UiO : Department of Mathematics
University of Oslo

MEK 4600
Experimental methods in Fluid Mechanics

Instrumentation

Goals of today

Get familiar with

1. Typical instruments for multiphase flow measurement

2. Working principle
   - Hot-wire anemometry
   - X-ray tomography

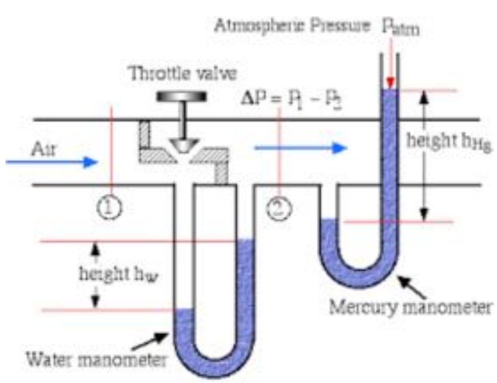
3. Error analysis

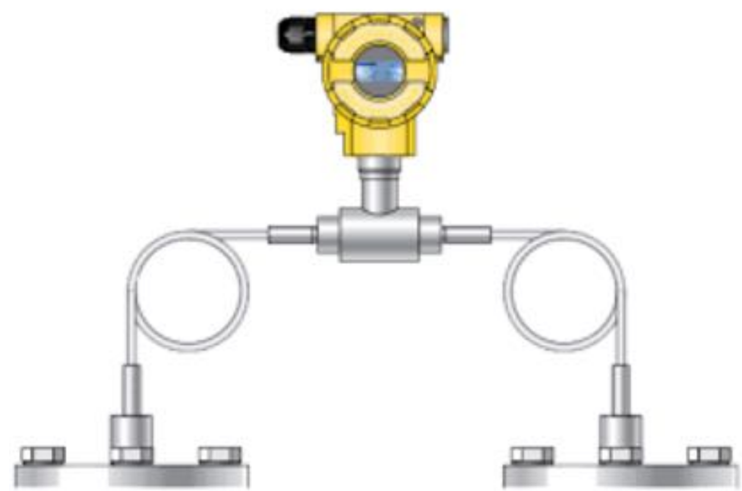
Important flow parameters

- Pressure drop
- Velocity field and turbulence
- Holdup or volume fraction
- Drop size and distribution
- Wave/slug characteristics etc.

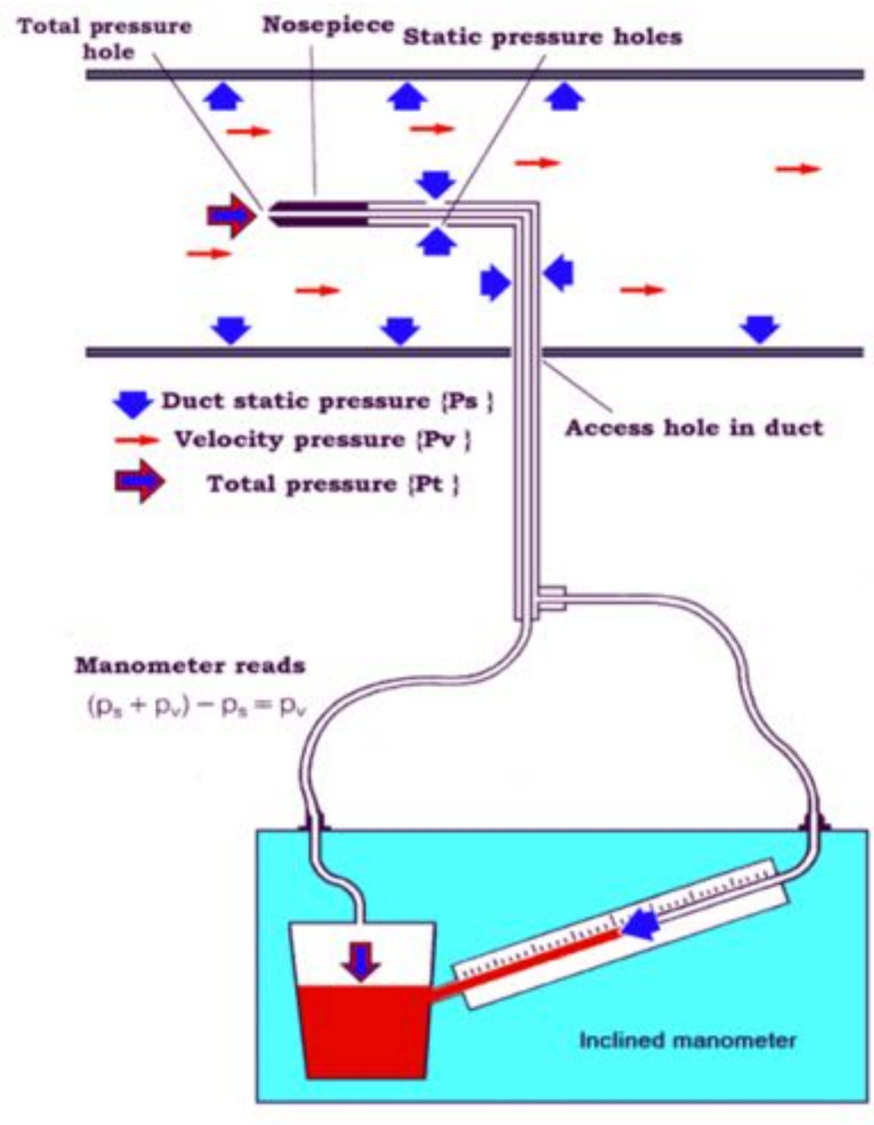
Pressure or pressure drop

- Manometer
- Pressure transducer (static, gauge and absolute)

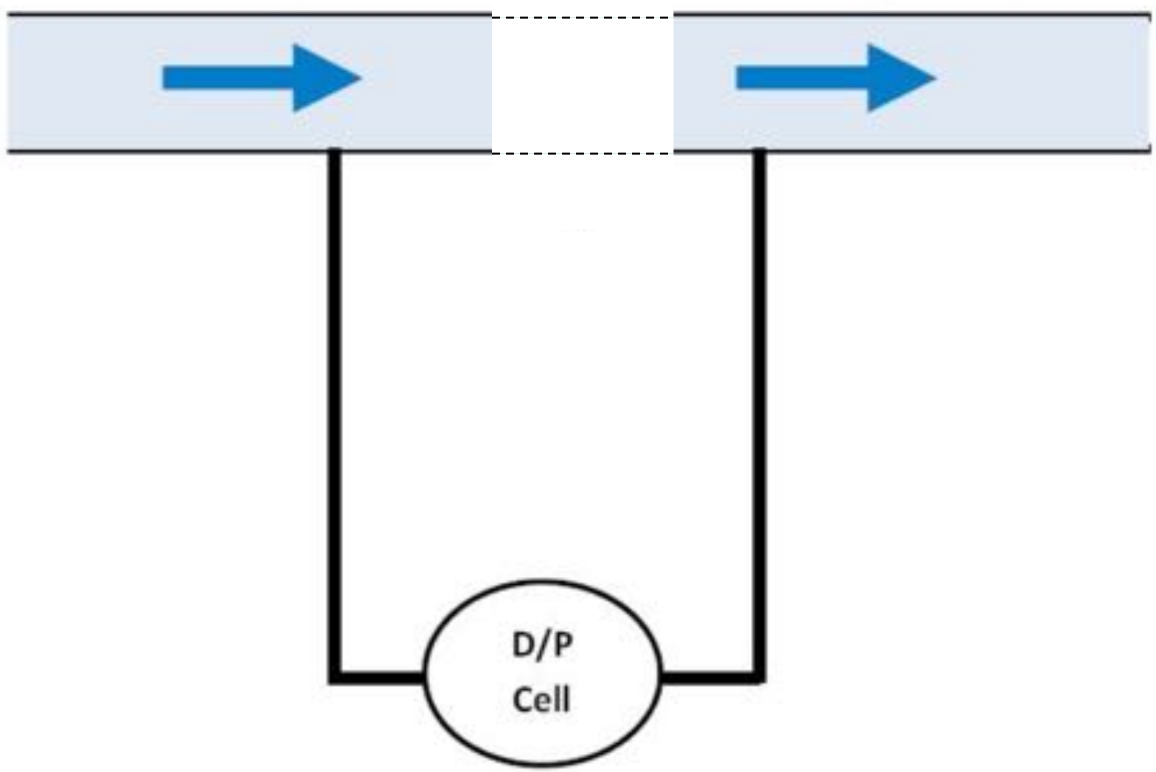




Pitot tube

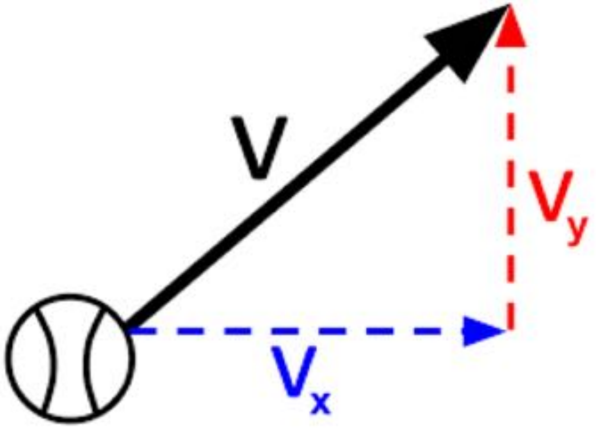

Total pressure hole
Nosepiece
Static pressure holes
Duct static pressure {Ps }
Velocity pressure {Pv }
Total pressure {Pt }
Access hole in duct
Manometer reads
$(p_s + p_v) - p_s = p_v$
Inclined manometer

Pressure drop in a pipeline



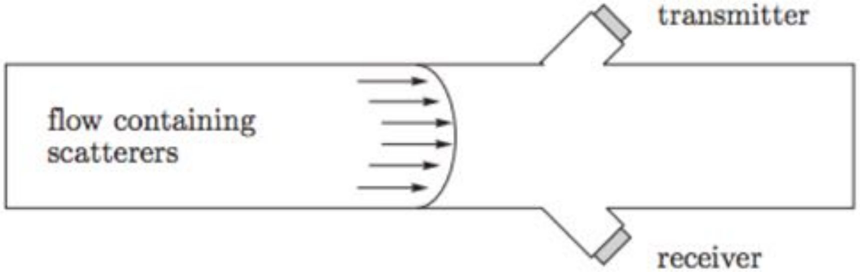
Velocity

- Particle imaging/tracking velocimetry (PIV, PTV)
- Ultrasonic
- Laser Doppler Velocimetry
- Hot-wire anemometry



Ultrasound device

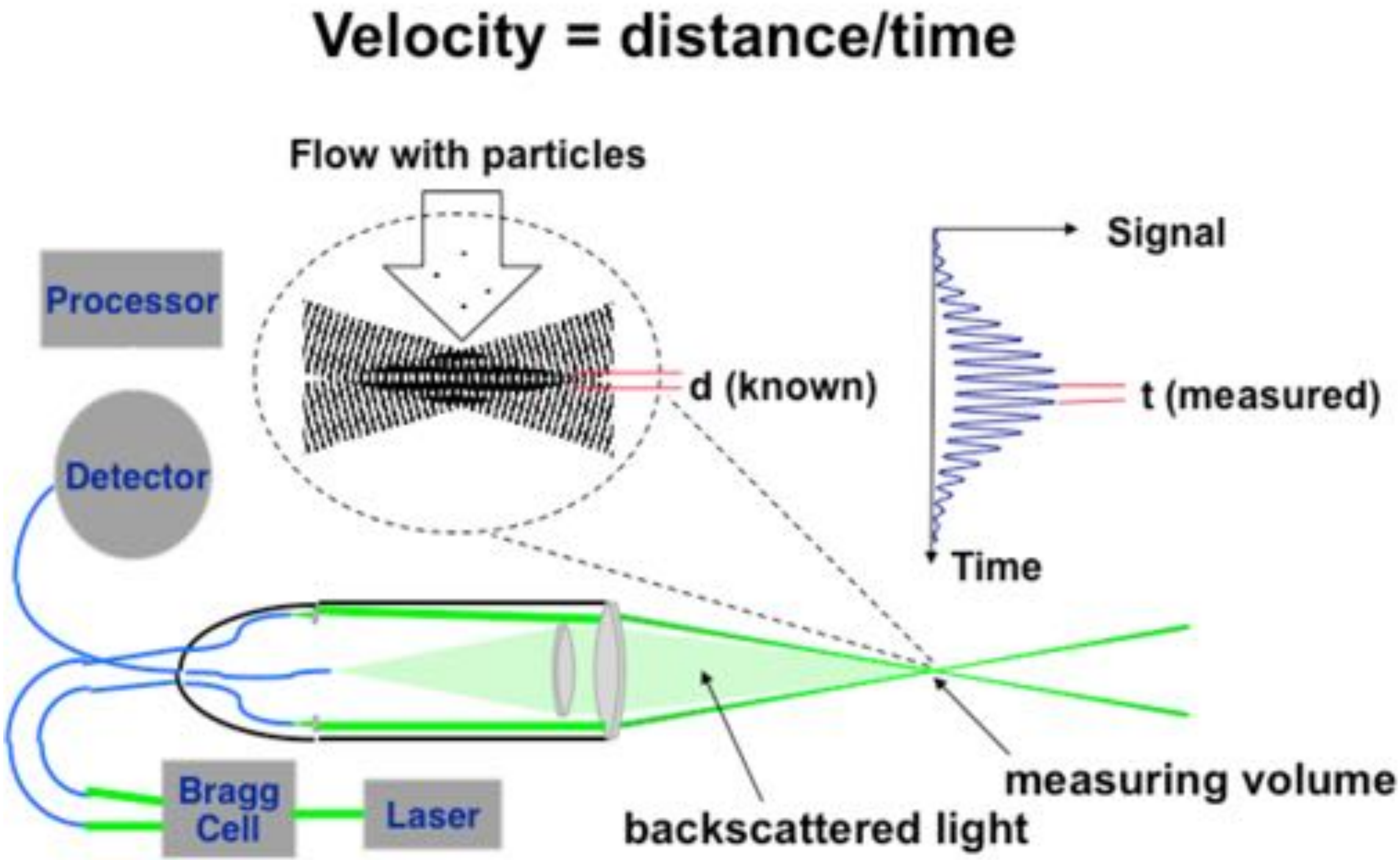
- Transmission or reflection mode
  - Velocity or holdup measurements
- Signals can be largely contaminated by
  - Scatters, refractions by bubbles, dispersions and interfaces
  - Near-wall acoustic properties



