7. Principles of Phase Doppler Anemometry

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General features of PDA

- **Extension of the LDA principle**

- **Simultaneous measurement of velocity (up to 3 components) and size of spherical particles as well as mass flux, concentration etc.**

- **First publication by Durst and Zaré in 1975**

- **First commercial instrument in 1984**

- **Non-intrusive measurement (optical technique), on-line and in-situ**

- **Absolute measurement technique (no calibration required)**

- **Very high accuracy**

- **Very high spatial resolution (small measurement volume)**

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Preconditions for the application of PDA

- **Optical access to the measurement area (usually from two directions)**

- **Sphericity of particles (droplets, bubbles, solids)**

- **Homogeneity of particle medium**
  (slight inhomogeneities may be tolerated if the concentration of the inhomogeneities is low and if the size of the inhomogeneities is much smaller than the wavelength used)

- **Refractive indices of the particle and the continuous medium must usually be known**

- **Particle size between ca. 0.5 µm and several millimeters**

- **Max. particle number concentration is limited**

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Principle setup of PDA

**Optical parameters
of a PDA setup:**

- **Beam intersection angle θ**

- **Scattering angle φ**

- **Elevation angle ψ**

- **Polarization (parallel or perpendicular to scattering plane)**

- **Shape and size of detector aperture**

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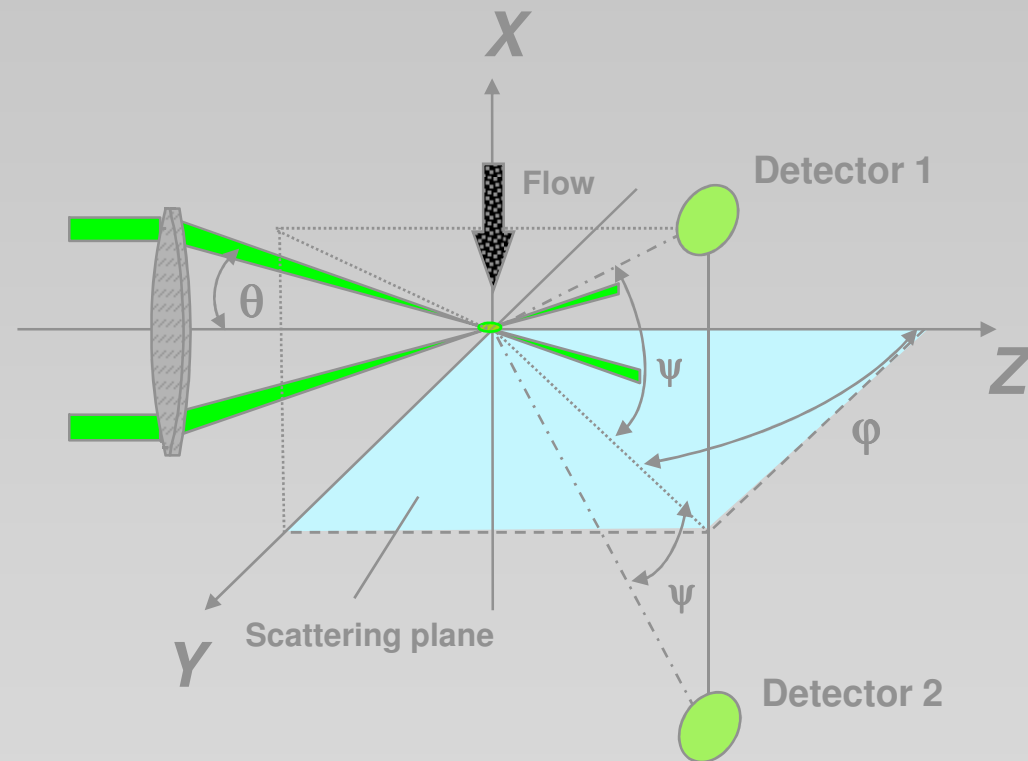
Optical principle of PDA

- **A particle scatters light from two incident laser beams**

- **Both scattered waves interfere in space and create a beat signal with a frequency which is proportional to the velocity of the particle**

- **Two detectors receive this signal with different phases**

- **The phase shift between these two signals is proportional to the diameter of the particle**

Detector 1

Detector 2

Incident beams

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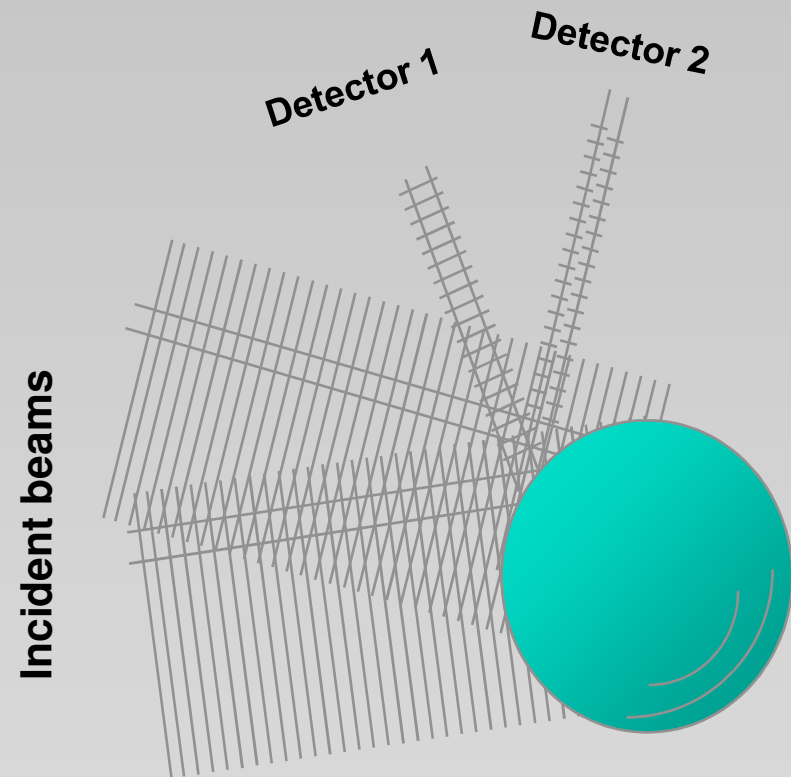
Light scattering principles

