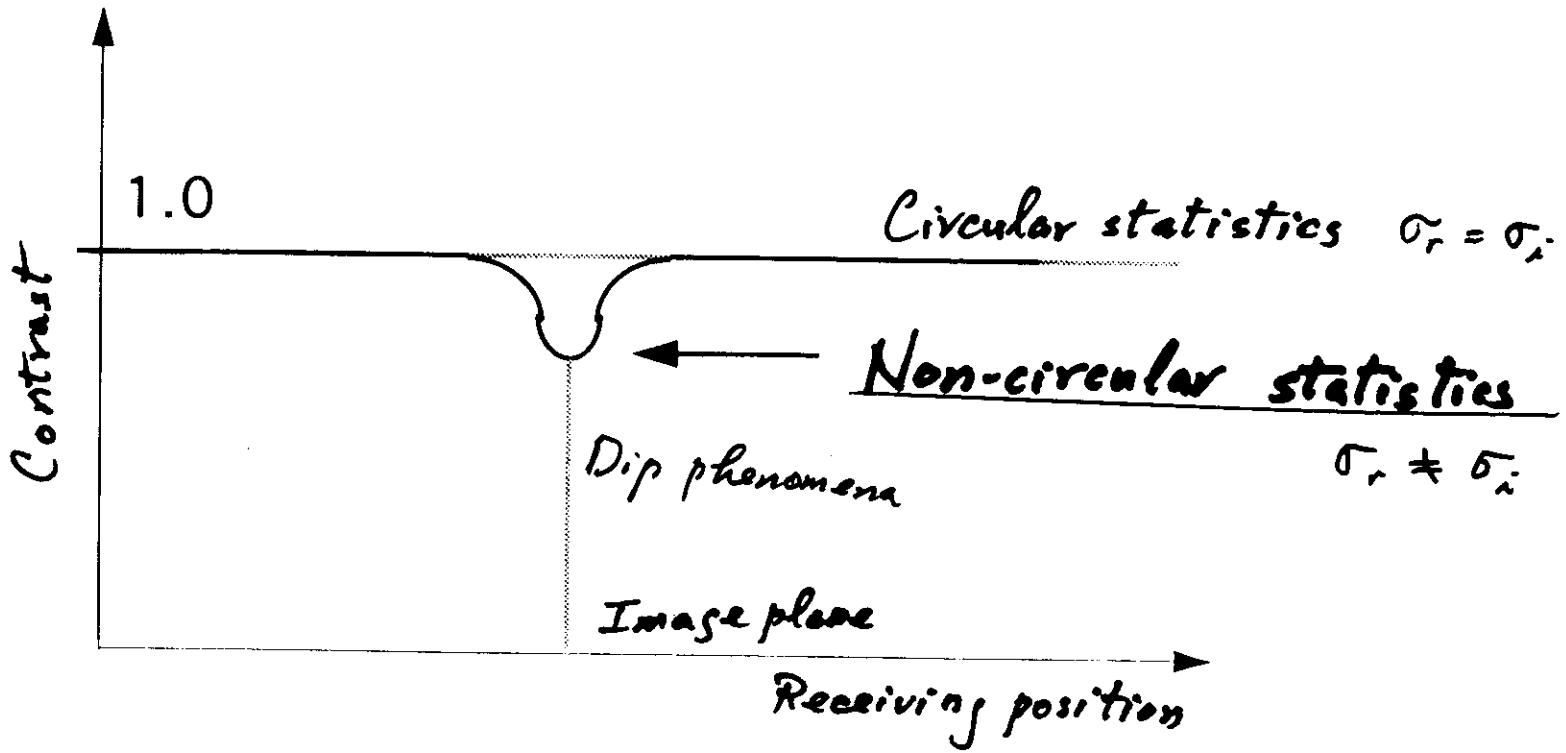


$$\Delta A_r = A_r - \langle A_r \rangle$$
$$\Delta A_i = A_i - \langle A_i \rangle$$
$$\rho = \frac{\langle \Delta A_r \Delta A_i \rangle}{\sigma_r \sigma_i}$$
$$\sigma_r = \langle A_r^2 \rangle - \langle A_r \rangle^2$$
$$\sigma_i = \langle A_i^2 \rangle - \langle A_i \rangle^2$$

Equi-probability density lin
(elliptic)