- "Due to the effect of gas bubbles in the liquid phase .... the ultrasonic Doppler sensor cannot reliably measure the bulk liquid velocity, or the homogeneous velocity"

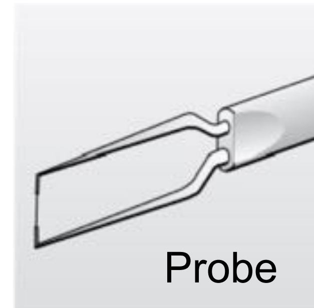
<u>*Huang et al. (2013) SPE 164442-MS*</u>

LDA


Velocity = distance/time
Flow with particles
Signal
Processor
d (known)
t (measured)
Detector
Time
Bragg
Cell
Laser
measuring volume
backscattered light

Hot wire anemometer: components

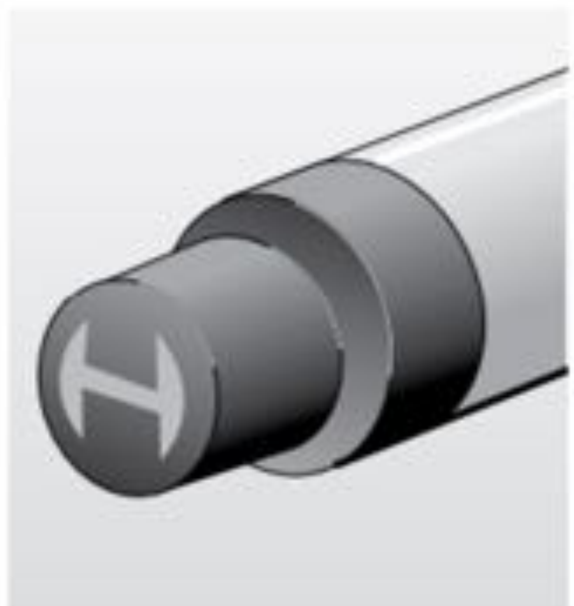
- Probe
- Anemometer + signal conditioner
- PC
- Calibration unit



CTA anemometer Calibration unit

Probes

X wire probe
(velocity)

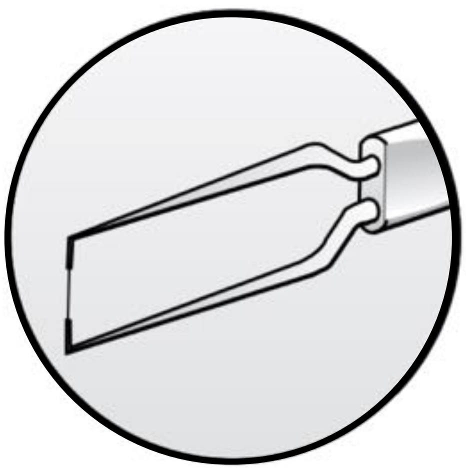


Flush mounted probe
(shear stress)

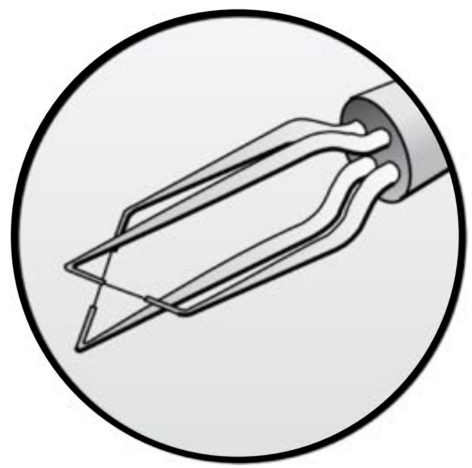
Glue-on probe
(shear stress)

Cylindrical sensor probes

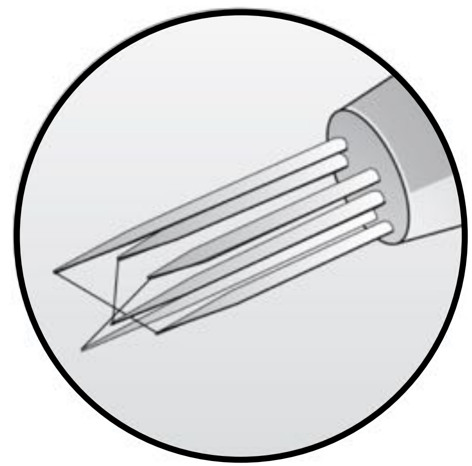
- 3 mm total wire length,
- 1.25 mm active sensor
- Copper ends, gold-plated



Single sensor



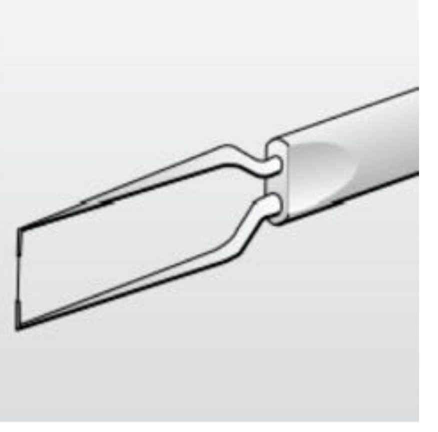
Dual sensors



Triple sensors

Two operation modes

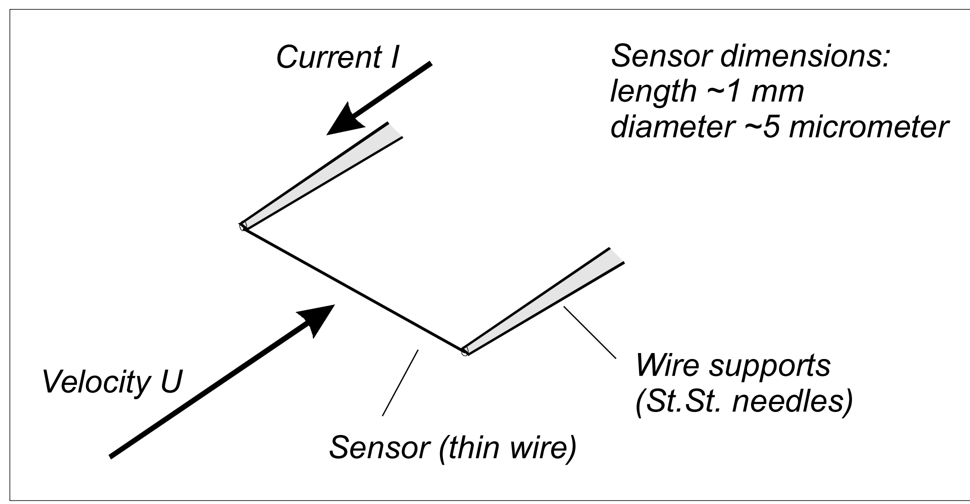
- Constant temperature anemometer (CTA)
  - Widely used for velocity measurement
  - Only applicable in isothermal flows



- Constant current anemometer (CCA)
  - Measure T fluctuations
  - Limited applications

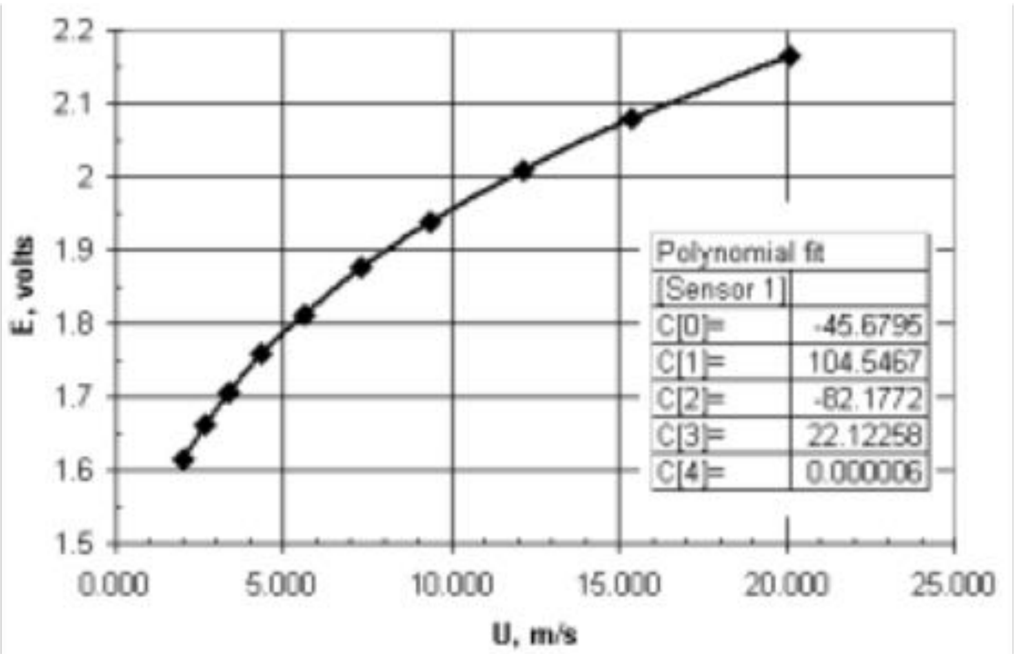
Working principle

- At equilibrium state, heat generated from the current is balanced by heat loss to the ambient fluids
- When velocity changes, wire temperature will change and new current is supplied to eventually reach a new equilibrium.