The principle of the PDA technique is the scattering of plane lightwaves by spherical particles.

A lightwave is fully described by:

- **wavelength**

- **intensity**

- **polarization**

- **phase**

Scattering is composed of:

- **diffraction**

- **reflection**

- **refraction**

- **absorption**

An exact description of the scattering of light by a homogeneous sphere is given by the full solution of Maxwell´s equations formulated by Mie in 1908.
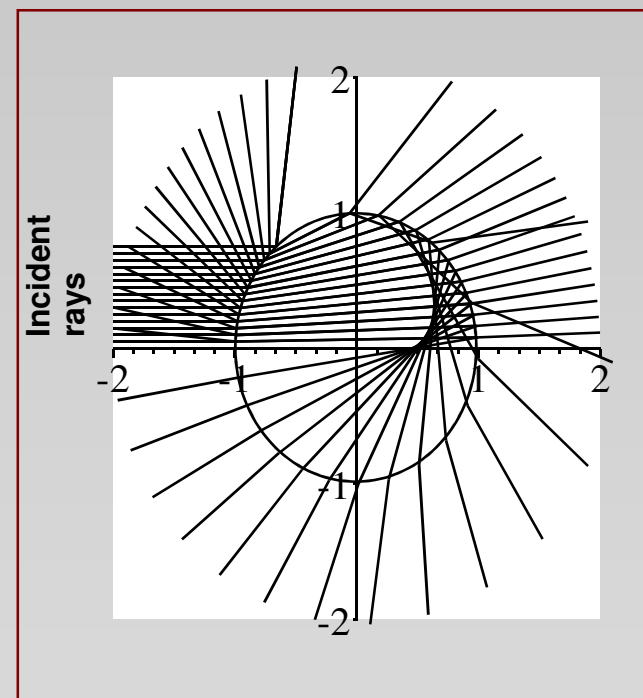
Geometric optics (Snell´s law) is a simplified way to describe light scattering.

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Light scattering by droplets and bubbles

Water droplet in air
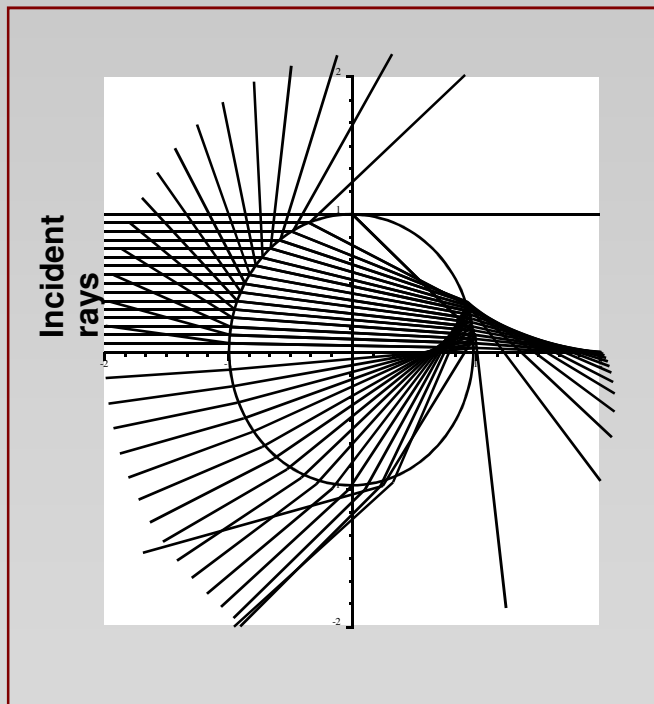
Air bubble in water

Phase relationships

The phase shift between two detectors is:

For reflection:

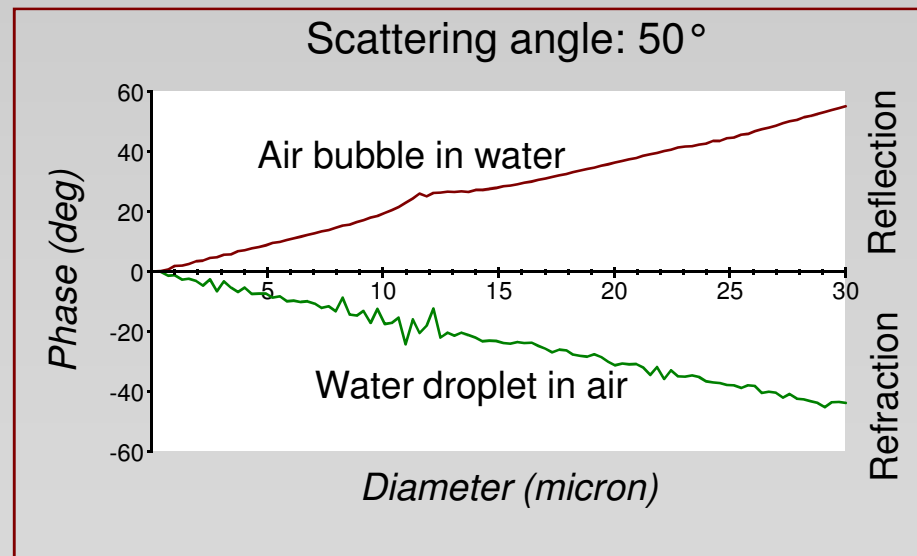$$\Phi = \frac{2\pi\, d_p}{\lambda}\, \frac{\sin\theta\ \sin\psi}{\sqrt{2(1-\cos\theta\ \cos\psi\ \cos\phi)}}$$

For 1st order refraction:

$$\Phi = \frac{-2\pi\, d_p}{\lambda}\, \frac{n_{rel}\ \sin\theta\ \sin\psi}{\sqrt{2\,(1+\cos\theta\ \cos\psi\ \cos\phi)\,(1+n_{rel}^2 - n_{rel}\ \sqrt{2\,(1+\cos\theta\ \cos\psi\ \cos\phi)}}}$$

No calibration constant is contained in these equations.

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Phase - diameter linearity

- **A linear relationship between measured phase difference and particle diameter only exists, if the detector is positioned such that one light scattering mode dominates.**

- **Simultaneous detection of different scattering modes of comparable intensity leads to non-linearities in the phase-diameter relationship.**
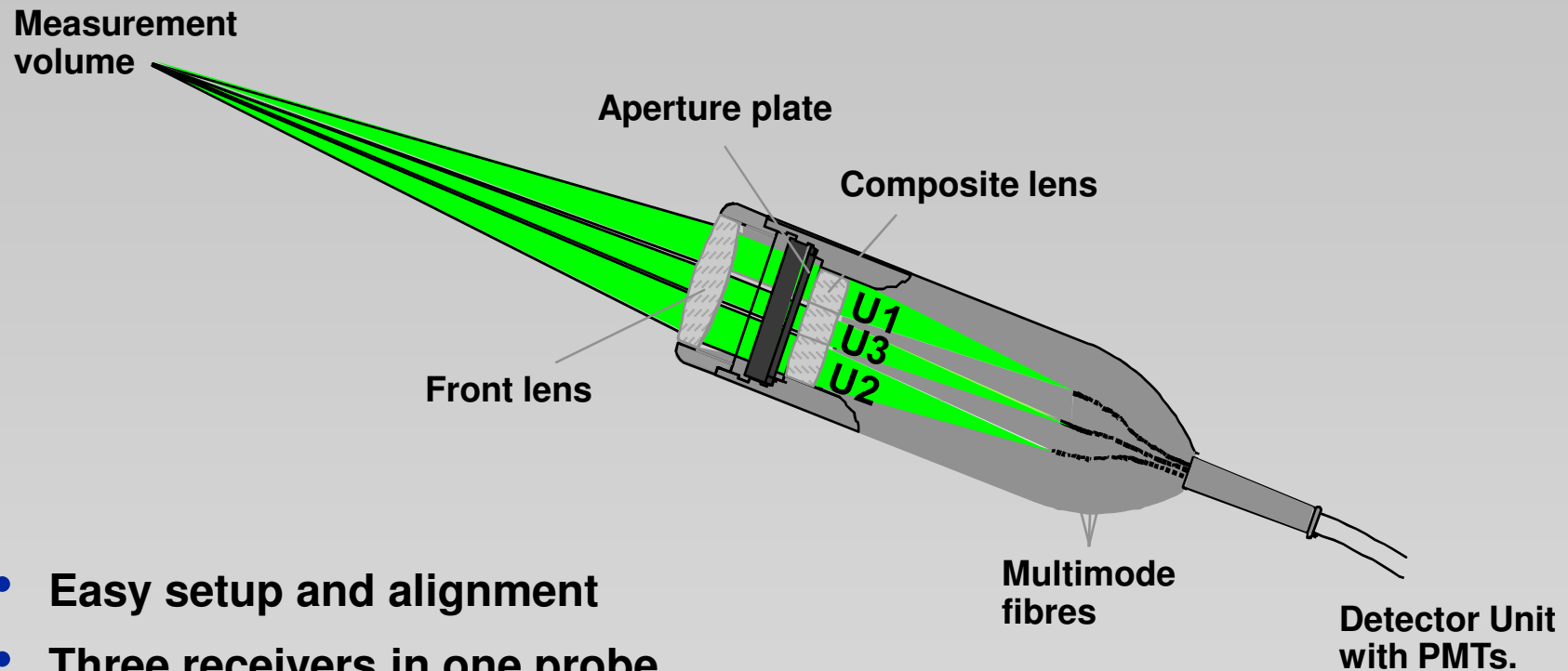
Scattering angle: 50°

Air bubble in water — Reflection

Water droplet in air — Refraction

Phase (deg): 60, 40, 20, 0, -20, -40, -60

Diameter (micron): 5, 10, 15, 20, 25, 30

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2π ambiguity in a two-detector system

- **The phase difference increases with increasing particle size.**

- **Since phase is a modulo 2π function, it cannot exceed 2π, i.e. 360°.**

- **Therefore, if a particle has a size that causes the phase to go beyond a 2π jump, a two-detector PDA cannot discriminate between this size and a much smaller particle.**

3-detector setup

- **Overcoming the 2π ambiguity**

- **Increasing the measurable size range**

- **Maintaining a high measurement resolution**

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Dantec 57X40 FiberPDA

Measurement volume

Aperture plate

Composite lens

U 1
U 3
U 2

Front lens

Multimode fibres

Detector Unit with PMTs.

