Level and contour measurements on liquid metal surfaces

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- **Problem formulation , measurement requirements**
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  - Interferometry ,
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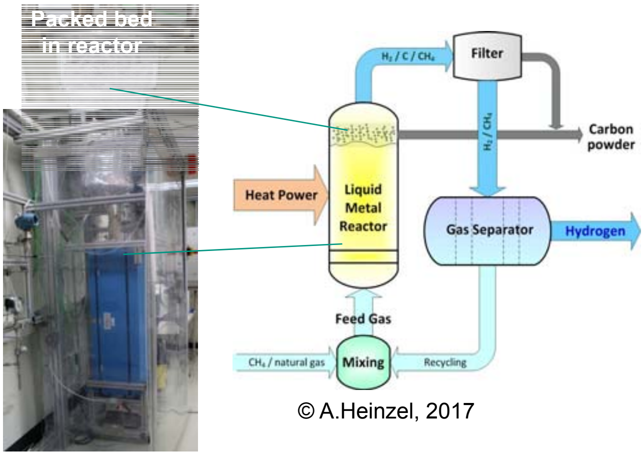
Background, Importance & Application

- **Level metering**
  - loop operation (state control variable)
    - Loop filling/draining
    - Indication of power level (volumetric fluid expansion)
    - Potential leaks or altered bypass-flows (e.g. HEX failure, guide vane deformation)
  - nuclear safety
    - Loss-of Coolant Accident (LOCA)
    - Pool sloshing –e.g. by earthquake,internal component defects (break)
  - process control (bubble column reactors, float glass process, casting)



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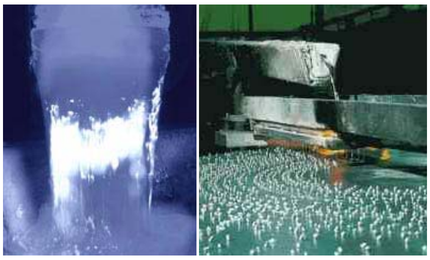
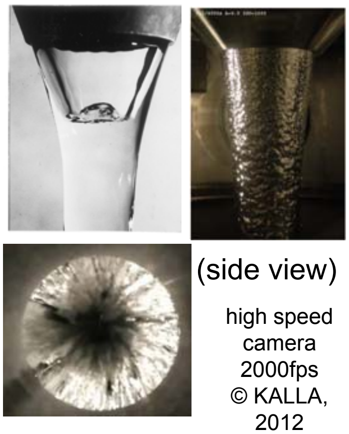


Alumina preparation for casting

Background, Importance & Application

- **Surface contour acquisition**
  - functional performance
    - neutron production targets - MEGAPIE, IFMIF, MYRRHA, SNS,
    - Ion-fragmentation-target (Super -FRS)
  - fabrication and manipulation technologies (Casting, automotive industry)

Myrrah-type target

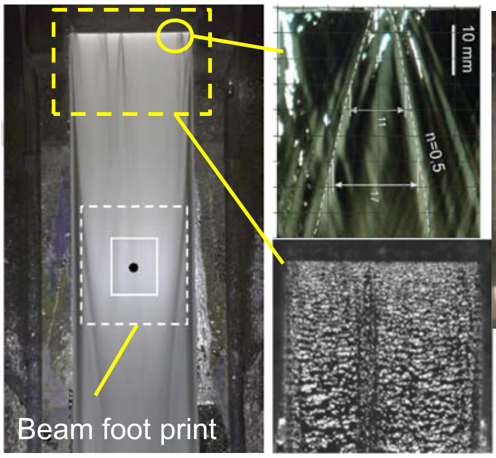


(side view)

high speed camera 2000fps © KALLA, 2012

$Pb^{45}Bi^{55}$ (top view)

IFMIF target (Li-flow)



© Kanemura, 2015

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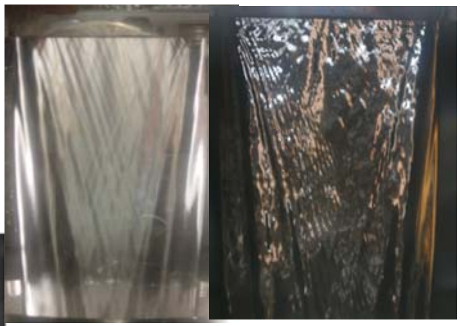
Super-FRS target (Na-flow)



conventional photograph

high speed camera 2000fps

Liquid metals properties

GENERAL FEATURES

- **opaque (τ=0)**
- **reflecting (specular $\rho \rightarrow 1$)**
- **high temperatures,**
- **corrosive**
- **large surface tension σ**
- **high electric conductivity σ_{el}**