Typical calibration curve

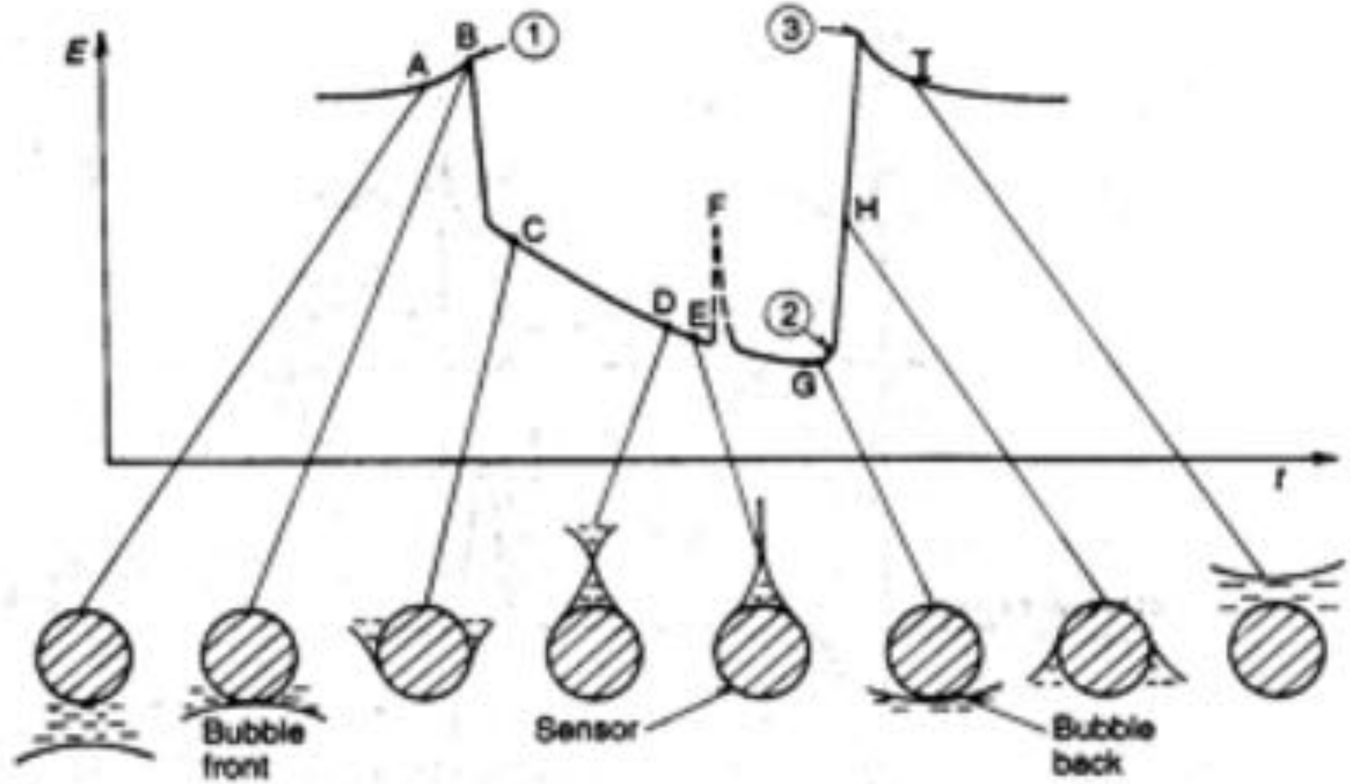
King´s law $E^2 = A + B \cdot U^n$



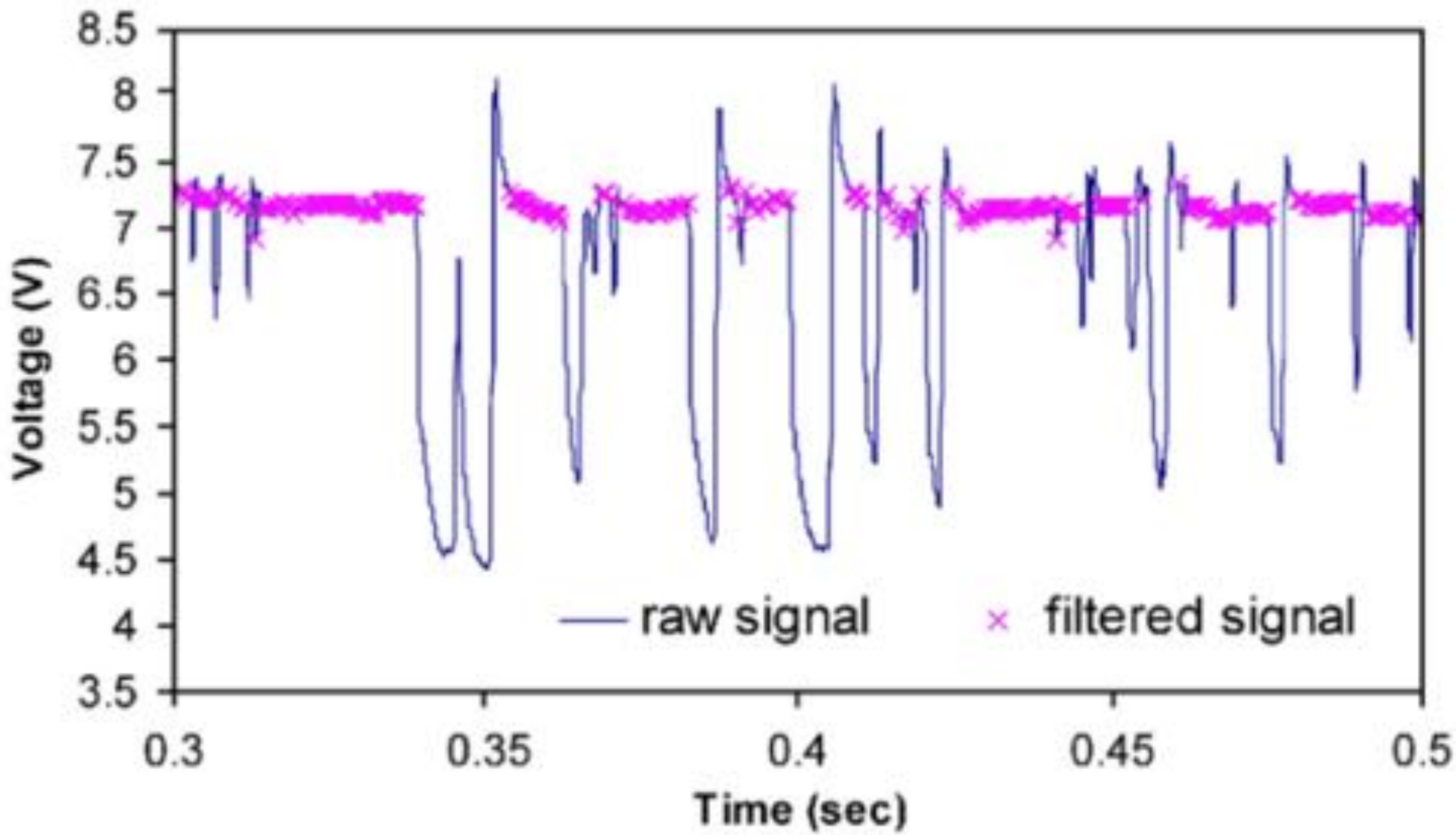
Temperature correction

$$E_{corr} = \left(\frac{T_w - T_0}{T_w - T_a} \right)^{0.5} \cdot E_a$$

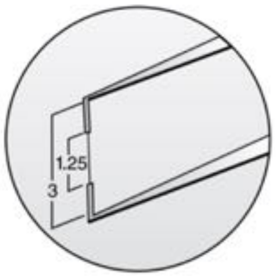
HFA in two-phase measurement

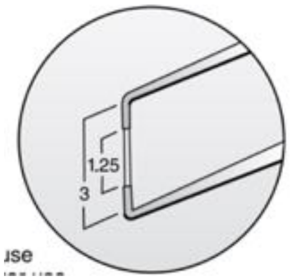


Typical signals from two-phase oil-water flows



Wire or film probes



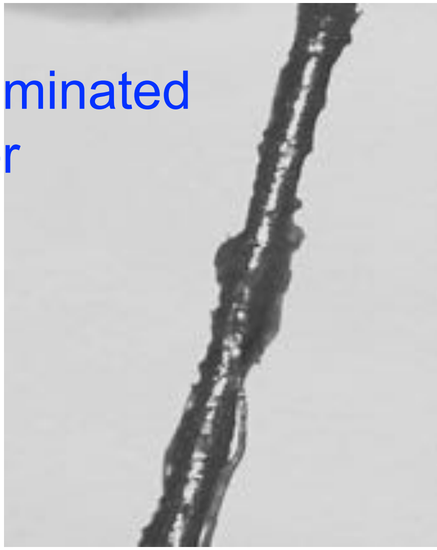


Wire probe (5 um dia.)	Film probe (70 um dia.)
Relatively inexpensive	Expensive but more rugged
Better frequency response	Worse frequency response
Can be repaired	Cannot be repaired
	Electrically insulated (can be used in water)
	Protected against mechanical and chemical actions

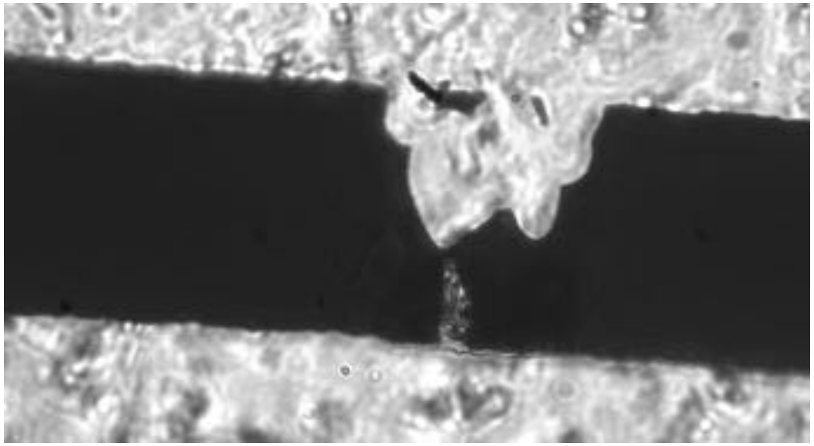
Extra attentions needed

- Probe needs to be cleaned regularly

Contaminated sensor



- Water can be problematic



Broken sensor when used in water

Hot-film anemometer

- Reasonably accurate for turbulence measurement
- Sensitive to temperature changes of ambient fluids
- Signal processes are complex in two-phase flow
- Sensors are fragile and expensive

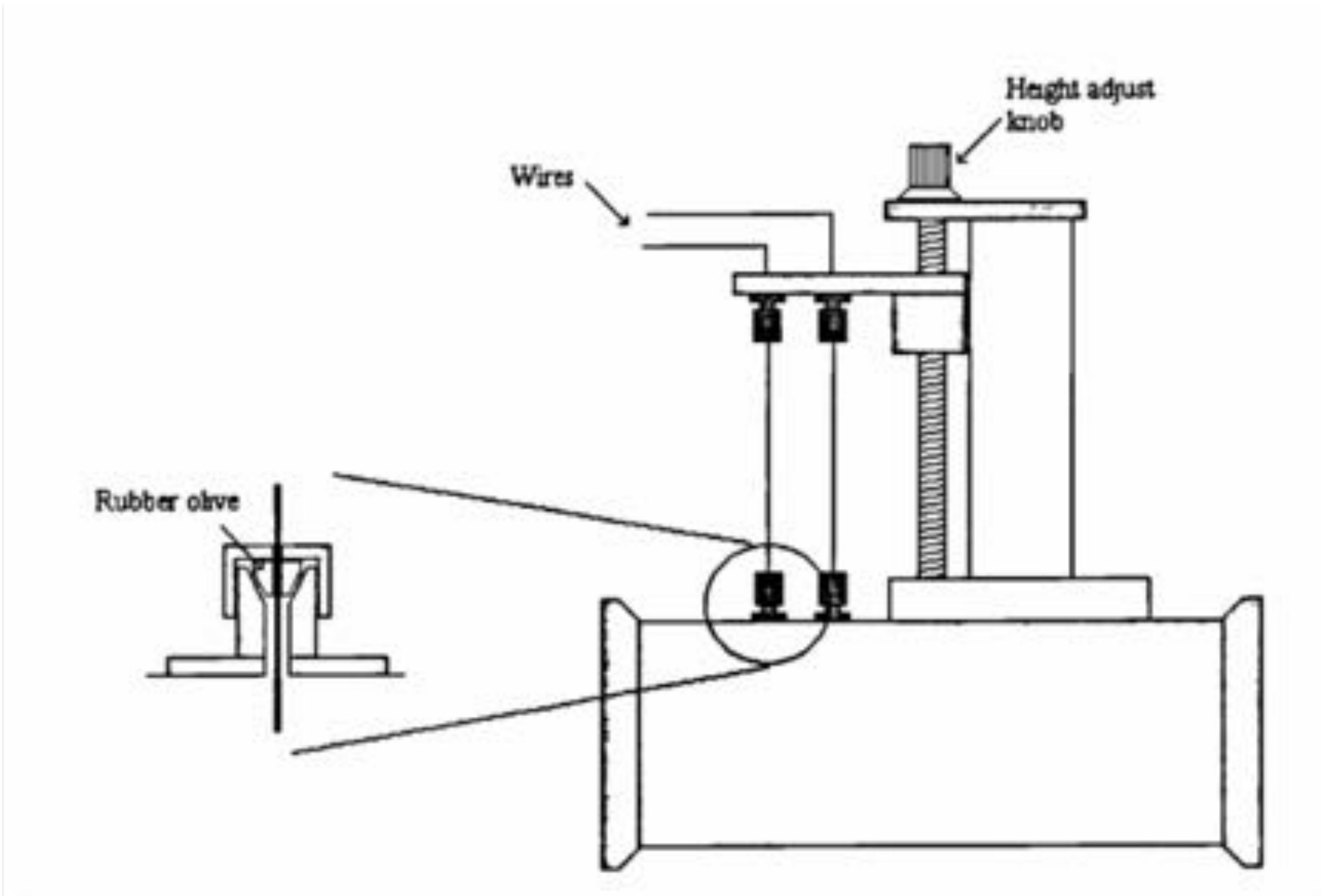
Holdup measurement

- Quick closing valve
- Impedance/conductivity probes
- ECT and ERT
- Wire-mesh probe
- Gamma densitometer
- X-ray system

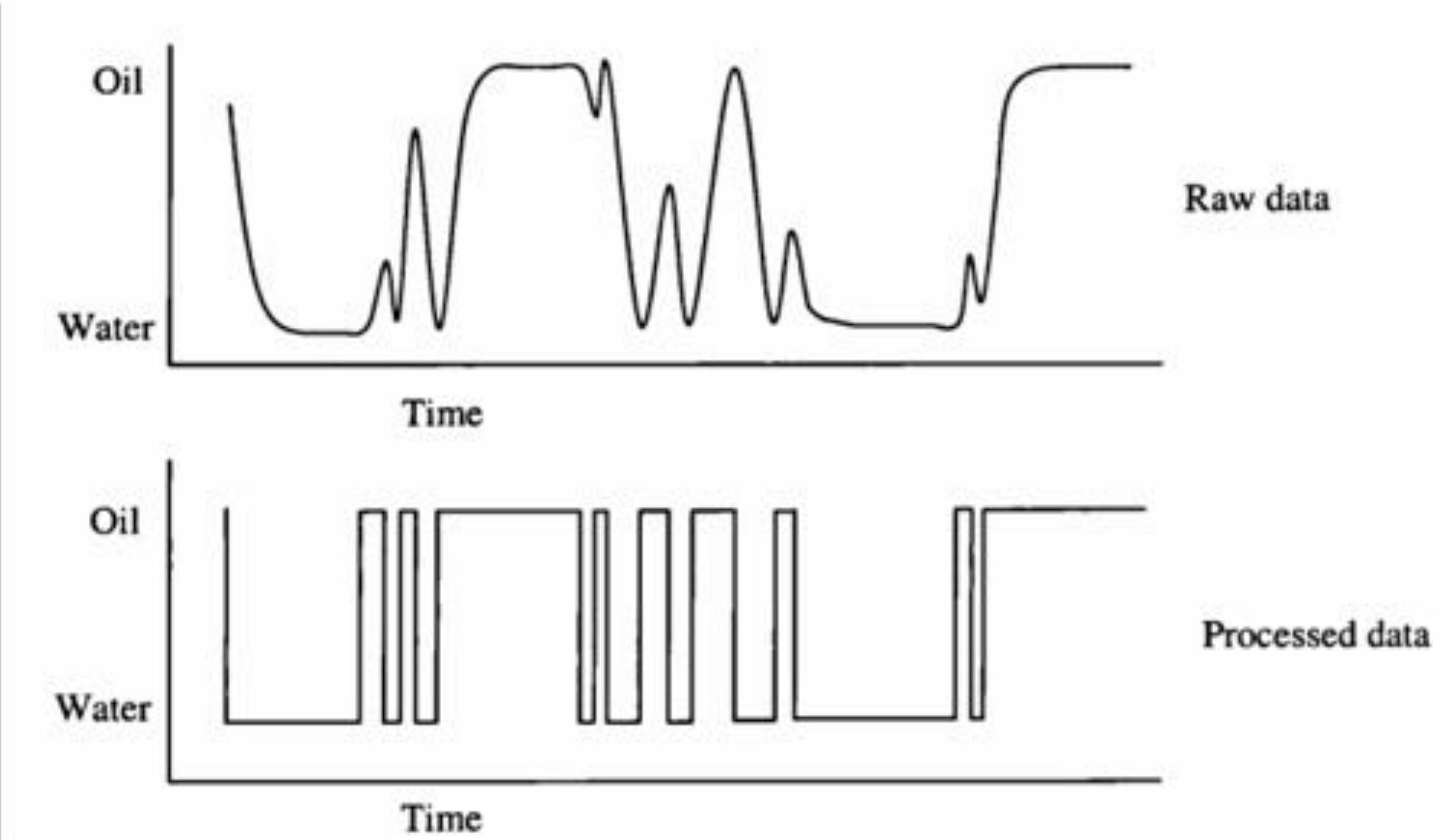
Quick closing valve

- Only provide time-averaged values
- Subject to flow conditions, slug or wave etc.