- **Easy setup and alignment**
- **Three receivers in one probe**
- **Exchangeable aperture masks**
- **Up to three velocity components**

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Applications

- **Sprays and liquid atomization processes**
  - **Water sprays**
  - **Fuel-, diesel injection**
  - **Paint coating**
  - **Agricultural sprays**
  - **Medical, pharmaceutical sprays**
  - **Cosmetic sprays**
- **Powder production**
  - **Spray drying**
  - **Liquid metal atomization**
- **Bubble dynamics**
  - **Cavitation**
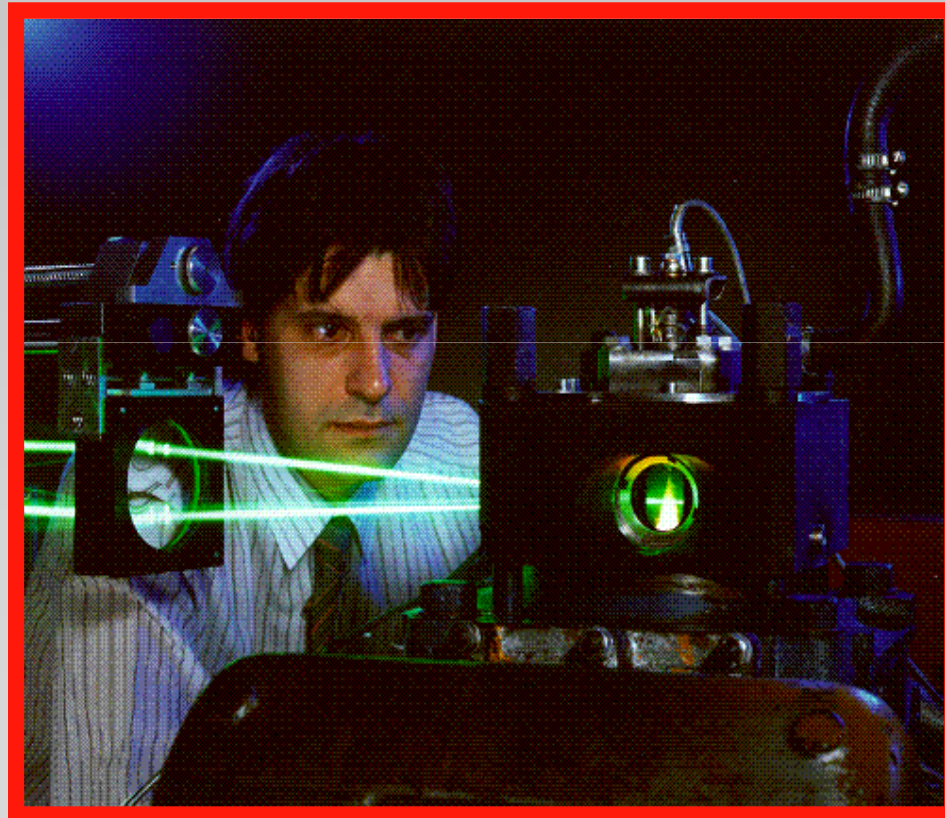 - **Aeration**
  - **Multiphase mass transfer**