Non-circular statistics

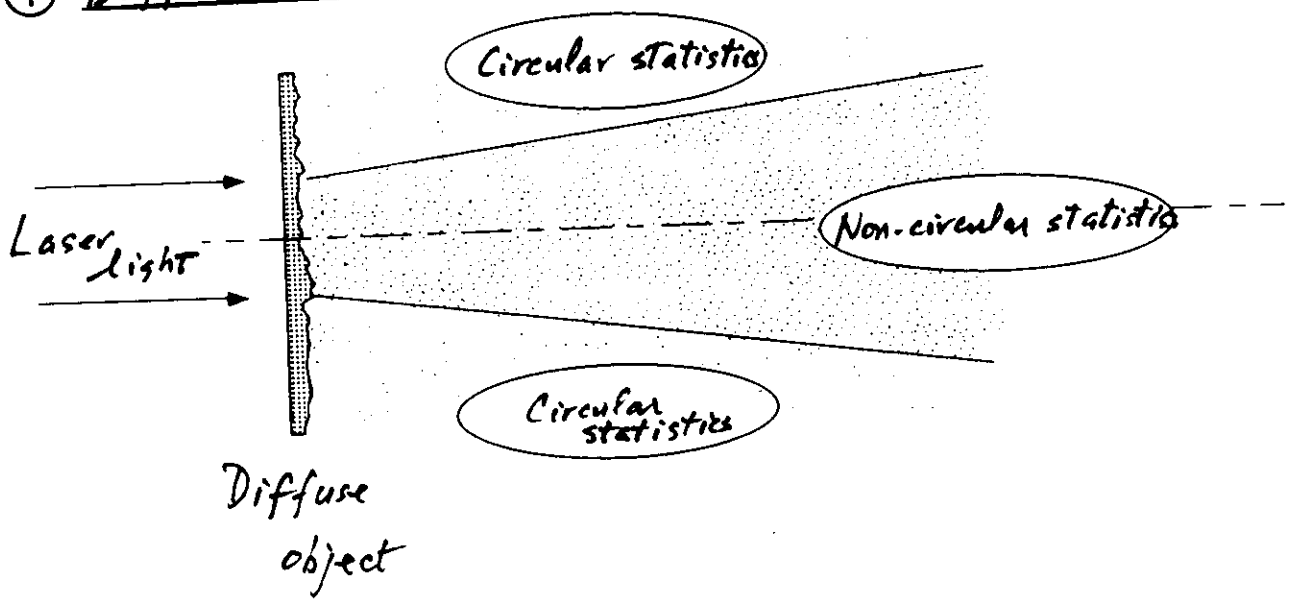
Circular statistics and non-circular statistics