Impedance probe



Impedance probe

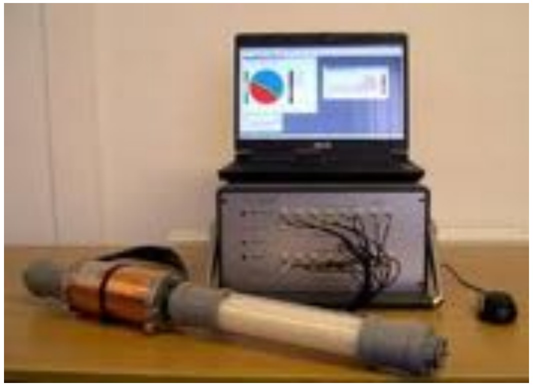


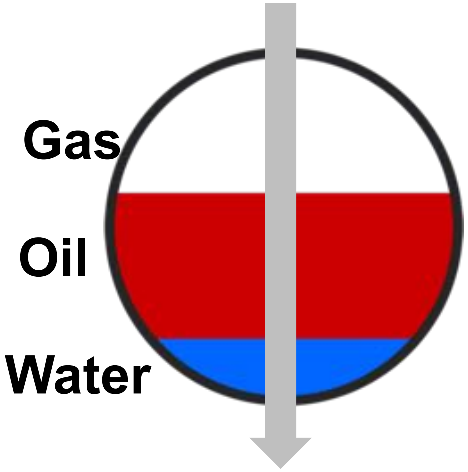
ECT/ERT

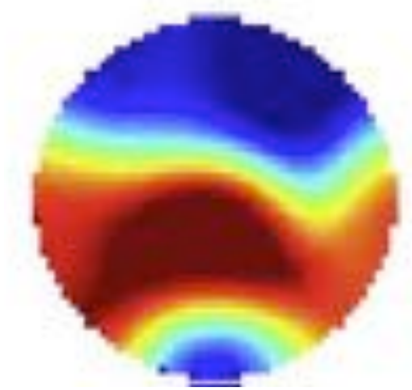
- Based on capacitance or resistance measurements
- 8 – 12 sensors mounted on external surface
- 6+ cm long for better signals

ECT/ERT

- Good qualitative instrument
- Poor accuracy
- Artefacts in reconstruction
- Unsuitable for 3-phase flows







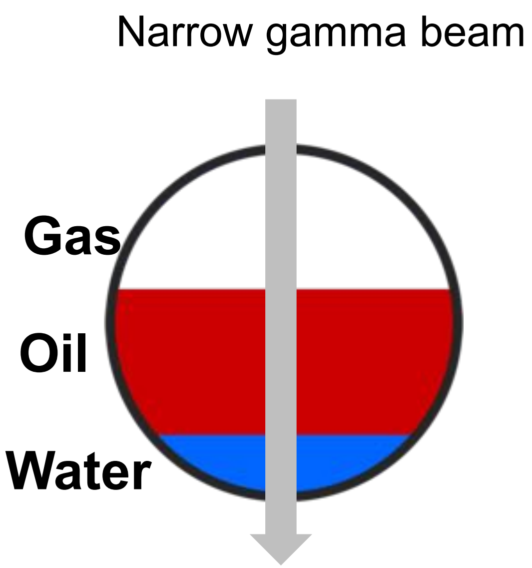
Measurement 66 (2015) 150–160

Wire-mesh probe

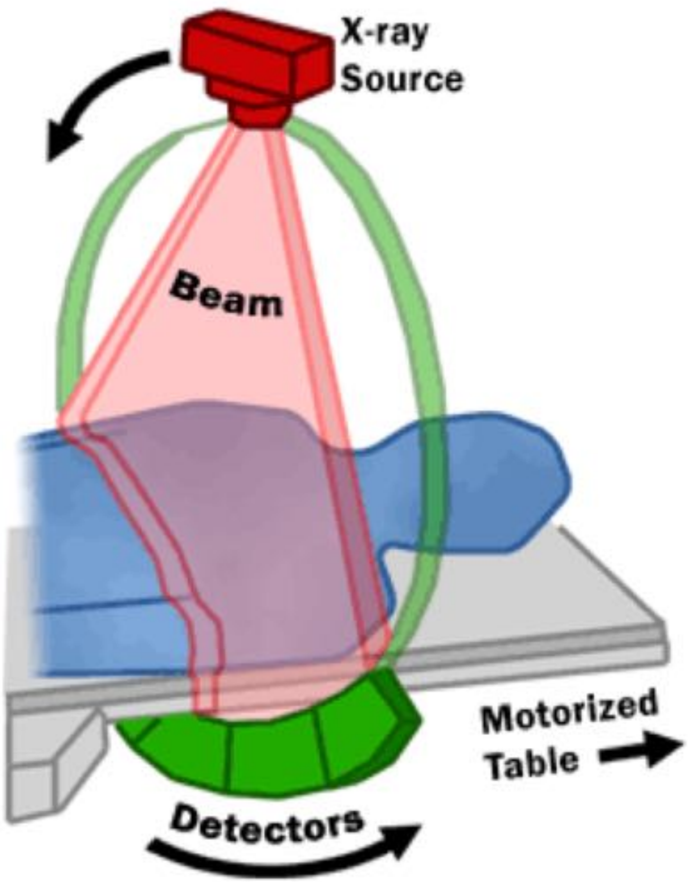
- Intrusive instrument based on ECT/ERT technology
- More accurate than other ECT/ERTs for two-phase flow
- NOT a three-phase instrument
- NOT suitable for flows with wax particles, sands or hydrates etc.

Gamma densitometer

- Low temporal response (1-10s) and low spatial resolution
- Only narrow beam data are reliable
- No flow information
- **Cross-section ≠ Centre line**



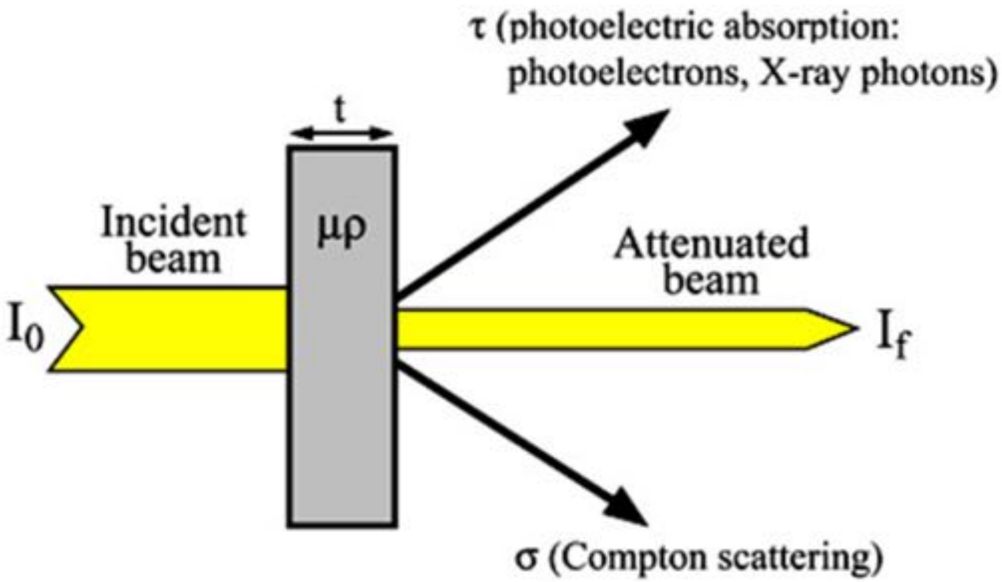
X-ray tomography system



Can we use such system to study multiphase flow?

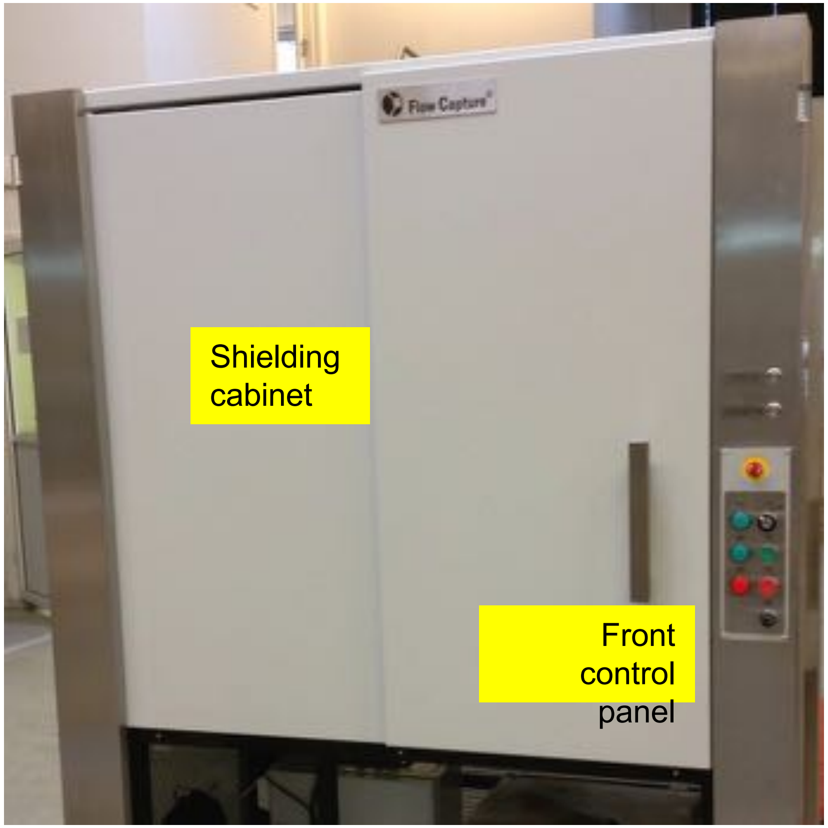
Working principle

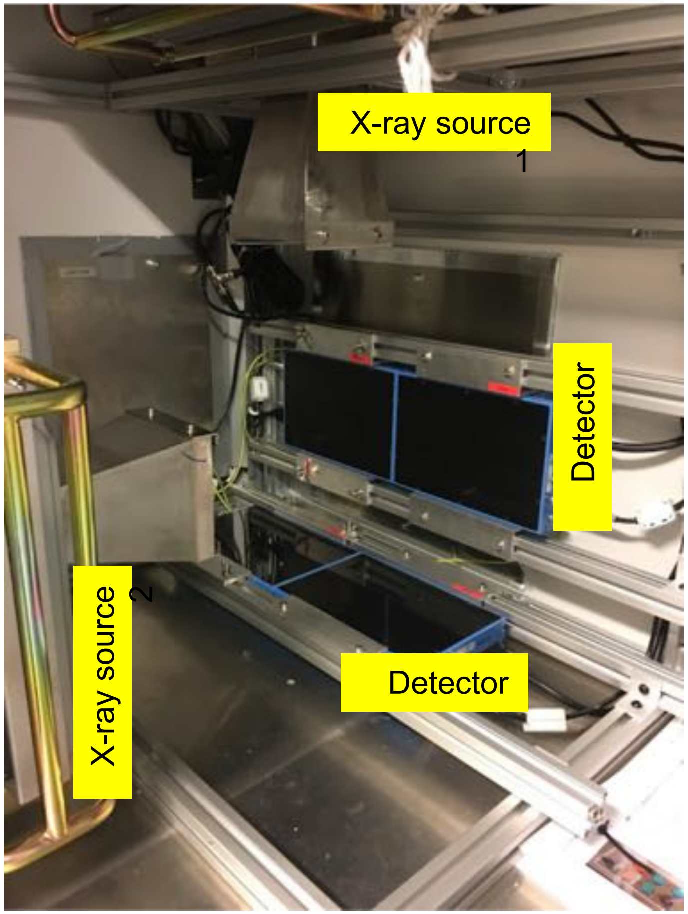
- X-ray intensity attenuates exponentially with penetration thickness
- Different materials have different attenuation property (**μρ**)



$$I_f = I_0 e^{-(\mu\rho)t}$$

REX-CELL™ XPTV at Univ. of Oslo





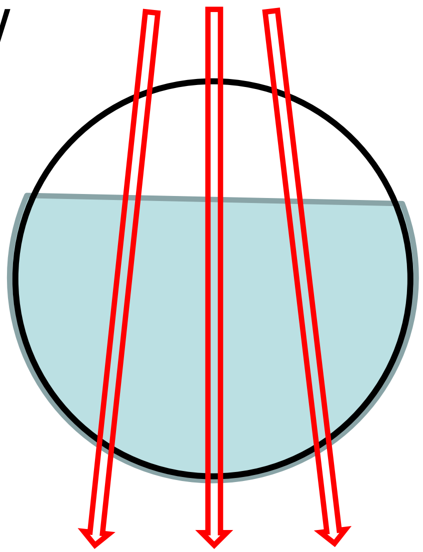
Holdup conversion in gas-water system

Given:

I_{Water} Measured with pipe filled with water

I_{Gas} Measured with empty pipe

I_{EXP} Measured in two-phase flow

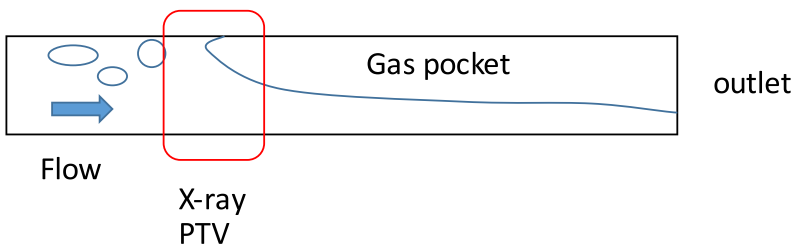


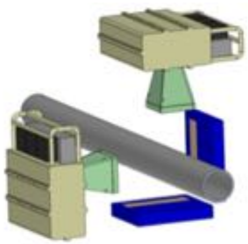
Derive gas volume fraction

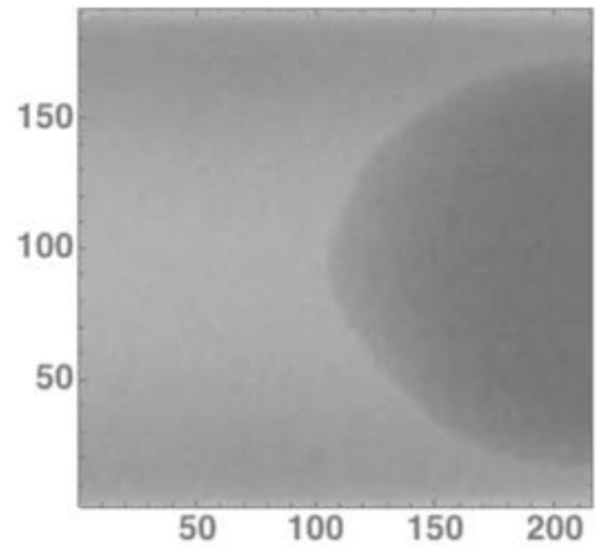
$$\alpha_{Gas} = ?$$

Flow around a stationary Benjamin bubble

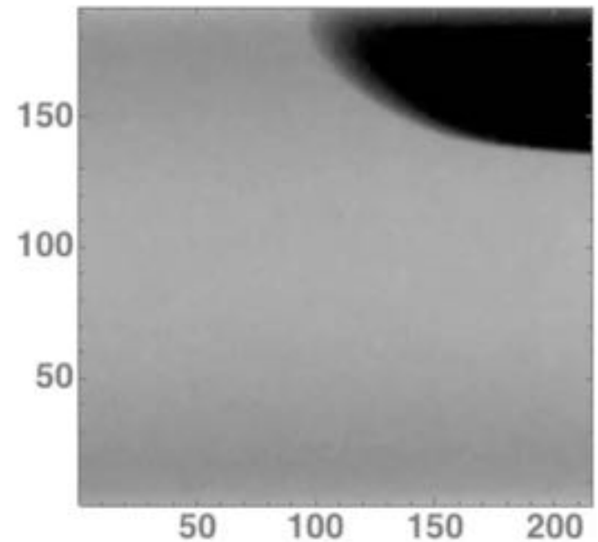
- Pixel size 300 um
- Tracer particles 1-1.5 mm
- 100 fps