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Automotive Fuel Injection

Photo: AVL, Graz, Austria

Nozzle Design
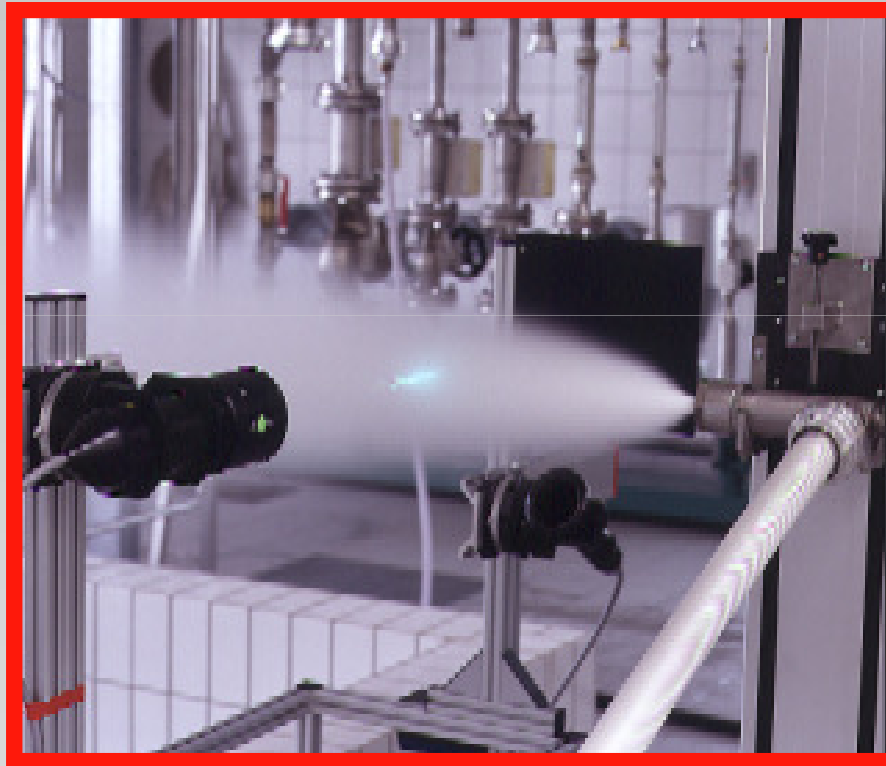
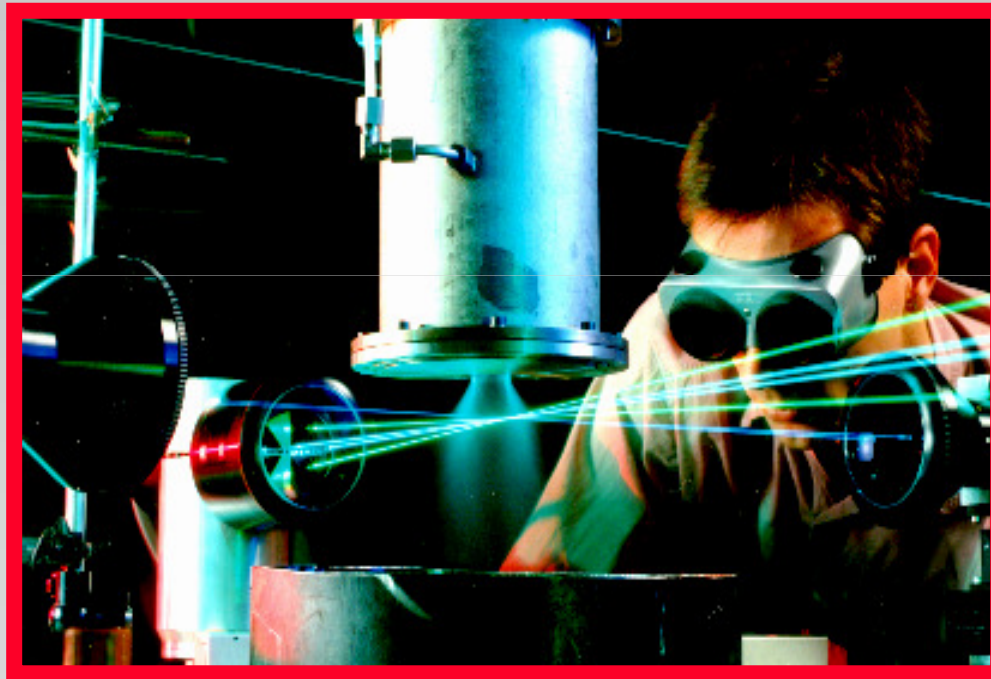Photo: Gustav Schlick GmbH & Co., Untersiemau, Germany
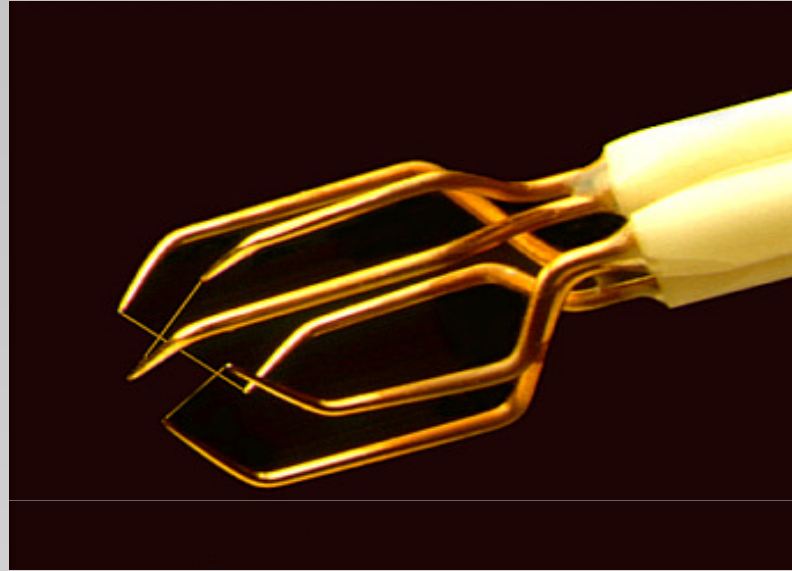
Aircraft Engine Fuel Injection