	Unit	Water (@25°C)	Lithium (300°C)	$Pb^{45}Bi^{55}$ (300°C)
melting point @ 0.1MPa	[°C]	0	180.5	125
boiling point @ 0.1MPa	[°C]	100	1317	1670
vapour pressure	Pa	**3158**	**$3.7 \cdot 10^{-5}$**	**$2 \cdot 10^{-5}$**
ρ density	[kg/m^3]	1000	505	10325
ν kinematic viscosity	[m^2/s]$\cdot 10^{-7}$	9.1	9	1.75
σ_{el} electric conductivity	[A/(Vm)]$\cdot 10^{5}$	**$2 \cdot 10^{-4}$**	**33.5**	**8.43**
α thermal expansion	[/] $\cdot 10^{-3}$	6	43.6	6.7
σ surface tension	[N/m]$\cdot 10^{-3}$	**52**	**421**	**410**
a sound speed	m/s	1498	**4500**	1700

a = sound speed air a=343m/s

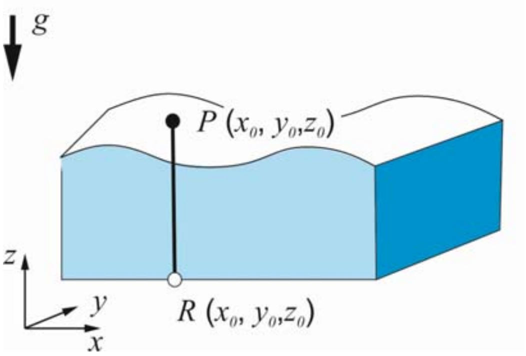
c = light speed c=2.997$\cdot 10^8$m/s

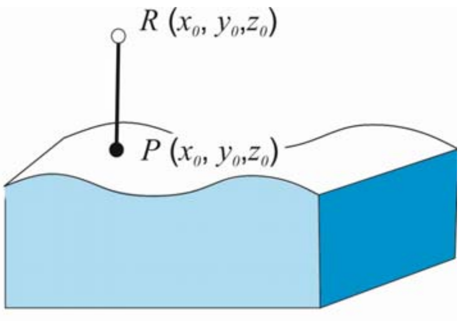
τ = optic transmission coefficient [/]

ρ = optic reflection coefficient [/]

Problem formulation –measurement requirements

- difference between **level** and **surface contour** ?





- level (h) =absolute value of distance vector $h = |\overrightarrow{RP}|$
- countour (vector-set) $s = \sum_{i=1}^{n} h\left(\overrightarrow{RP}\right)$ being steady & differentiable
- choice of reference point R decides on technique to acquire P !!
- most relevant in application is the resolution in z-direction

Problem formulation –measurement requirements

- **Sensing aspects requirements**

quantity & range	operational devices	functional devices
robustness, maintenance	life-time equipment	regular exchange
sensing distance	device dependent	device dependent
intervention measuring ambience	not excluded	not desired
auto-calibration	mandatory	indispensible
accuracy - temporal resolution - spatial resolution - repeatability [% meas. range] - stability [% ob meas. value]	 50ms –10s x· mm- x·cm ~5% 0.3%-1%	 ms 100nm-1mm < 1% <1%
signal to noise ratio (SNR)	>>10	>1
Price , access.	not relevant	selection aspect

- **Sensing options –challenges**
  - electric contact (geometry) ➡ surface tension, intrusive
  - force (gravity, buoyancy) ➡ spatial integration, intrusive
  - pressure **waves** (ultrasound) ➡ spatial integration, transmission
  - electromagnetic **waves** (high frequency –HF, optic) ➡ ambiguity, encoding, acquisition

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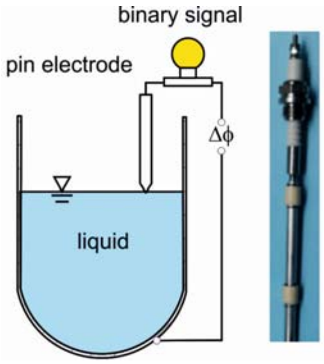
Level metering -classical devices

- electrical contact
  - safety equipment (expansion tank, pool arrangements)

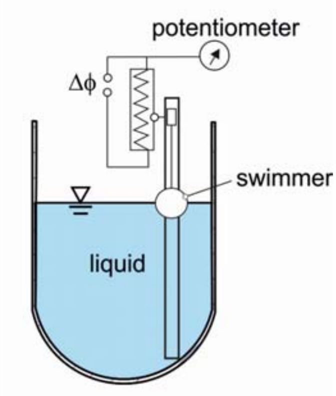


functionality
- electric contact on touch

accuracy
- given by geometry of built in (temperature dependent, surface tension)

acquisition
- binary signal, SNR→ ∞

- mechanical force
  - safety &operational equipment (expansion tank, pools)