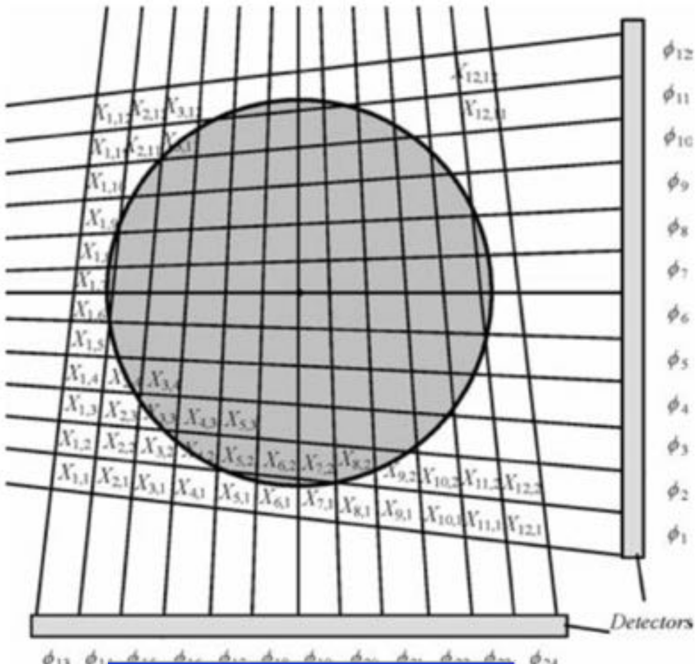


Top view

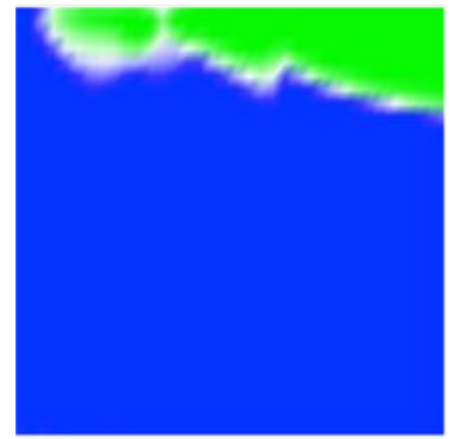


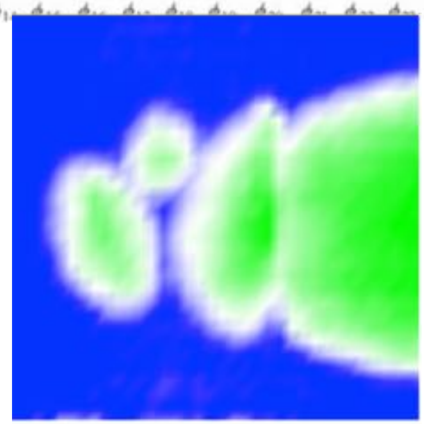
Side view

X-ray projections (radiography)



Side view





Top view

Reconstructed tomography

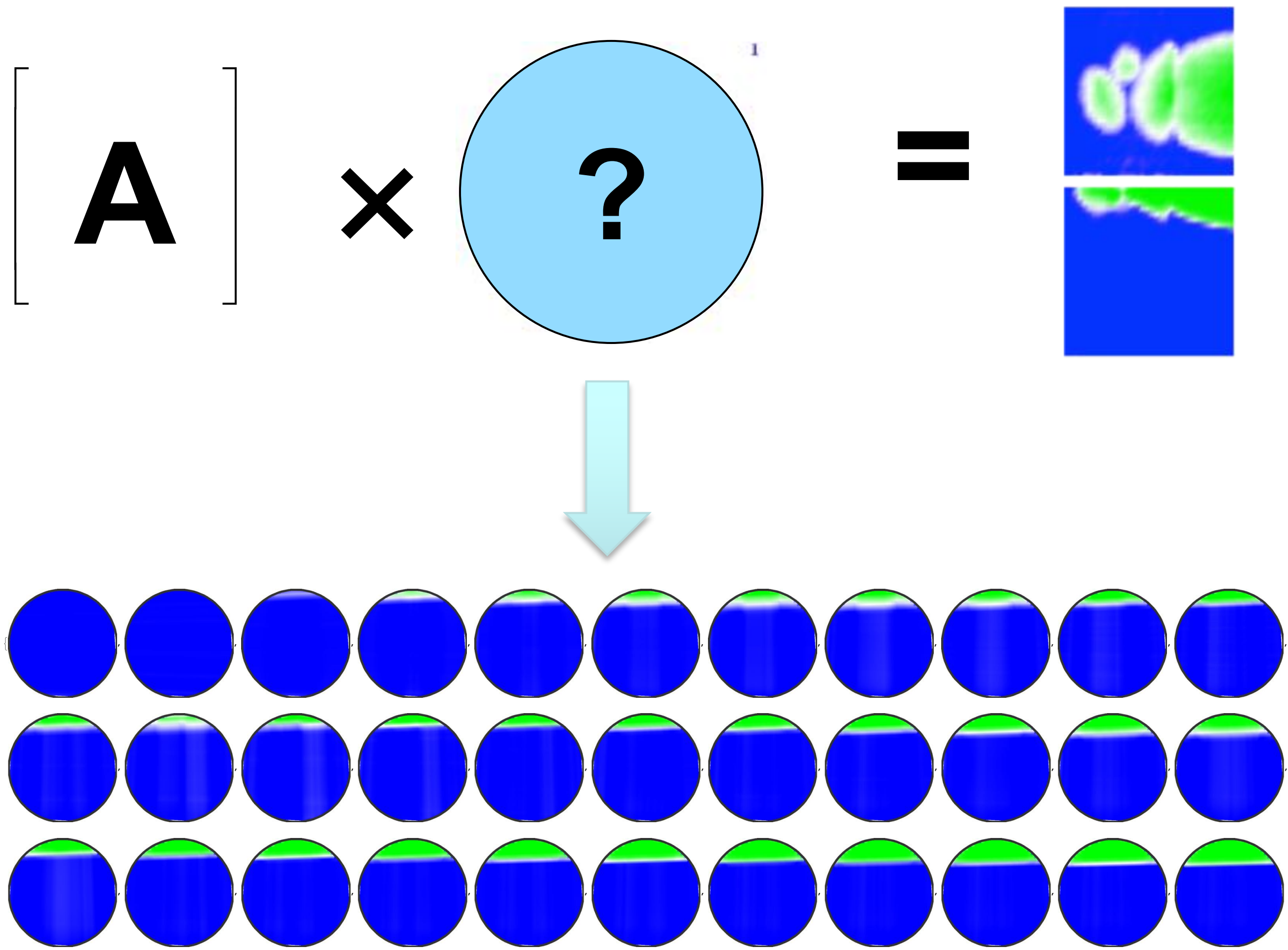
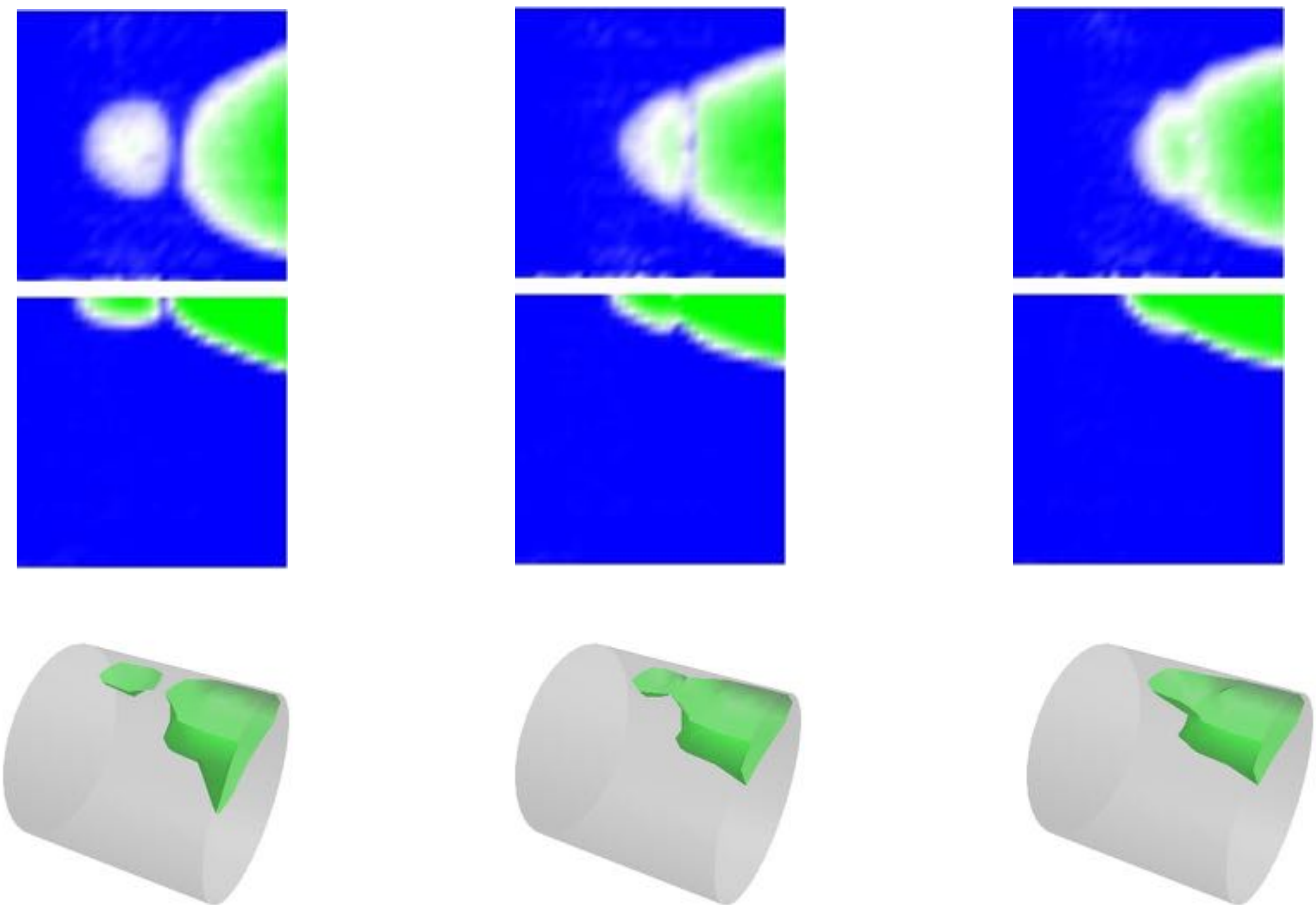
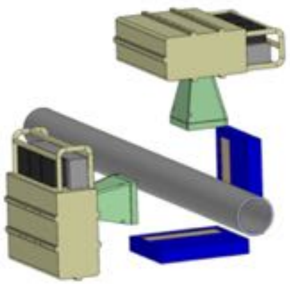