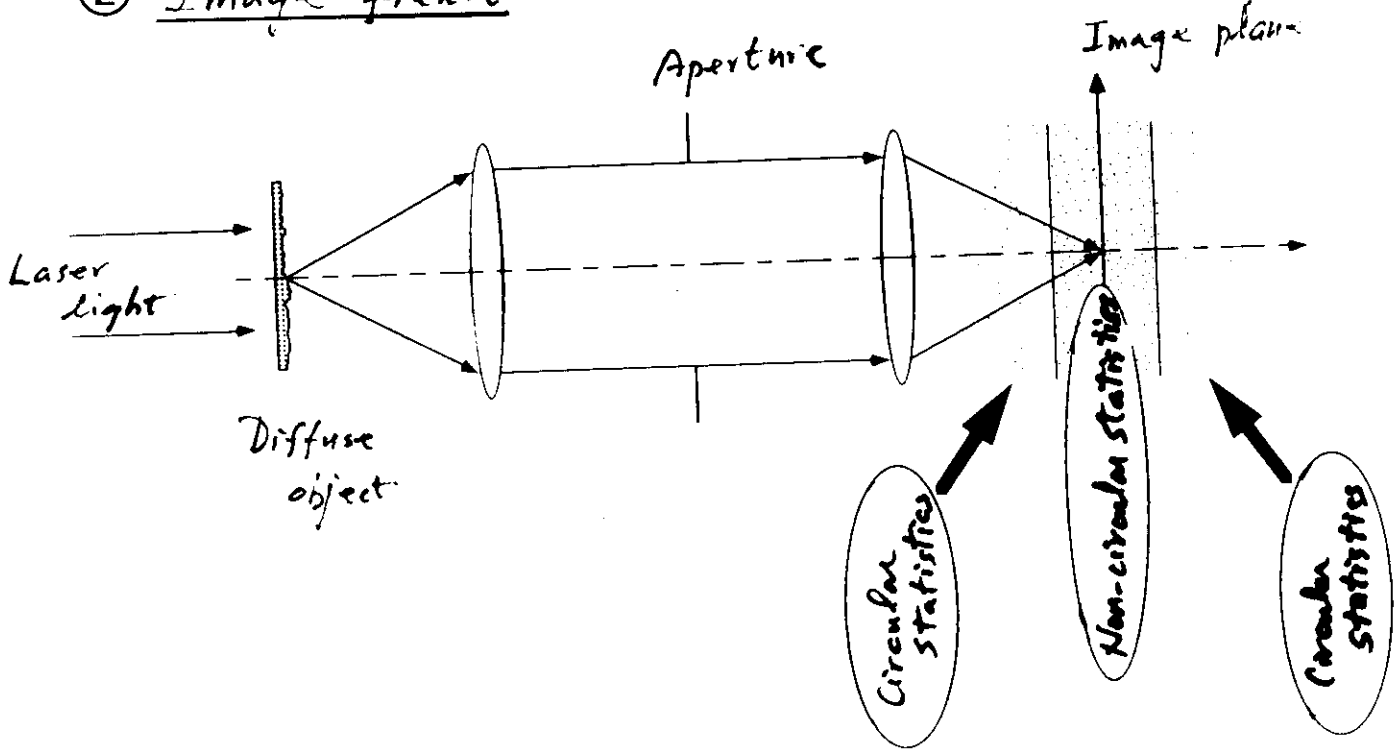
$$C = \frac{\sqrt{2\left(\sigma_r^{\,2} + \sigma_i^{\,2}\right) + 4\left\langle A_r \right\rangle^2 \sigma_r^{\,2}}}{\sigma_r^{\,2} + \sigma_i^{\,2} + \left\langle A_r \right\rangle^2}$$