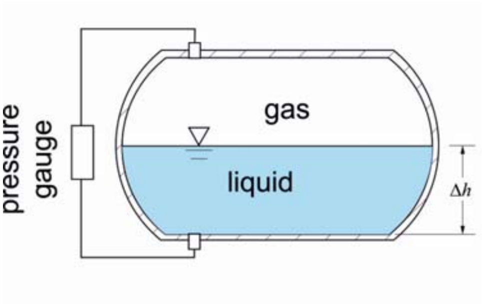
functionality
- Buoyancy =Gravity $F_{Buoyancy} = \rho_f \cdot V_O \cdot g = F_{g,Swimmer}$

accuracy
- integration over swimmer dimensions (temperature dependent, surface tension)

acquisition
- continuous signal, temporal resolution inertia dependent

Level metering -classical devices

- differential pressure
  - operational equipment



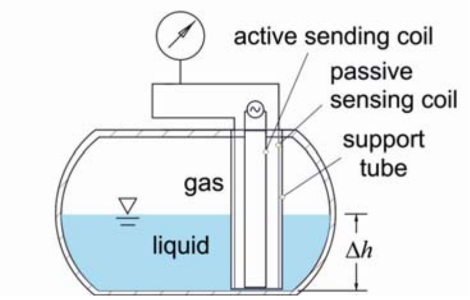
functionality
- hydrostatic pressure $\Delta p = \rho \cdot g \cdot \Delta h$

accuracy
- resolution of pressure gauge (temperature dependent, integration of column heights)

acquisition
- continuous signal, transducer depende time resolution

$\mu = 4\pi \cdot 10^{-7}$ N/ A^2
f=frequency (Hz)
σ= spec. electric fluid conductivity A/(Vm)
ρ=density (kg/m3)
g=gravity constant m/s^2

- inductive*
  - operational equipment (sump tank)



functionality
- breakdown of induced voltage in sensing coil at liquid level
- limitation of frequency by skin depth $\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$

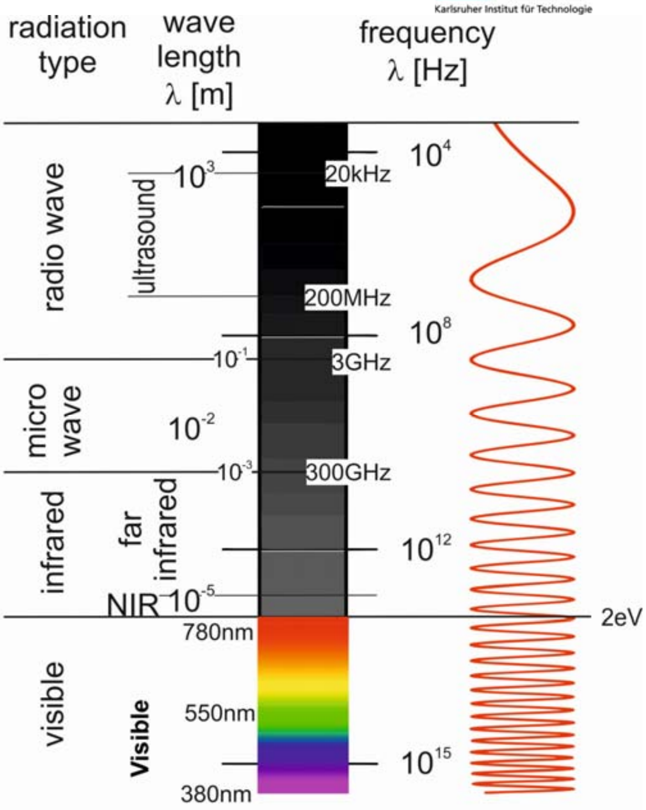
accuracy
- integration over diameter of tube (temperature dependent), accuracy ~3-5%

acquisition
- indirect signal, temporal resolution related to transmission frequency
- typical f=50-400Hz,