Image reconstruction

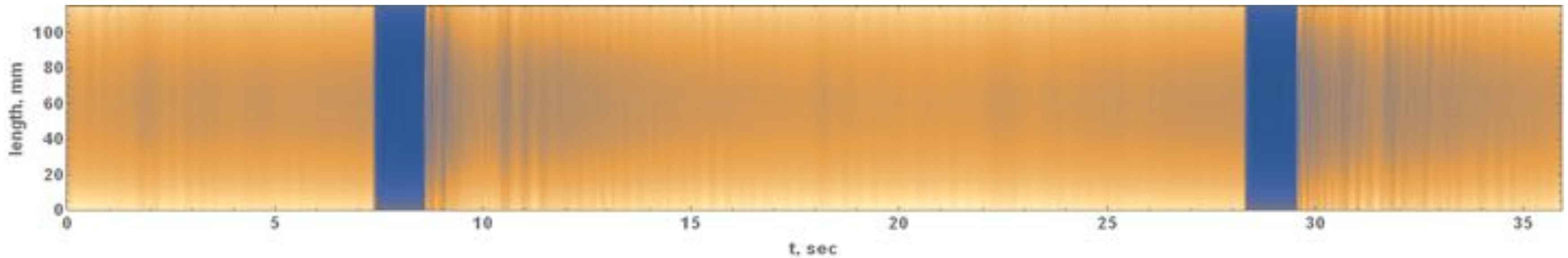


Details of slug flow

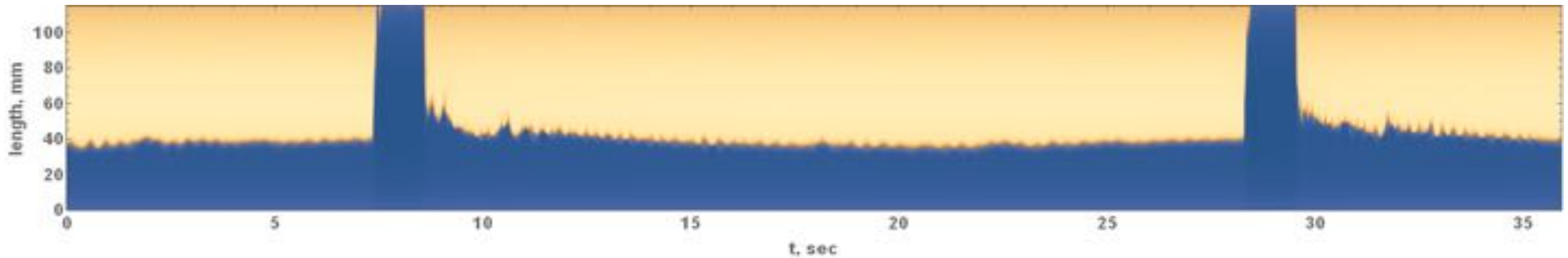


- 4 inch horizontal pipeline at UiO
- Air-water at atmospheric pressure

Top view

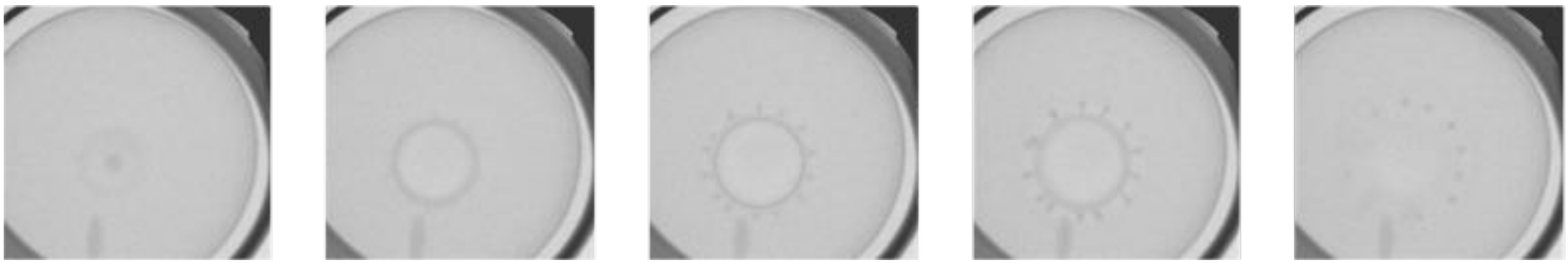


Side view



Milk crown

Top view

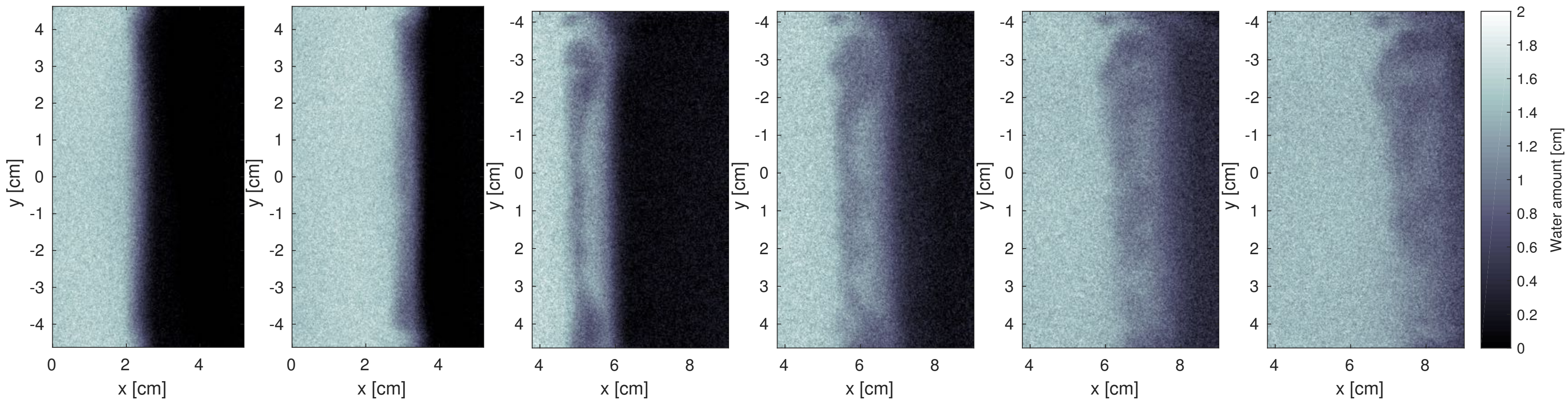


Side view

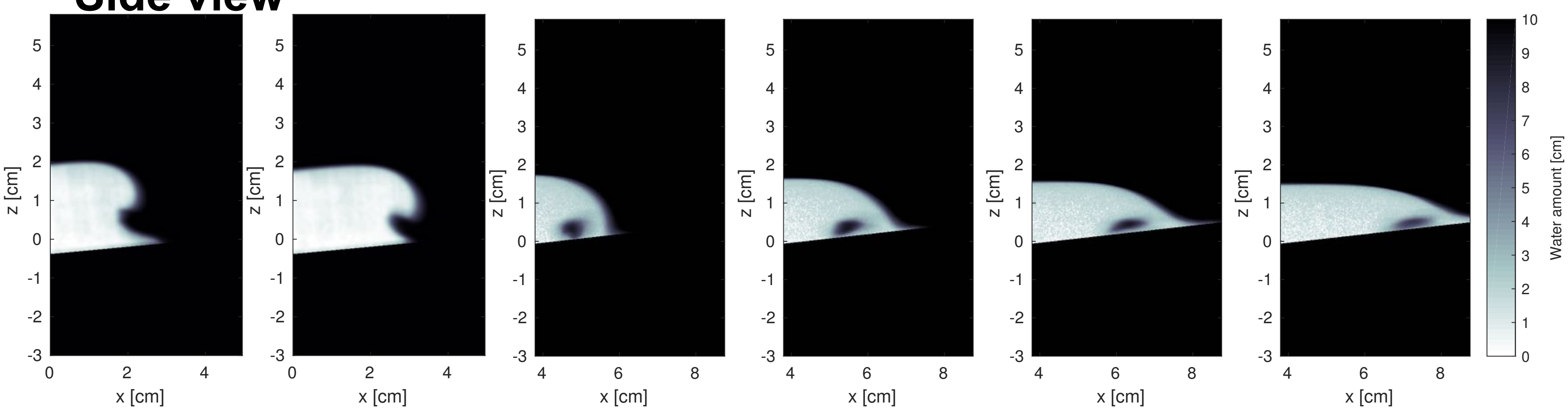
Breaking solitary wave

Top view

Smith (2017)

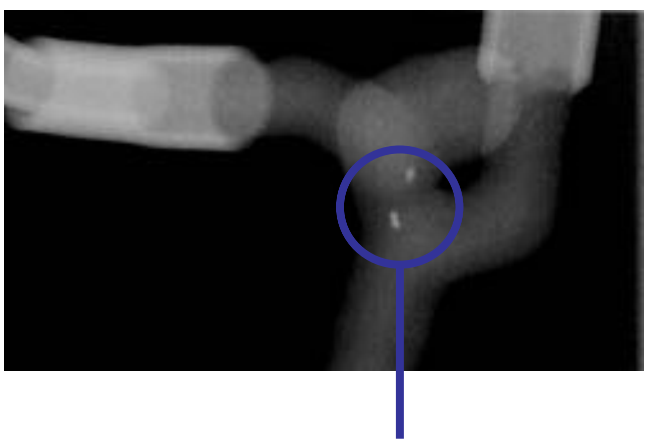


Side view

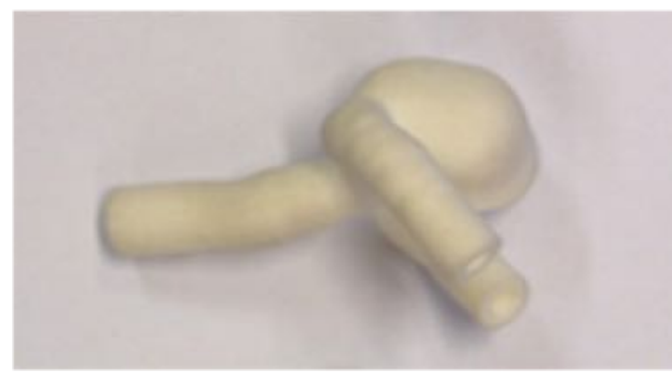


Flows in aneurysm (recent work at UiO)

- Geometry: 3D printed aneurysm model
- Sampling rate: 150 fps
- Pixel size: 150 um
- Focus: Flow pattern, flow velocity

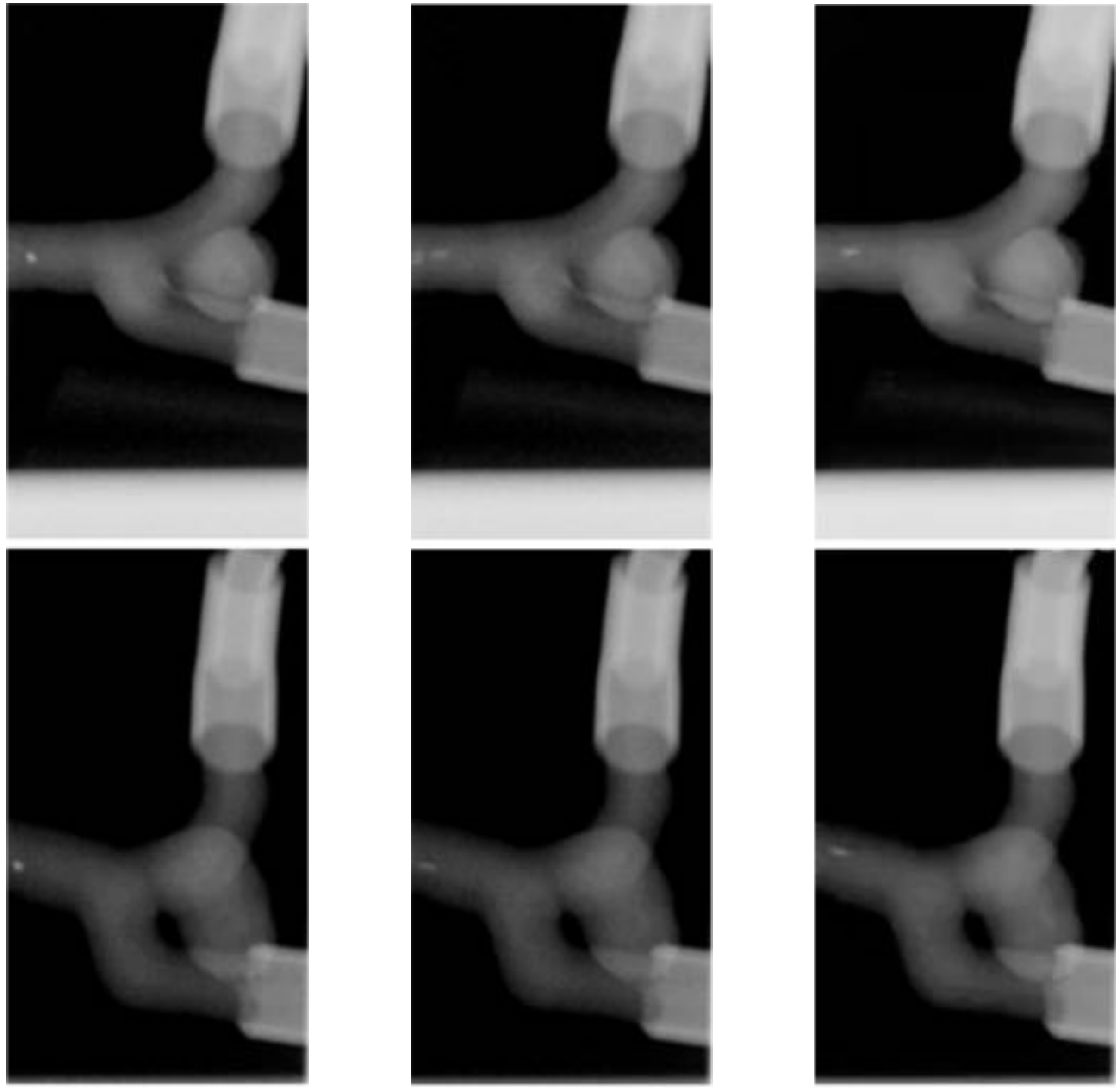


Tracer particles



Frostelid (2016)

Flows in aneurysm at different Reynolds numbers

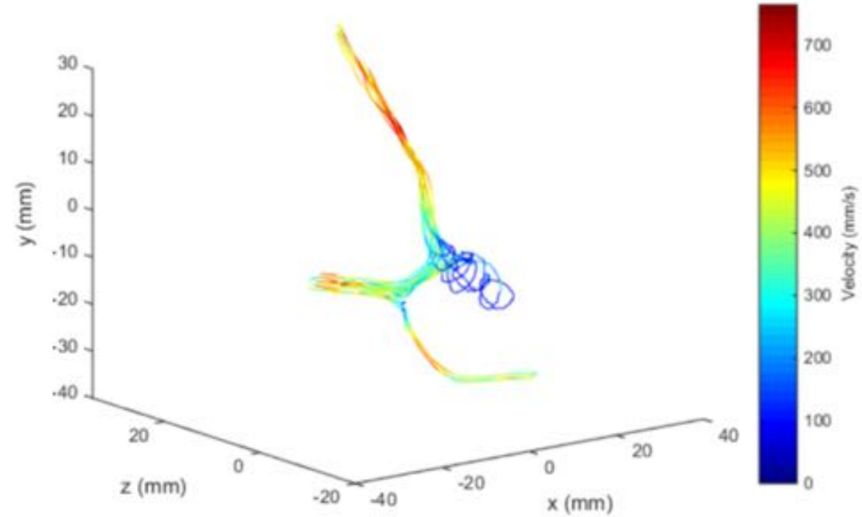


Re = 400 Re = 900 Re = 1700

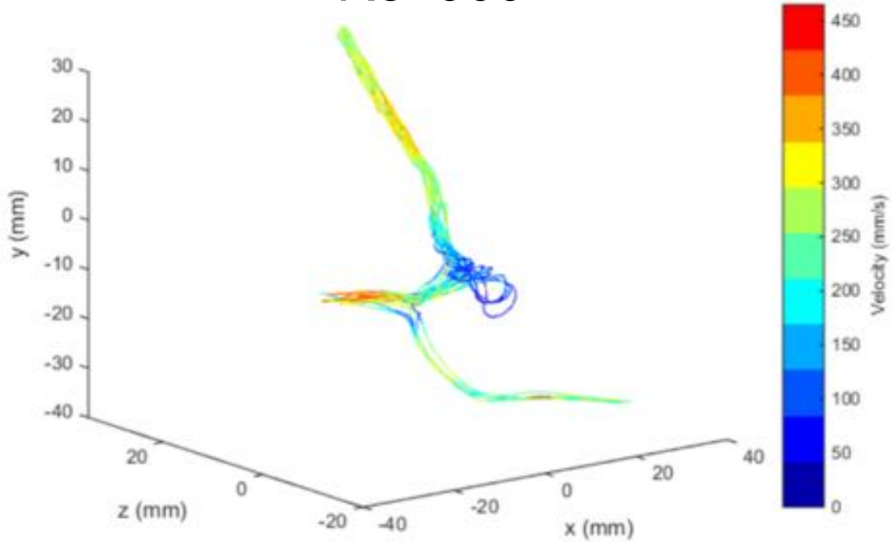
V. Frostelid (2016)