Regions of circular statistics and non-circular statistics

① Diffraction field

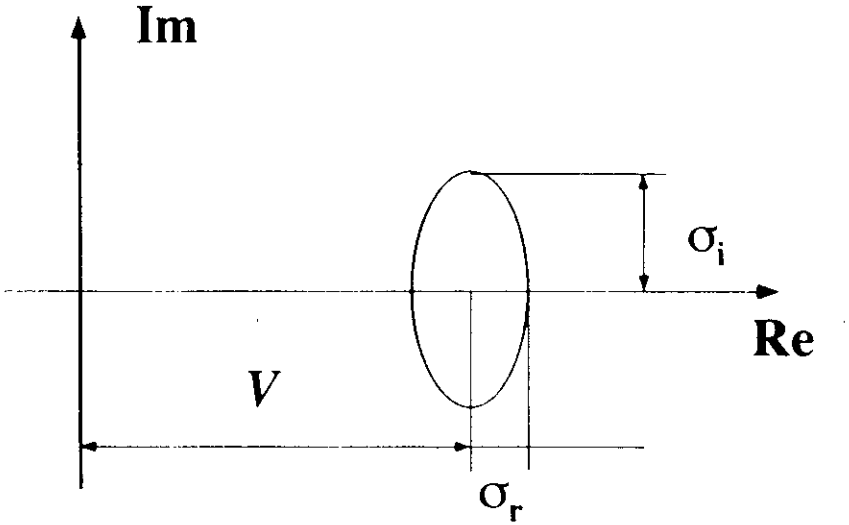


② Image field



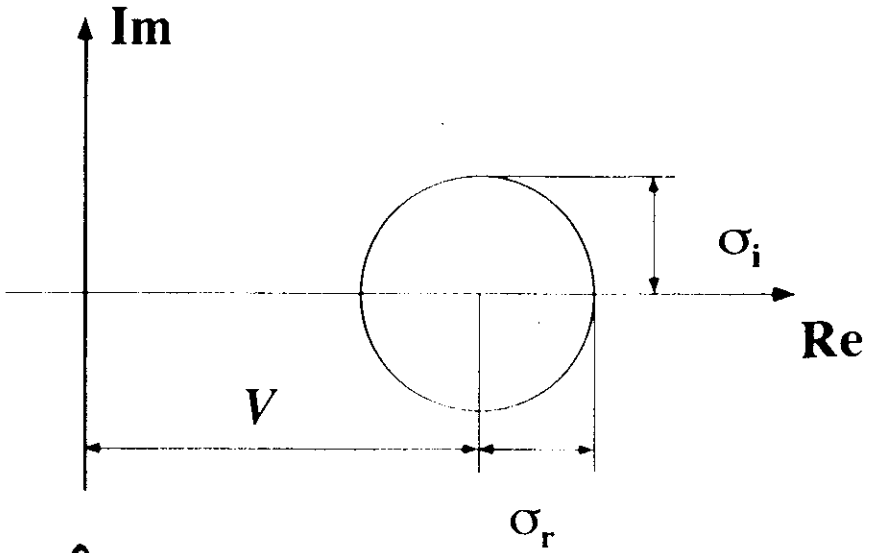
Non-circular statistics

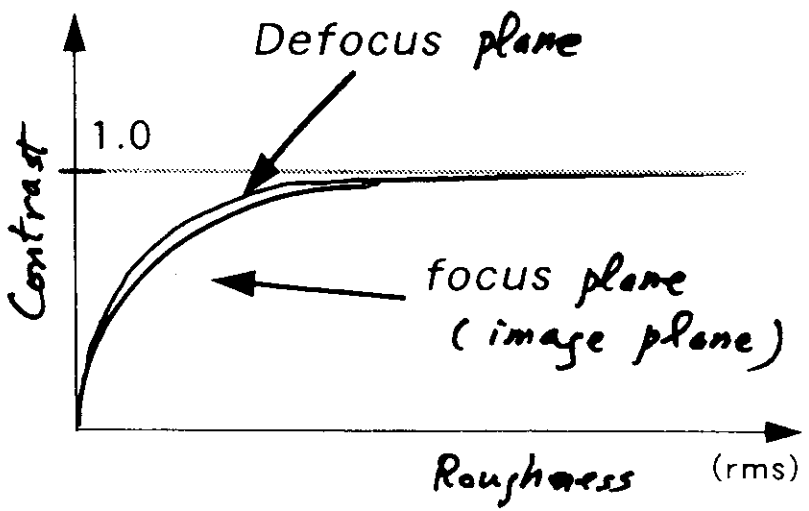
$$\sigma_r^{\,2} \neq \sigma_i^{\,2}$$

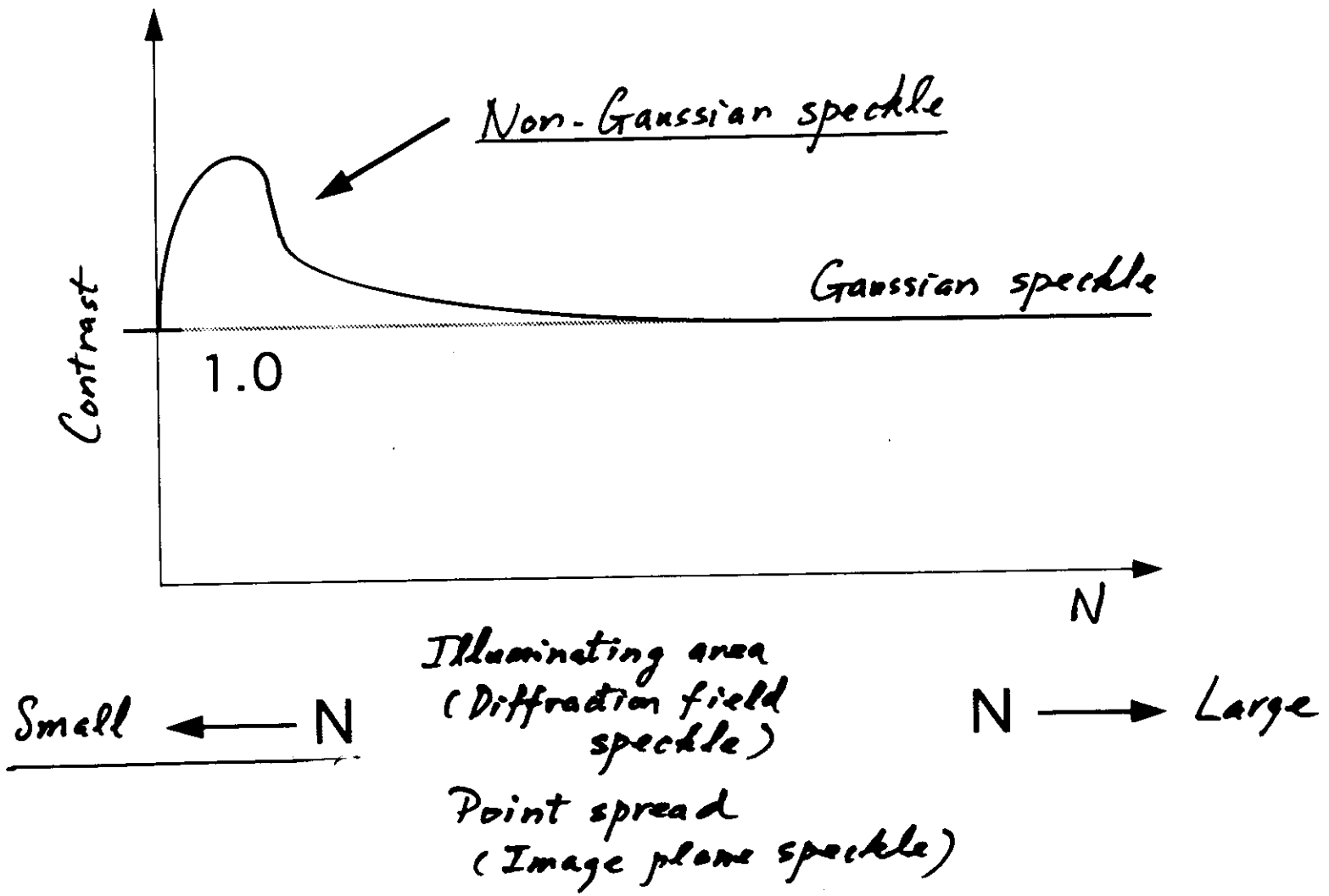


Circular statistics

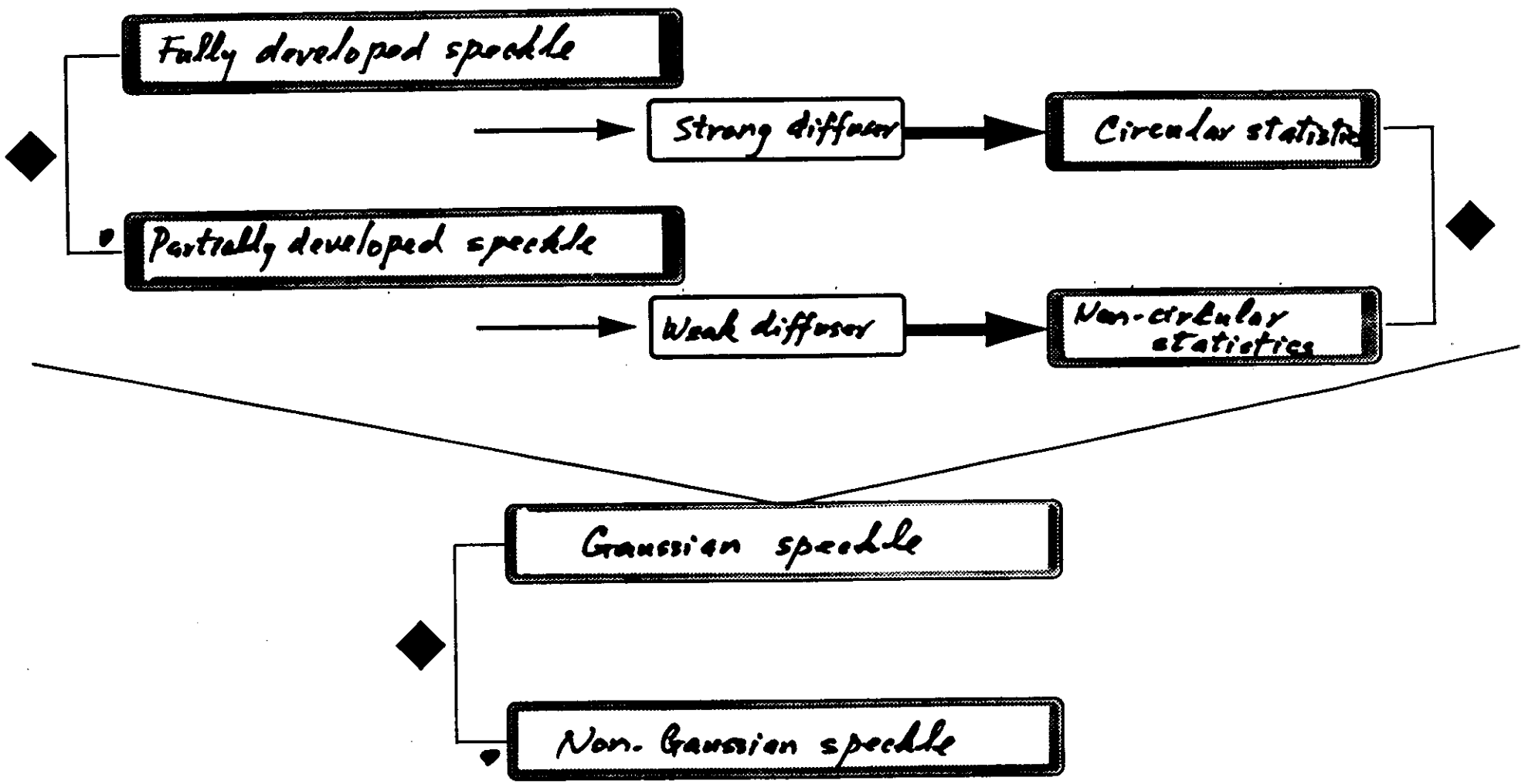
$$\sigma_r^{\,2} = \sigma_i^{\,2}$$

