Module Certificate

Enrolment for the module

- Within six weeks after starting the lectures

Requirements for written examination

- Regular participation in lectures and exercises

→ **Written examination**

Monday, 22nd February 2016, 10:00 – 12:00 hours,
lecture hall 2, Abbeanum

→ **4 credit points**

1.1. Contents of the Lectures

November 2010

Contents

References

Bass (Ed.)	*Handbook of Optics II*, McGraw-Hill, New York, 1995
Born/Wolf	*Principles of Optics*, Pergamon Press, Oxford, 1999
Gasvik	*Optical Metrology*, Wiley & Sons, Chichester, 1987
Goodman	*Introduction to Fourier Optics*, McGraw-Hill, New York, 1988
Hariharan	*Interferometry*, Cambridge Univ. Press, 1986
Hernandez	*Fabry-Perot-Interferometer*, Cambridge Univ. Press, 1986
Hecht	*Optics* , *Addison Wesley*, San Francisco, 2002
Klein/Furtak	*Optik*, Springer-Verlag, Berlin 1986
Kreis	*Holographic interferometry*, Akademie Verlag, Berlin, 1996
Lauterborn	*Kohärente Optik*, Springer-Verlag, Berlin, 1993
Ludmann u.a.	*Holography for the new millenium*, Springer, New York, 2002

References

Malacara u.a. *Handbook of Optical Engineering*, Dekker, New York, 2001

Mandel/Wolf *Optical Coherence and Quantum Optics*, Cambridge Press, 1995

Pedrotti u.a. *Optik*, Prentice Hall, München, 1996

Reynolds u.a. *Physical Optics Notebook: Tutorials in Fourieroptics*, SPIE, 1989

Sirohi (Ed.) *Speckle Metrology*, Dekker, New York, 1993

SPIE *Proceedings*

Steel *Interferometry*, Cambridge University Press, Cambridge, 1987

Young *Optik, Laser, Wellenleiter*, Springer-Verlag, Berlin, 1997

Wolf (Ed.) *Progress in Optics*, North-Holland Physics Publishing, Amsterdam, Book series since 1961

Optical metrology → essentially measurement of length

<u>Industry:</u> Precision measuring technique

<u>Demands</u>

- Positioning accuracy of workpieces < 20 nm
- Reproducibility of dimensional measurements < 10 nm

<u>Machine building</u>

- Lengths to be measured $\leq$ 100 mm (... some m) with $\pm$ 1 μm

(1 μm = extension of a Fe-rod (1 m) for ΔT = 1 K)

Characterization of measuring devices

1) Test piece/specimen/measuring object scanning/sensing
2) Measurement signal (material measure, standard, etalon)
3) Amplification of the signal
4) Indication of the measured value

If 1) or 2) or 3) is performed out optically

Optical measuring instrument

Methods

Wave nature of light

Diffraction

Interference (Coherence)