Photo: DLR, Institut für Antriebstechnik, Köln, Germany

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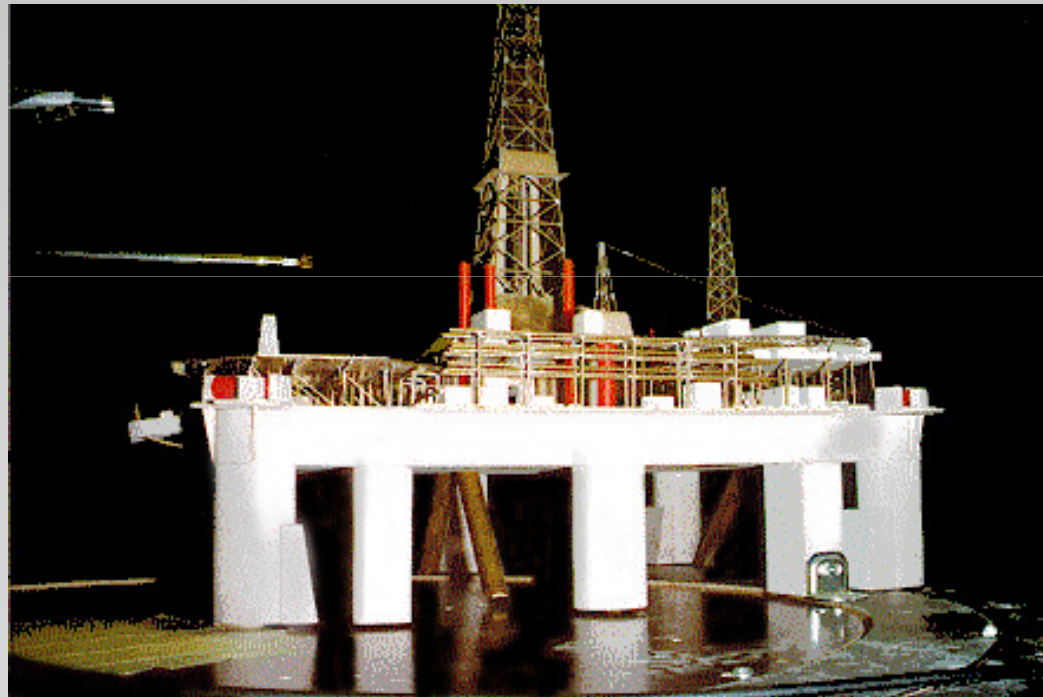Measurement Technology

8. Hot-Wire Anemometry

- **Purpose:**

  to measure mean and fluctuating variables in fluid flows (velocity, temperature, etc.): mean velocity, turbulence characteristics

HWA Application

**Flow field over helicopter landing pad**

(Danish Maritime Institute, Lyngby Denmark)

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Anemometer signal output

The thermal anemometer provides an analogue output which represents the velocity in a point. A velocity information is thus available anytime.

Note that LDA signals occur at random, while PIV signals are timed with the frame grapping of illuminated particles.
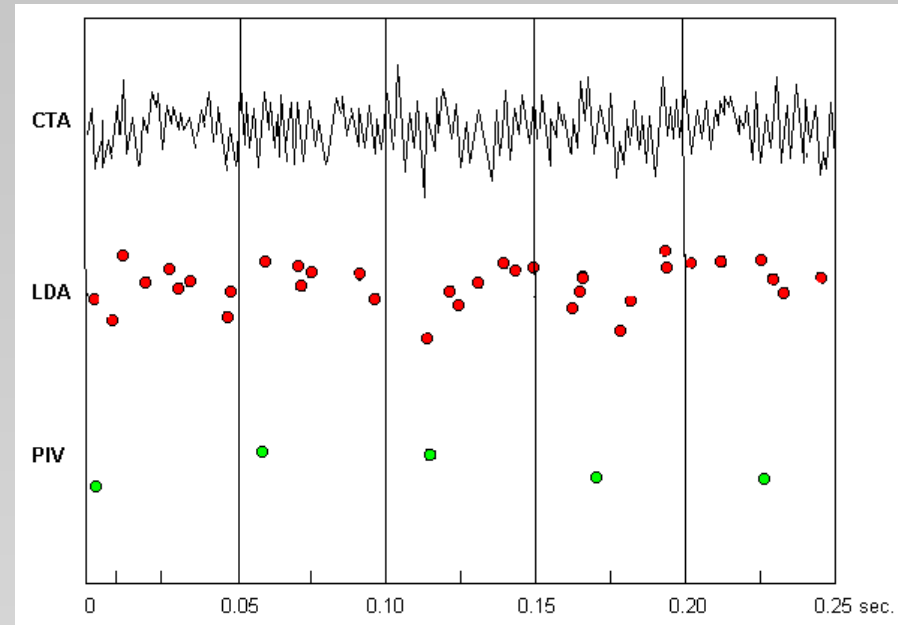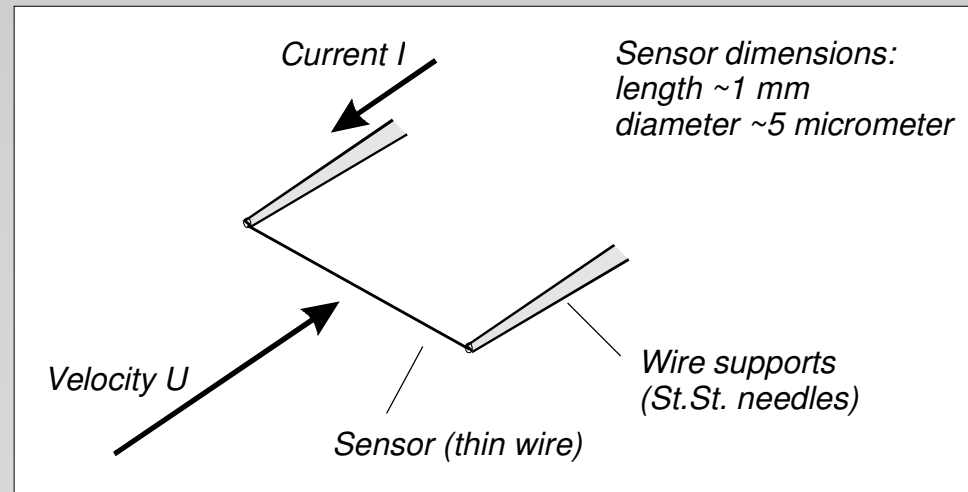
Principles of operation