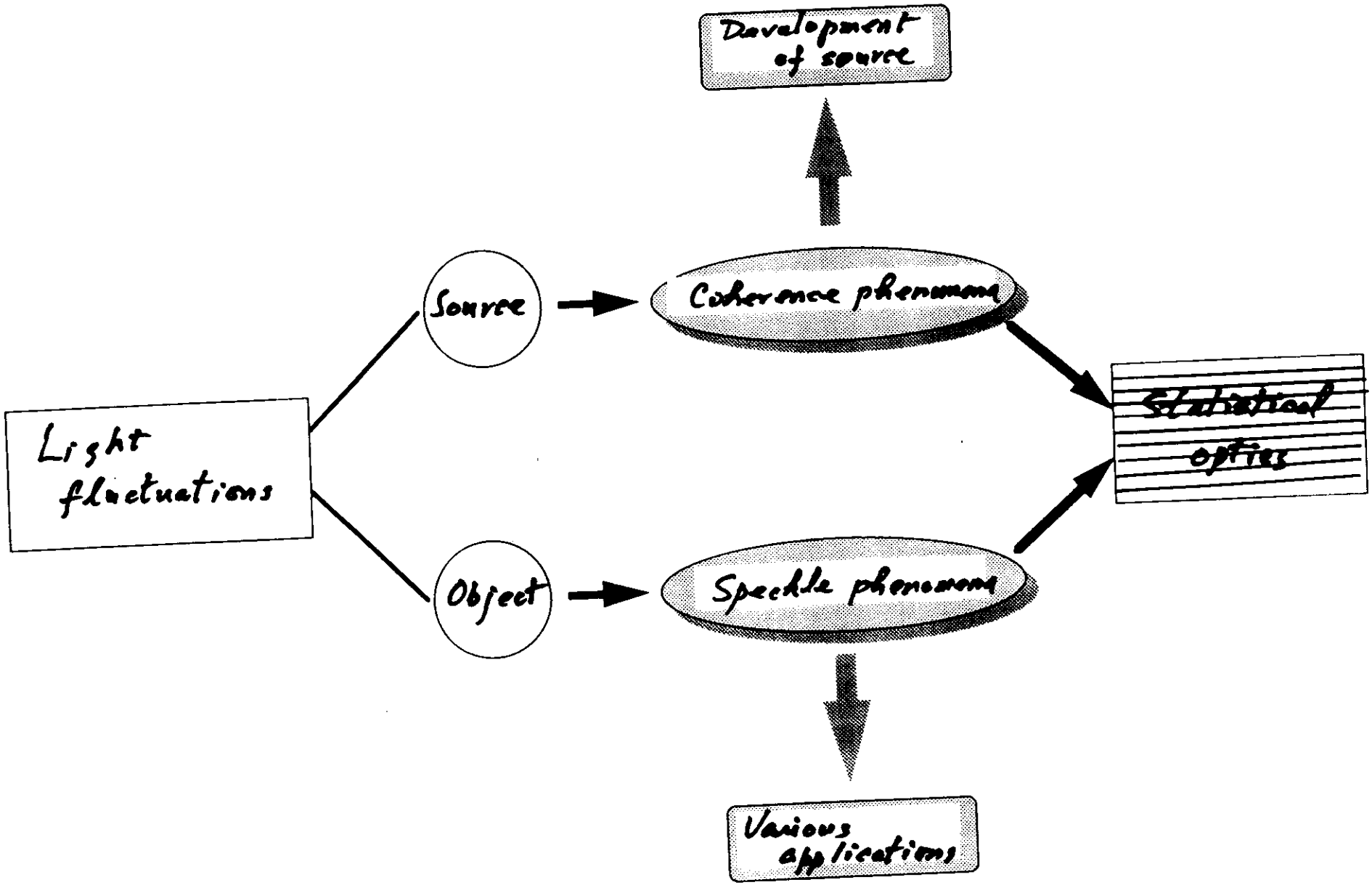





Non-Gaussian speckle
Gaussian speckle
Contrast
1.0
N
Illuminating area
(Diffraction field speckle)
Small ← N
N → Large
Point spread
(Image plane speckle)

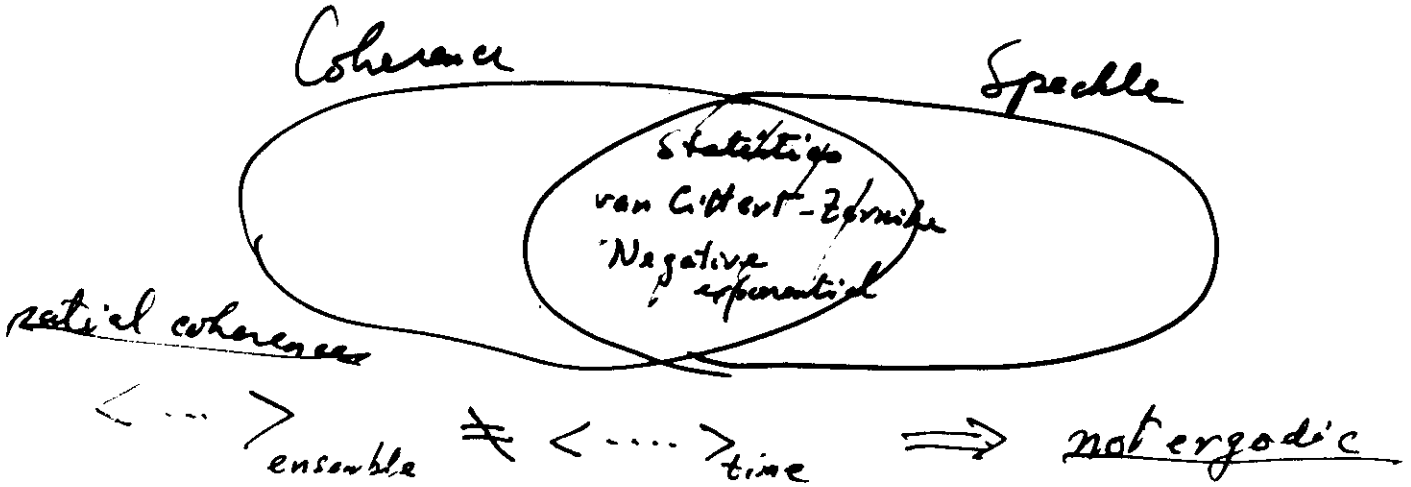
New phenomena (Speckle)




Development of source
Source
Coherence phenomena
Statistical optics
Light fluctuations
Object
Speckle phenomena
Various applications

Coherence and Speckle

	Coherence	Speckle
Cause of fluctuations	Source	Scatterers
Fluctuations	Temporal and spatial	Temporal and/or spatial
Observation	Invisible	Visible
Average	$\langle \rangle_e = \langle \rangle_T$ time average	$\langle \rangle_e = \langle \rangle_s$ spatial average
Field expression	Analytic signal	Non-analytic
Young's fringe condition	Two-pinhole within coherence area	Two-pinholes over whole area



$\langle \cdots \rangle_{ensemble} \neq \langle \cdots \rangle_{time} \Rightarrow$ <u>not ergodic</u>

Problems on speckle

- Role of polarization in speckle
- Statistical properties of the speckle phase
- White-light and polychromatic light speckles
- Time-varying speckle < Boiling, Translation (Partially coherent light)
  - Dynamic speckle
    - Speckled speckle
    - Superposition of speckles — Reduction of speckle
    - Fiber speckle — Modal noise
    - Bio-speckles : Dynamic speckle
      - Speckle from fractals