Interferometer

Laser

Laser dimension measuring devices

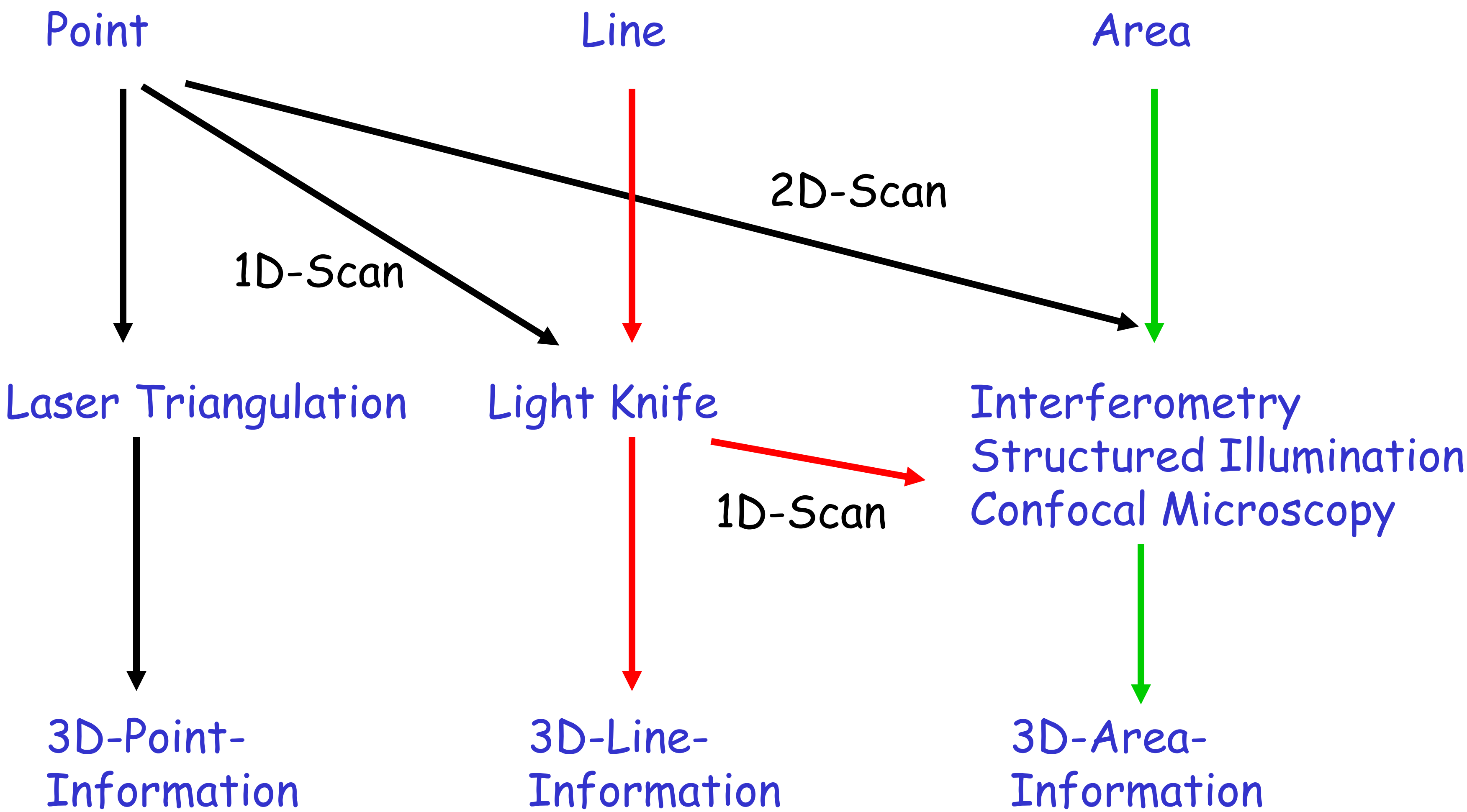
Holographic Techniques

Speckle-Techniques

Other Systems

1.2. Characterization of the Field

Classification



Result of Measurement = Measured Value ± Uncertainty of Measurement

Measurement Terms

Accuracy: In situations where we believe that the measured value is close to the true value, we say that the measured value is accurate.

Precision: When values obtained by repeat measurements of a particular quantity exhibit little variability, we say that those values are precise.

Attention: Precision and accuracy are qualitative terms!

Measurement Terms

Repeatability: (of a gage) How capable a gage is of providing the same reading for a single user when measuring a specific sample.

Reproducibility: Ability for different users to get the same reading when measuring a specific sample.

Resolution: Smallest amount of input signal change the instrument can detect reliably.

Sensitivity: Smallest signal the instrument can measure.

Result of Measurement = Measured Value ± Uncertainty of Measurement

Errors (selection)

- Material measure (standard, etalon)
- Mechanical “failures” of the system
- Distortion of the Abbe comparator principle
- Environments
- Experimenter/observer

1.2. Characterization of the Field

Systematic and Random Errors

Systematic errors with unknown sign

Correction of the measured value

Uncertainty of Measurement

Normal (Gaussian) distribution of measured values

Within interval $\pm\,\sigma$ are 68.27 % $\forall$ measured values (statist. certainty: 68.27 %)

Within interval $\pm\,2\sigma$ are 95.45 % $\forall$ measured values (statist. certainty: 95.45 %)

Within interval $\pm\,3\sigma$ are 99.73 % $\forall$ measured values (statist. certainty: 99.73 %)

Denotation:

For a given statistical certainty the corresponding range is called $\pm c\cdot\sigma$ confidence interval (CI).

The true value lies within the confidence interval for a given statistical certainty if there are no systematic errors.