- **Consider a thin wire mounted to supports and exposed to a velocity *U*.**

  When a current is passed through wire, heat is generated ($I^2 R_w$). In equilibrium, this must be balanced by heat loss (primarily convective) to the surroundings.

- **If velocity changes, convective heat transfer coefficient will change, wire temperature will change and eventually reach a new equilibrium.**

Current I

*Sensor dimensions:
length ~1 mm
diameter ~5 micrometer*

Velocity U

*Wire supports
(St.St. needles)*

Sensor (thin wire)

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Governing equation

- **Governing Equation:** $\dfrac{dE}{dt} = W - H$

  E = thermal energy stored in wire

  $E = CwTw$

  Cw = heat capacity of wire

  W = power generated by Joule heating

  $W = I^2 Rw$

  recall $Rw = Rw(Tw)$

  H = heat transferred to surroundings

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Simplified static analysis I

- **For equilibrium conditions the heat storage is zero:**

$$\frac{dE}{dt} = O \quad \therefore W = H$$

and the Joule heating W equals the convective heat transfer H

- **Assumptions**

- **Radiation losses small**
- **Conduction to wire supports small**
- ***Tw* uniform over length of sensor**
- **Velocity impinges normally on wire, and is uniform over its entire length, and also small compared to sonic speed.**
- **Fluid temperature and density constant**

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Simplified static analysis II

Static heat transfer:

$$W = H \implies I^2 R_w = hA(T_w - T_a) \implies I^2 R_w = Nu \, k_f/dA(T_w - T_a)$$

h = film coefficient of heat transfer
A = heat transfer area
d = wire diameter
k_f = heat conductivity of fluid
Nu = dimensionless heat transfer coefficient

Forced convection regime, i.e. $Re > Gr^{1/3}$ **(0.02 in air) and** $Re < 140$ $\implies$

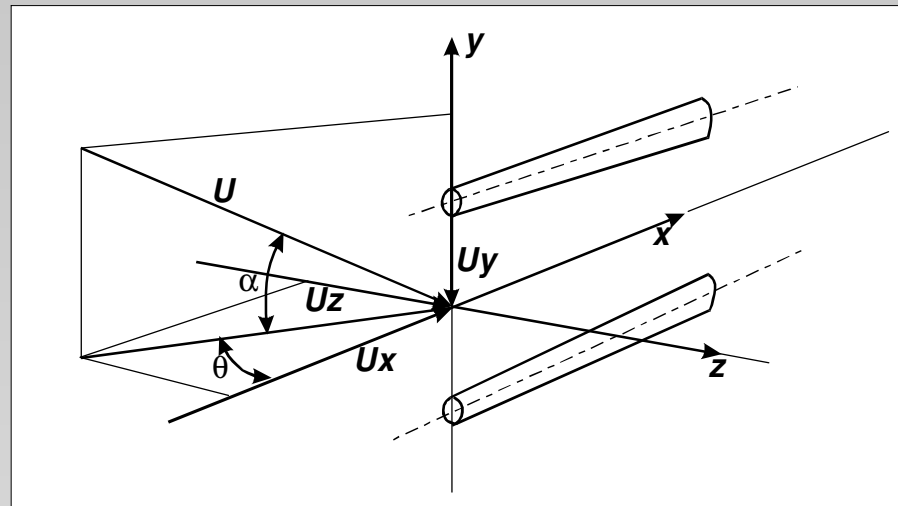$$Nu = A_1 + B_1 \cdot Re^n = A_2 + B_2 \cdot U^n$$

$$I^2 R_w^2 = E^2 = (T_w - T_a)(A + B \cdot U^n) \qquad \text{"King's law"}$$

The voltage drop is used as a measure of velocity $\Rightarrow$ **data acquisition, processing**

A, B, n: BY CALIBRATION

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Directional response

Probe coordinate system

Velocity vector *U* is decomposed into normal *Ux*, tangential *Uy* and binormal *Uz* components.

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Probe types I

- **Miniature Wire Probes**

  Platinum-plated tungsten, 5 μm diameter, 1.2 mm length

- **Gold-Plated Probes**

 **3 mm total wire length, 1.25 mm active sensor copper ends, gold-plated**

Advantages:
- **accurately defined sensing length**
- **reduced heat dissipation by the prongs**
- **more uniform temperature distribution along wire**
- **less probe interference to the flow field**