Path lines of particles

Re=1700



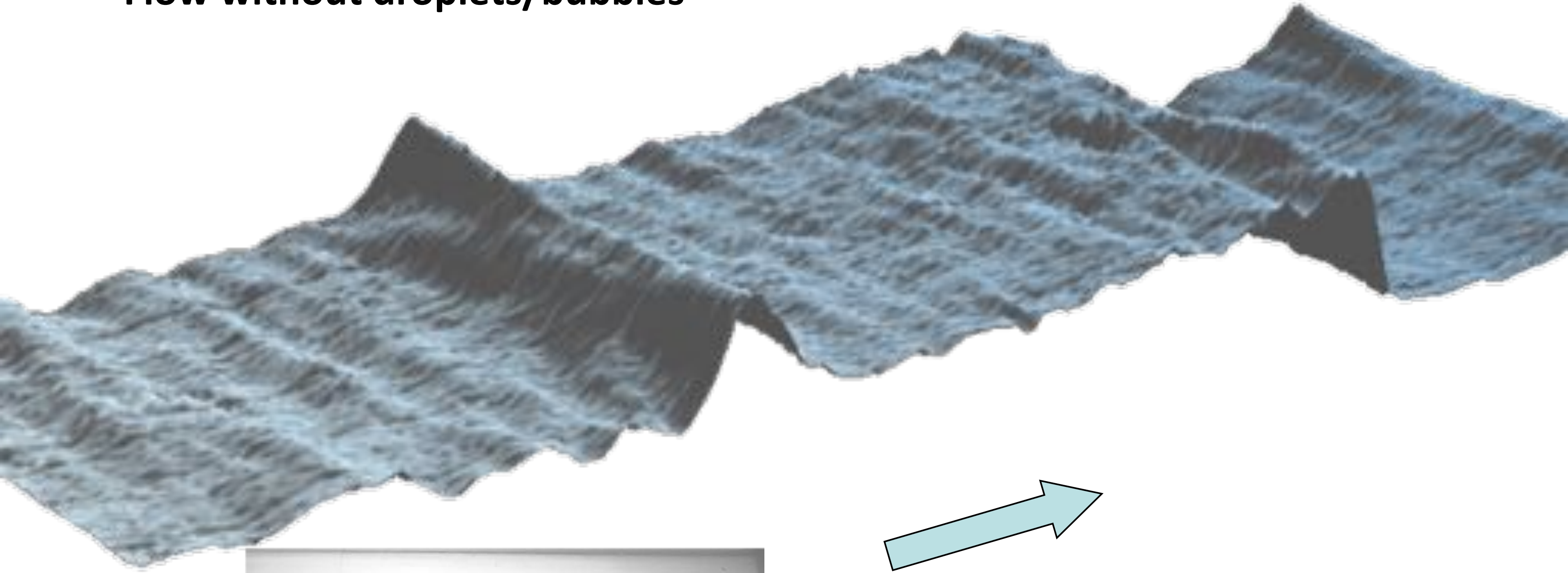
Re=900



Frostelid (2016)

3D interface of stratified wavy flow

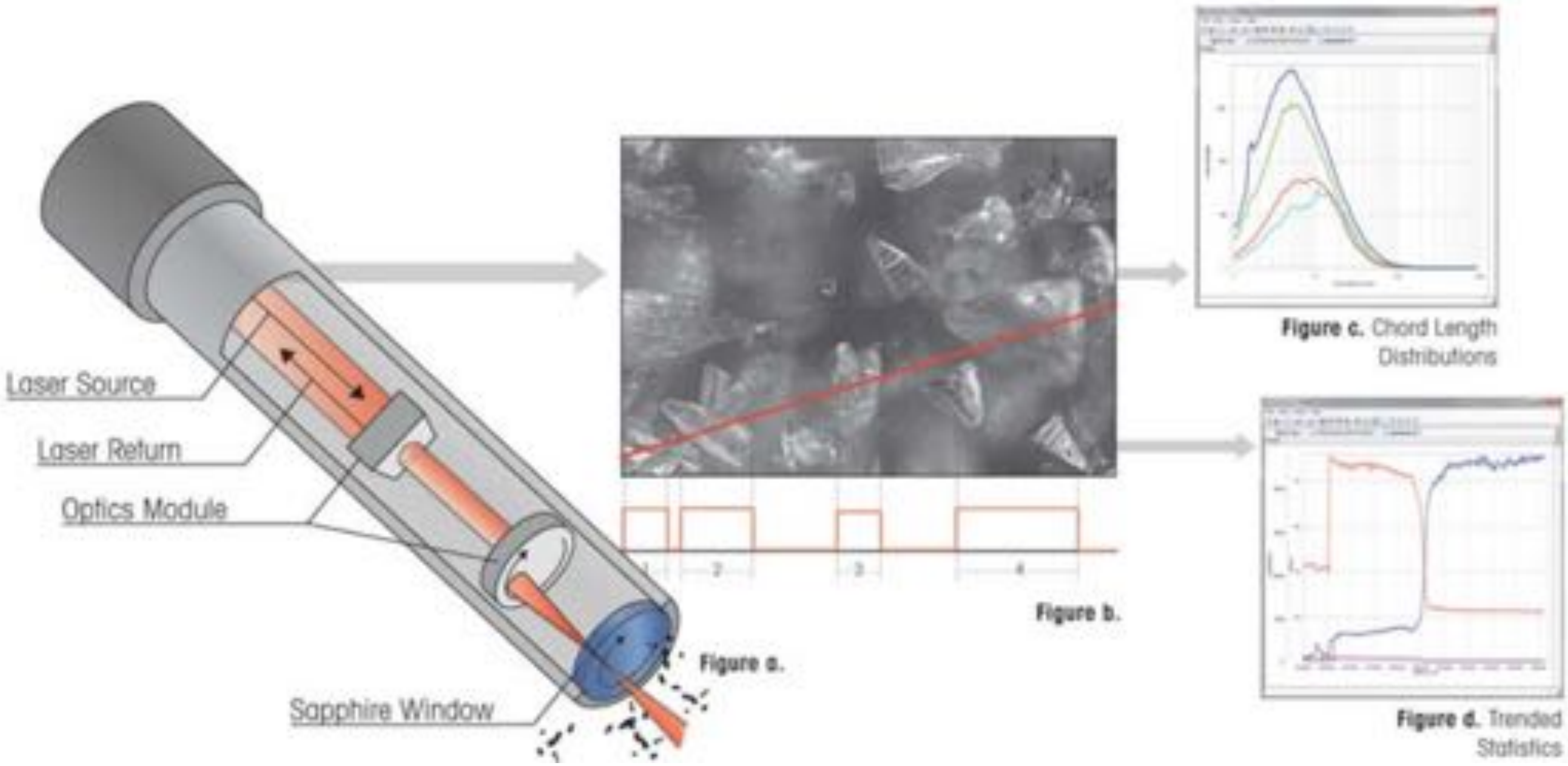
Flow without droplets/bubbles



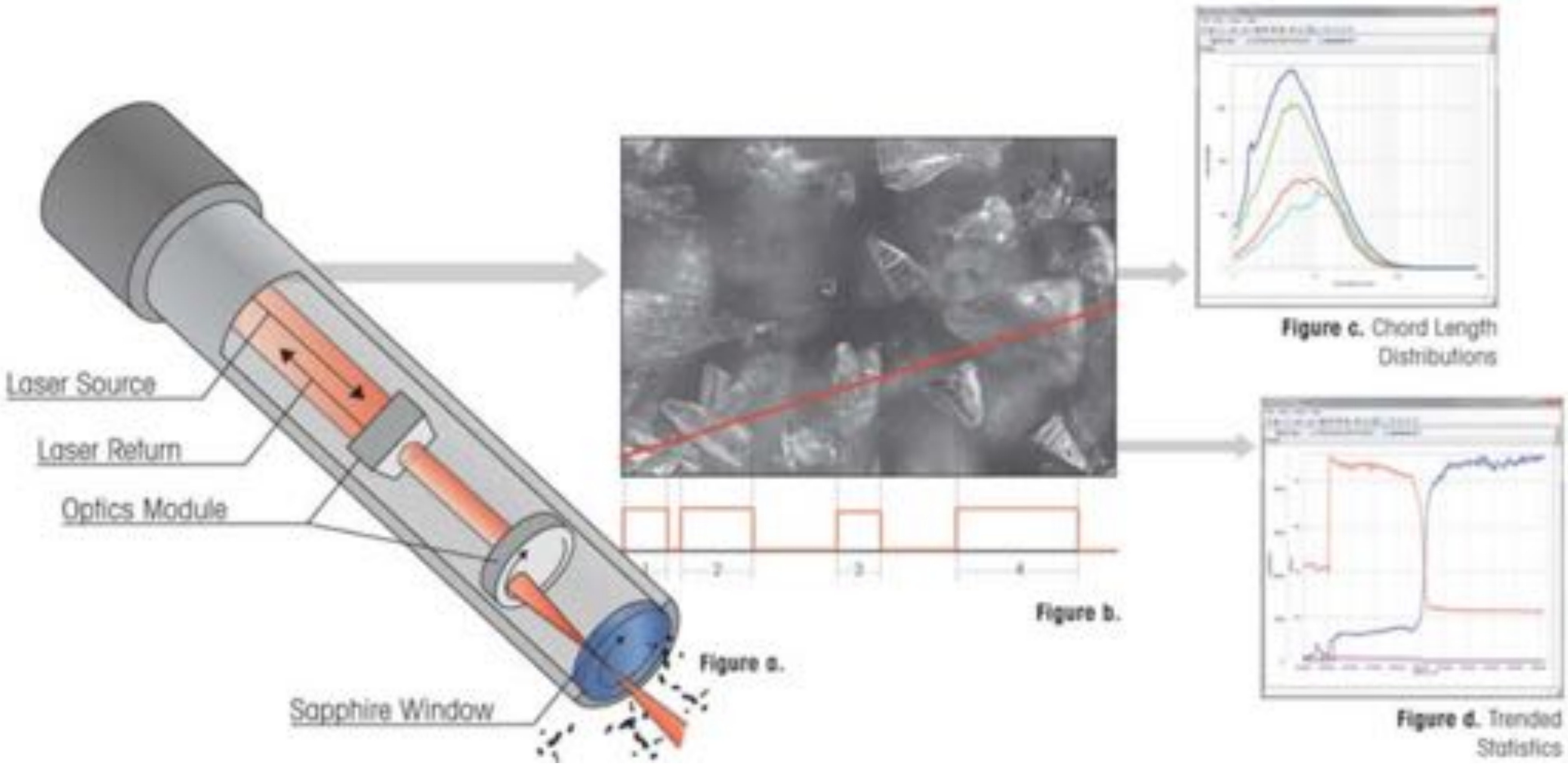
Drop size

- Impedance/conductivity probe
- FBRM
- PVM
- Endoscope
- Ultrasonic probe

FBRM

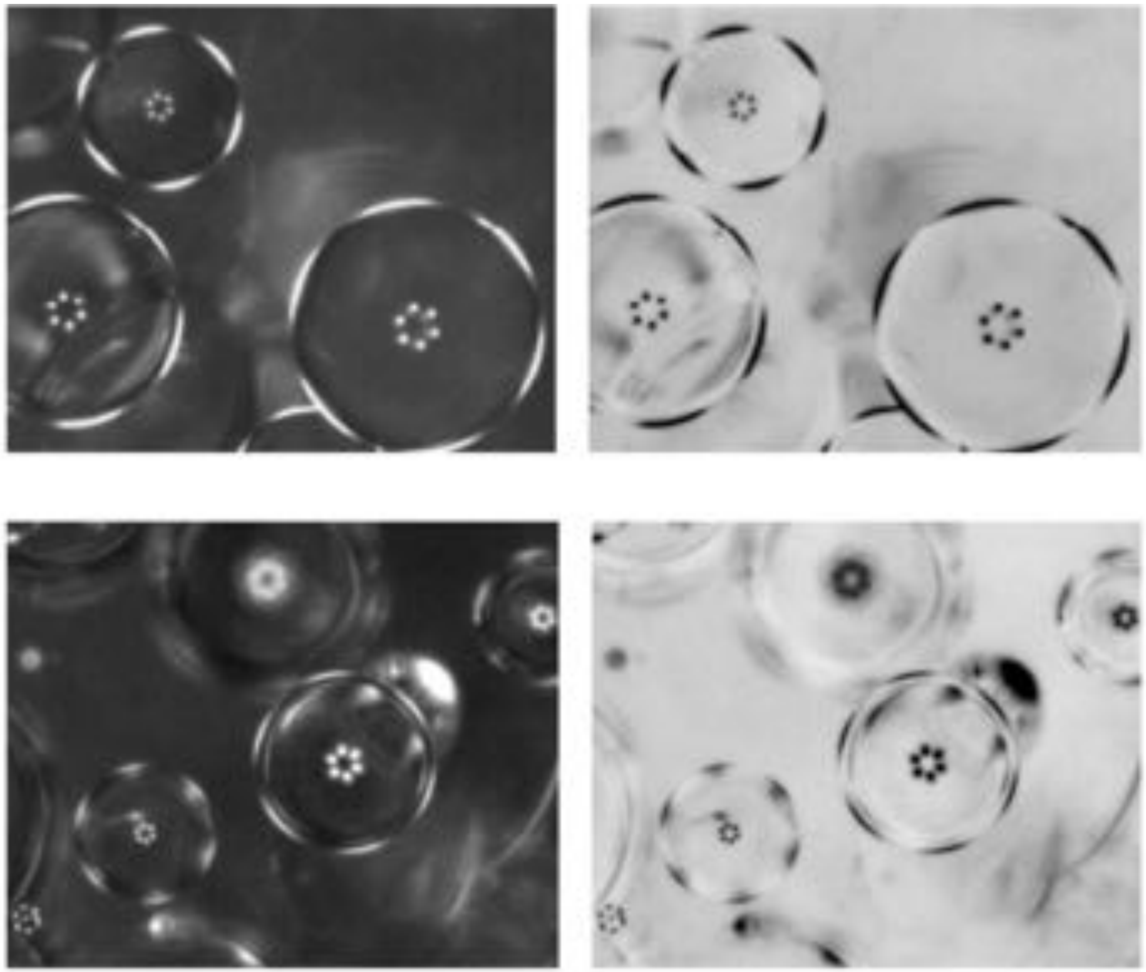

Laser Source
Laser Return
Optics Module
Sapphire Window
Figure a.
Figure b.
Figure c. Chord Length Distributions
Figure d. Trended Statistics