Propagation of errors

Systematic Errors:

$$df = \frac{\partial f}{\partial x}dx + \frac{\partial f}{\partial y}dy + \frac{\partial f}{\partial z}dz$$

Statistical Errors:

$$u = \pm\sqrt{\left(\frac{\partial f}{\partial x}\right)^2 (dx)^2 + \left(\frac{\partial f}{\partial y}\right)^2 (dy)^2 + \left(\frac{\partial f}{\partial z}\right)^2 (dz)^2}$$

Definition of the Meter

1791: French Academy of Sciences

1 m = one ten-millionth part of the quadrant of the earth's meridian

1875: **Treaty of the Meter (Meter Convention)**

General Conference on Weights and Measures (GCPM)

International Bureau of Weights and Measures (BIPM)

1889: **International Prototype**

("final" definition 1927 by 7th GCPM)

1.3. Definition of the Meter

Uncertainty of the Prototype

1. External conditions

$\Delta T = \pm 0.001^{\circ}$ $\longrightarrow$ $\boxed{\Delta l/l = \pm 10^{-8}}$

2. Measurement procedure

- Engraved lines
- Illumination, cross section, contamination

$\longrightarrow$ $\boxed{\Delta l/l = \pm 2 \cdot 10^{-7}}$

3. Instability

$$\longrightarrow \boxed{\textbf{Uncertainty} \begin{cases} > \pm 10^{-7} \\ < \pm 10^{-6} \end{cases}}$$

1.3. Definition of the Meter

Required Accuracy

Everyday life: $\Delta l/l = \pm 10^{-3}$ (commerce)

$\Delta l/l = \pm 10^{-6}$ (gauge block)

Physics: $\Delta l/l = \pm 10^{-7}$

Problems with the Prototype

- arbitrary unit
- unique unit

→ Hierarchy of secondary standards, prototypes

→ Propagation of errors

1.3. Definition of the Meter

Definition of the Meter based upon the Wavelength

1893: Michelson: 1st measurement with red Cd-line

1906: Benoit, Fabry, Perot: measurement repeated

1927: 7th GCPM

red Cd - Line = primary standard for spectroscopy

(dry air, 15 °C, 101.33 kPa, carbonic acid 0.03 volume percent)

Disadvantages

1) Wavelength in air
2) Cd - emission non-monochromatic
3) Michelson - Lamp
4) Bad reproducibility
5) Insensitive SEM's

1.3. Definition of the Meter

1960: 11th GCPM

Kr - wavelength = new standard

1m = 1,650,763.73 vacuum wavelength of the radiation of

$$^{2}p_{10} \longrightarrow {}^{5}d_{5} \text{ of } {}^{86}_{36}\mathrm{Kr}$$

(λ = 605.8 nm)

Advantages

1) Vacuum
2) No Hyperfine structure
3) No instruction for the generation of the radiation

Uncertainty

$$\Delta l/l = \pm 10^{-8} \ldots \pm 4 \cdot 10^{-9}$$

1.3. Definition of the Meter

<u>1983:</u>

1 m = length of the path travelled by light in vacuum during a time interval of 1/299,792,458 s

SI base units	relative uncertainty (realization)
s	10^{-14}
m	10^{-14}
kg	0
A	10^{-6}
K	10^{-6}
mol	10^{-5}
Cd	$5 \cdot 10^{-3}$

1.4. Some Basics

Coherence = Capability of Interference

→ Correlation of wave fields
(coherence function)

a) Spatial Coherence

Coherence = f (dimensions of the source of light)

→ Point source = spatially coherent

Measurement procedure: Young Interferometer

b) Temporal Coherence

Finite „wave train“

path difference too high → no interference

Measurement procedure: Michelson interferometer

1.4. Some Basics

Temporal Coherence

Source	$\Delta\lambda$ [nm]	$\Delta\nu$ [Hz	Δl_c [m]
Hg (high-pressure) 546 nm	10	10^{13}	$3\cdot10^{-5}$
Hg (low-pressure) 546 nm	1	10^{12}	$3\cdot10^{-4}$
Ar-Laser 514 nm	$9\cdot10^{-3}$	10^{10}	$3\cdot10^{-2}$
He-Ne-Laser (multimode) 633 nm	$4\cdot10^{-3}$	$3\cdot10^{9}$	0,1
He-Ne-Laser (stabilized) 633 nm	$1.3\cdot10^{-10}$	100	$3\cdot10^{6}$
LED 631 nm	$3\cdot10$	$3\cdot10^{13}$	10^{-5}