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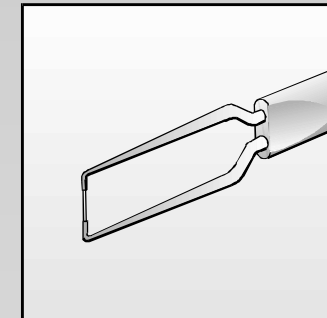Measurement Technology
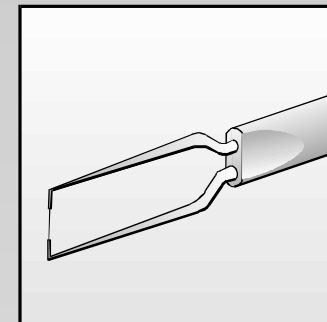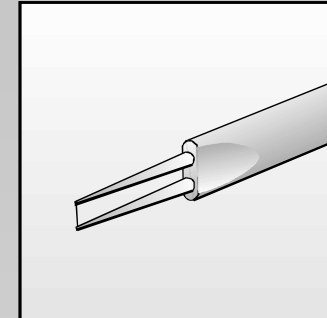
Probe types II

- **Film Probes**

  Thin metal film (nickel) deposited on quartz body. Thin quartz layer protects metal film against corrosion, wear, physical damage, electrical action
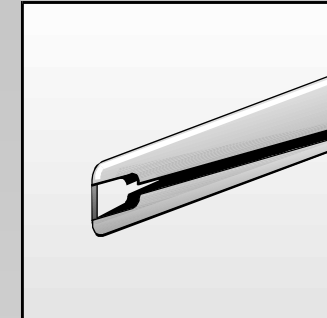
- **Fiber-Film Probes**

  "Hybrid" - film deposited on a thin wire-like quartz rod (fiber) "split fiber-film probes."

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Probe types III

- **X-probes for 2D flows**

  2 sensors perpendicular to each other. Measures within $\pm 45^o$.

- **Split-fiber probes for 2D flows**

  2 film sensors opposite each other on a quartz cylinder. Measures within $\pm 90^o$.

- **Tri-axial probes for 3D flows**

  3 sensors in an orthogonal system. Measures within 70° cone.

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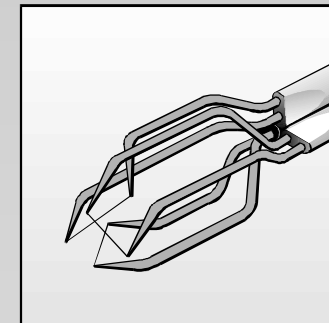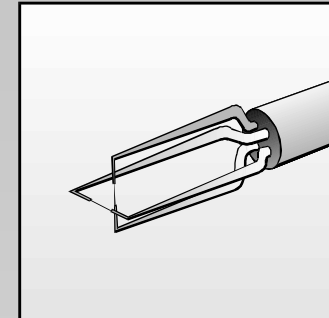
Constant Temperature Anemometer CTA
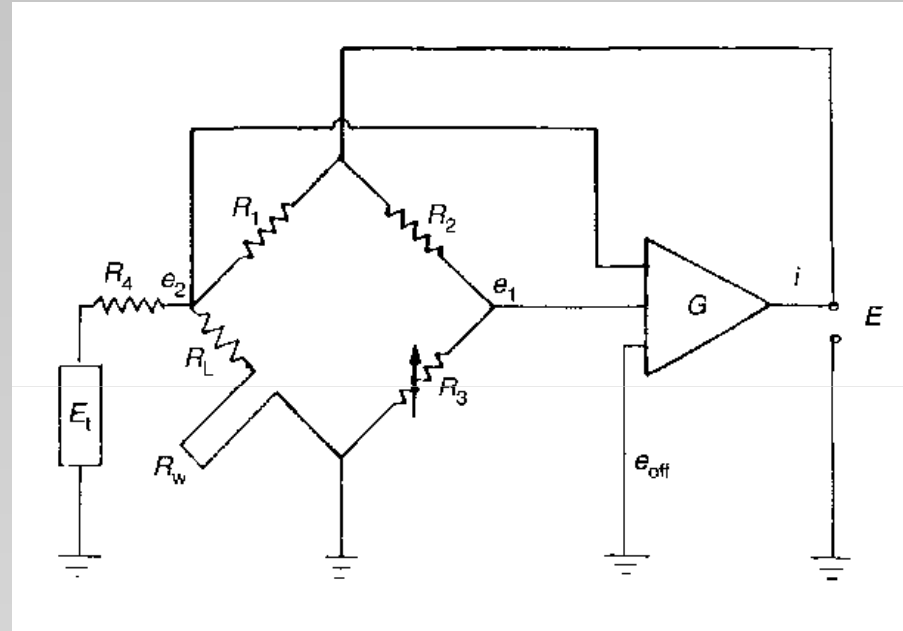
- **Principle:**

  Sensor resistance is kept constant by servo amplifier

- **Advantages:**

  - **Easy to use**
  - **High frequency response**
  - **Low noise**
  - **Accepted standard**

- **Disadvantages:**

  - **More complex circuit**

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Velocity calibration (Static cal.)

- **Despite extensive work, no universal expression to describe heat transfer from hot wires and films exist.**

- **For all actual measurements, direct calibration of the anemometer is necessary.**

Dynamic calibration

- **To calibrate the internal dynamics of the instrumentation (electronics etc.)**

Problem Sources
Temperature Variations

- **Fluctuating fluid temperature**

  Heat transfer from the probe is proportional to the temperature difference between fluid and sensor.

  $$E^2 = (Tw\text{-}Ta)(A + B \cdot U^n)$$

  As *Ta* varies:

  - **heat transfer changes**
  - **fluid properties change**

  TO BE HANDLED

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