FBRM

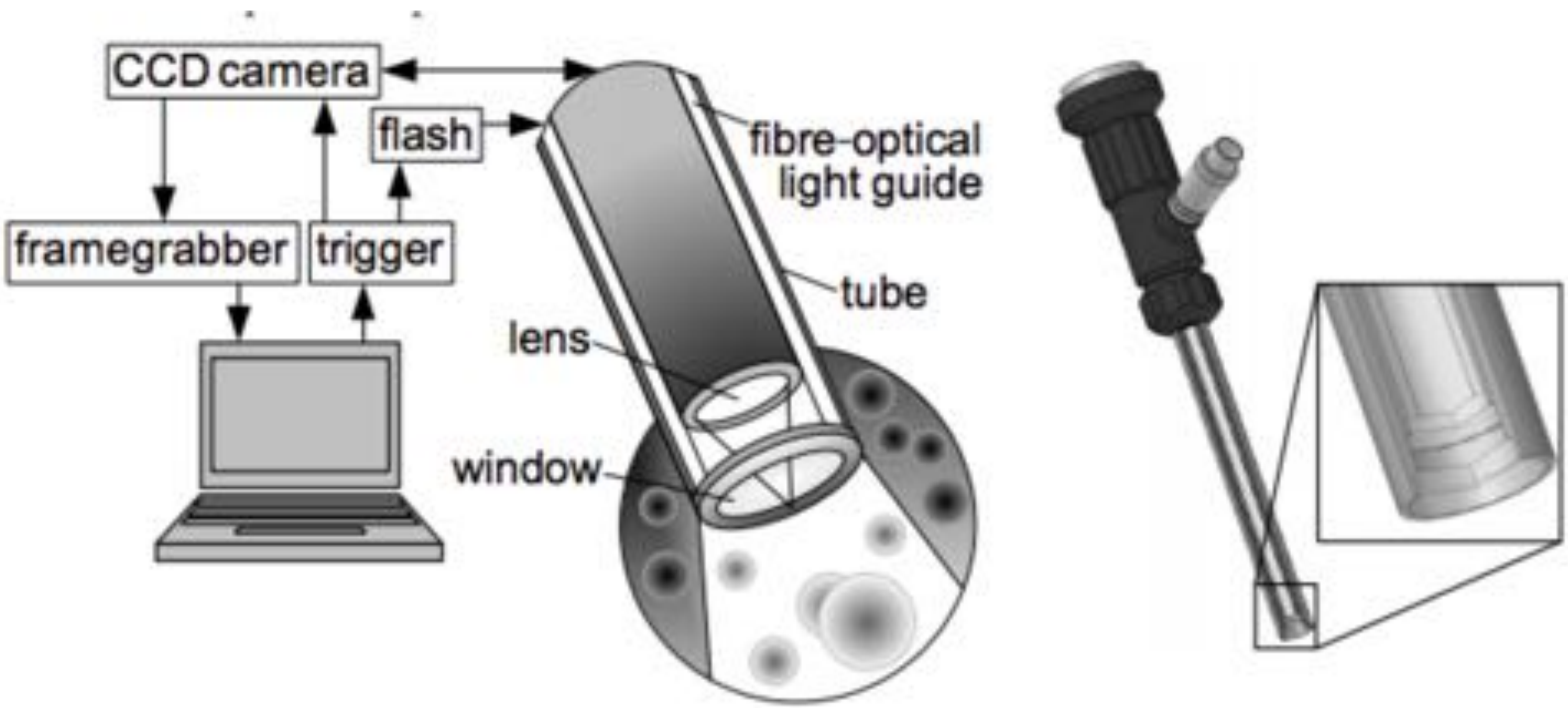


FBRM®, are able to show the change of the drop size distribution and the point of time, where the change starts, but they are not able to measure the exact size of the drops. They

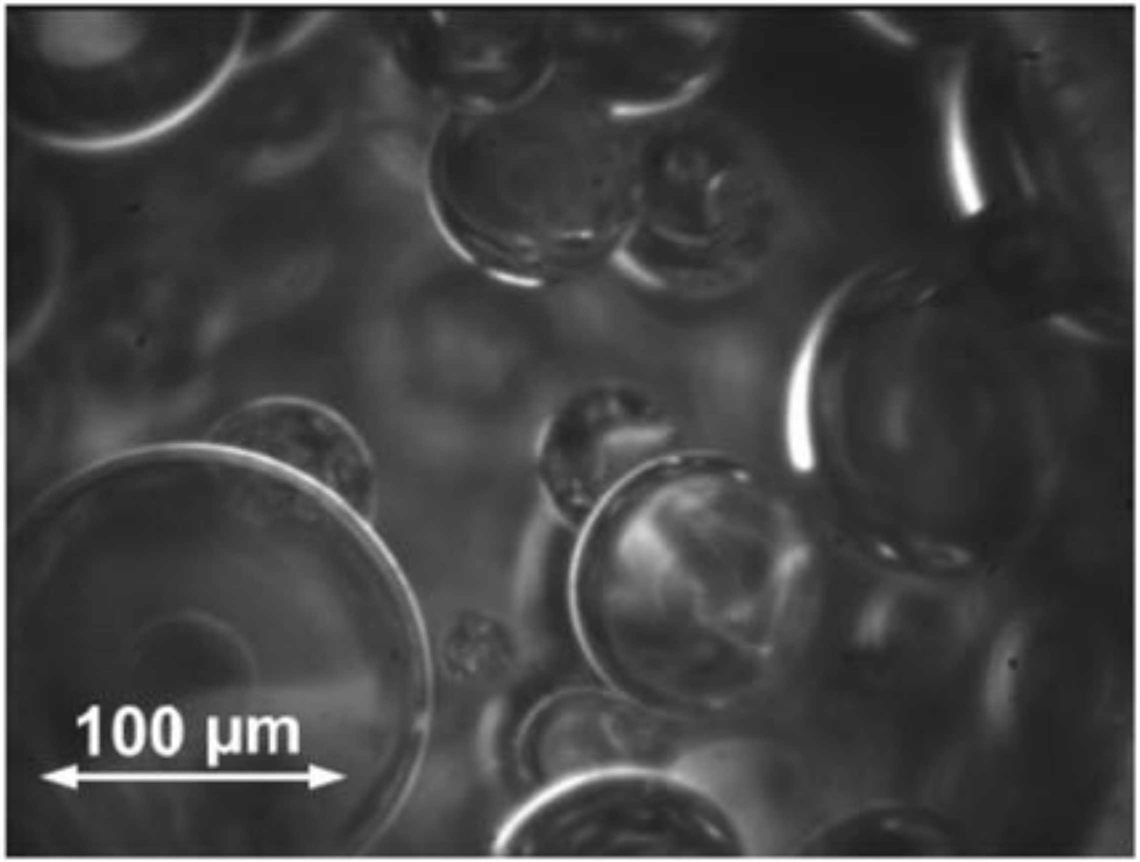
PVM



Endoscope

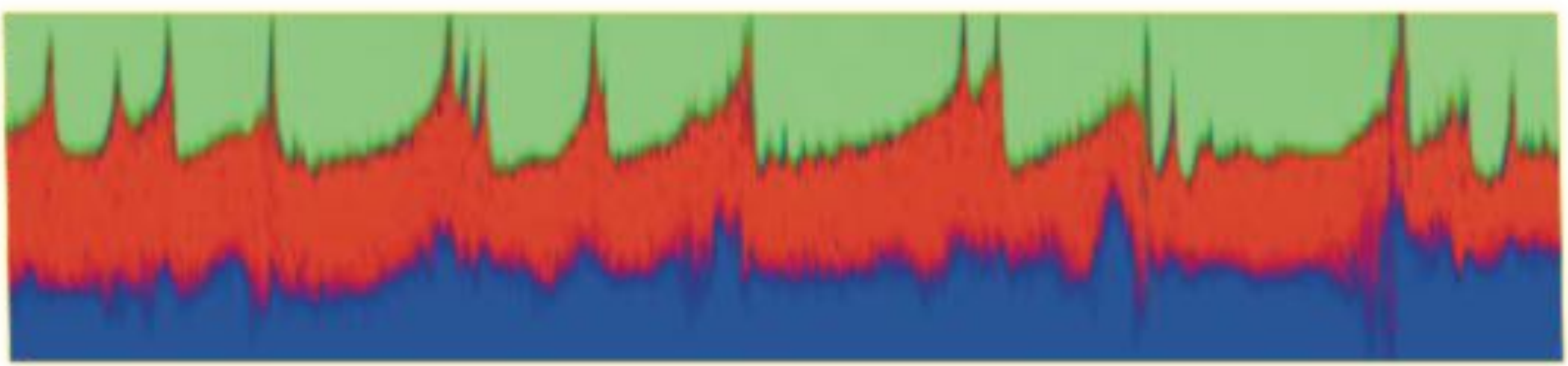

CCD camera
flash
fibre-optical
light guide
framegrabber
trigger
tube
lens
window

Endoscope



More specific parameters

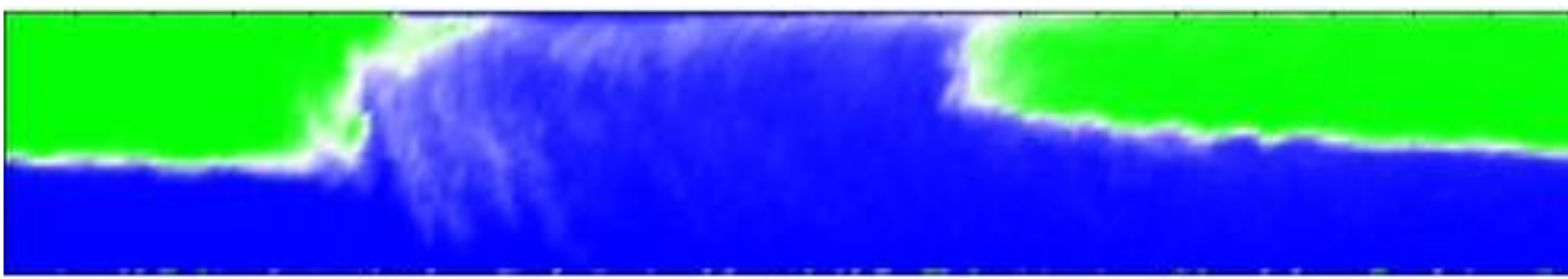
- Slug and wave characteristics
- Droplet entrainment and deposition
- Gas entrainment in slug



Top and side views of a slug flow

Top view

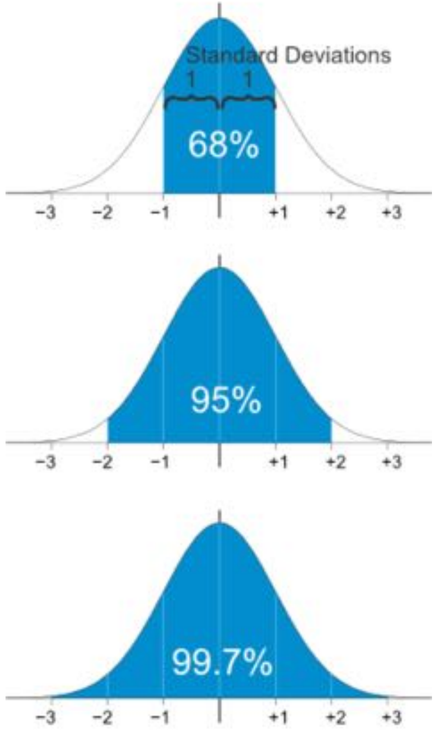
Flow



Side view

Uncertainty analysis

- Uncertainties are relatively small, standard deviation/mean less than 0.3
- Uncertainties have a normal (Gaussian) distribution
- Uncertainties have no significant covariance



$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)}$$

$$\mu_R = \sum_{i=1}^{p} \mu_i$$

$$\sigma_R^2 = \sum_{i=1}^{p} \sigma_i^2$$

Error sources

- Components evaluated by statistical methods
  - random errors cannot be corrected
  - biases can be corrected or eliminated from the result.

- Components evaluated by other means
  - Experience
  - Scientific judgement
  - Reference standards calibrated by another laboratory
  - Physical constants used in the calculation of the reported value
  - Environmental effects that cannot be sampled
  - Possible configuration/geometry misalignment in the instrument
  - Lack of resolution of the instrument

Error propogation

- The propagation of error formula for

$$Y = f(X, Z, \dots)$$

$$s_y = \sqrt{\left(\frac{\partial Y}{\partial X}\right)^2 s_x^2 + \left(\frac{\partial Y}{\partial X}\right)^2 s_z^2 + \cdots + \left(\frac{\partial Y}{\partial X}\right)\left(\frac{\partial Y}{\partial Z}\right) s_{xz}^2 + \cdots}$$

where

- s_x is the standard deviation of the X measurements
- s_z is the standard deviation of Z measurements
- s_y is the standard deviation of Y measurements
- $\partial Y/\partial X$ is the partial derivative of the function Y with respect to X, etc.
- s_{xz} is the estimated covariance between the X, Z measurements

Functions

If the measurements of A and B are independent, the associated covariance term is zero

Function	Variance
$f = aA$	$\sigma_f^2 = a^2\sigma_A^2$
$f = aA + bB$	$\sigma_f^2 = a^2\sigma_A^2 + b^2\sigma_B^2 + 2ab\,\sigma_{AB}$
$f = aA - bB$	$\sigma_f^2 = a^2\sigma_A^2 + b^2\sigma_B^2 - 2ab\,\sigma_{AB}$
$f = AB$	$\sigma_f^2 \approx B^2\sigma_A^2 + A^2\sigma_B^2 + 2AB\,\sigma_{AB}$
$f = \frac{A}{B}$	$\sigma_f^2 \approx f^2\left[\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 - 2\frac{\sigma_{AB}}{AB}\right]$ [11]
$f = aA^b$	$\sigma_f^2 \approx \left(abA^{b-1}\sigma_A\right)^2 = \left(\frac{fb\sigma_A}{A}\right)^2$
$f = a\ln(bA)$	$\sigma_f^2 \approx \left(a\frac{\sigma_A}{A}\right)^2$ [12]
$f = a\log_{10}(A)$	$\sigma_f^2 \approx \left(a\frac{\sigma_A}{A\ln(10)}\right)^2$ [12]
$f = ae^{bA}$	$\sigma_f^2 \approx f^2\left(b\sigma_A\right)^2$ [13]
$f = a^{bA}$	$\sigma_f^2 \approx f^2\left(b\ln(a)\sigma_A\right)^2$
$f = A^B$	$\sigma_f^2 \approx f^2\left[\left(\frac{B}{A}\sigma_A\right)^2 + \left(\ln(A)\sigma_B\right)^2 + 2\frac{B\ln(A)}{A}\sigma_{AB}\right]$

Summary

- Know the basics on multiphase flow measurement
  - Velocity
  - Drop size
  - Holdup

- Understand the propagation of uncertainties