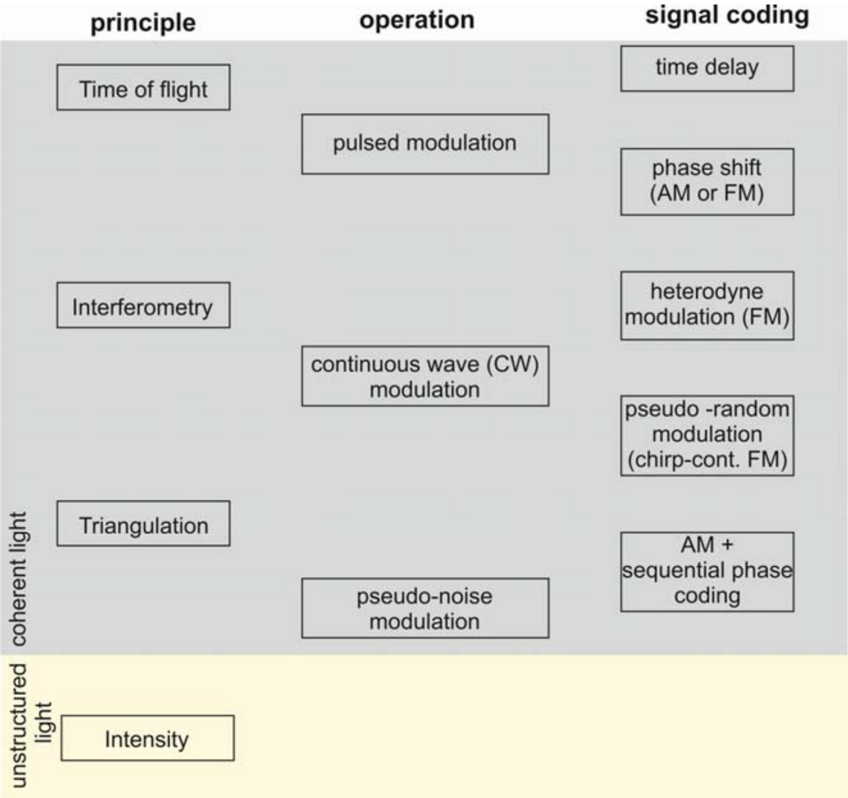
*GEC Energy systems (1981), LE8 3LH, United Kingdom; Khalilov, *Measurement Techniques, Vol. 50, No. 8, 2007*

Range sensing by waves – general

- wave utilization allow benefitting from wave characteristics
  - Time-of-Flight (ToF)
  - wave modulation (amplitude, frequency, interferometry)
  - stereo vision techniques (phased arrays, antenna fields, multiple cameras, ...)
- **applying various physics princples**
  - time measurement Δt
  - cross-correlation techniques
  - en-/decoding techniques
- **but, with all drawbacks of waves**
  - speckle noise(from interference)
  - multiple reflections (uniqueness-ambiguity)
  - jitter (transit time, phase)
  - crosstalk (ambient sources)



Electro-magnetic range sensing options



principle

operation

signal coding

Time of flight

Interferometry

Triangulation

pulsed modulation

continuous wave (CW) modulation

pseudo-noise modulation

time delay

phase shift (AM or FM)

heterodyne modulation (FM)

pseudo -random modulation (chirp-cont. FM)

AM + sequential phase coding

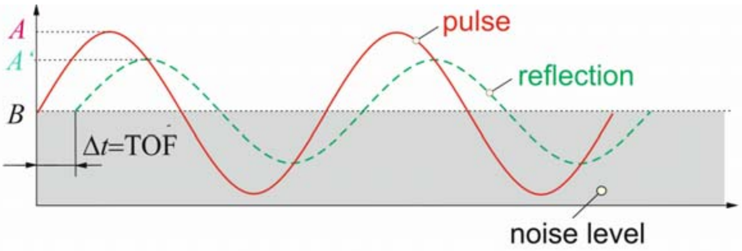
coherent light

unstructured light

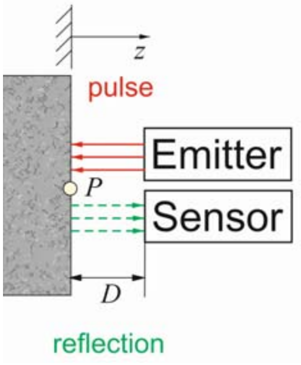
Intensity

Time of Flight (ToF) -principle

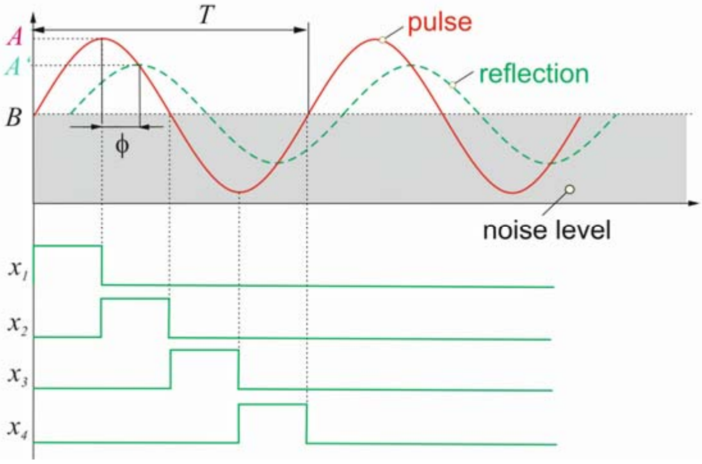
- time delay Δt



$$D = \frac{c}{2}\cdot\Delta t$$



- phase shift ϕ



$$D = \frac{c}{2}\cdot\frac{\phi}{\omega} = \frac{c}{2}\cdot\frac{\phi\cdot T}{2\pi}$$

integration of photons in time interval x_i

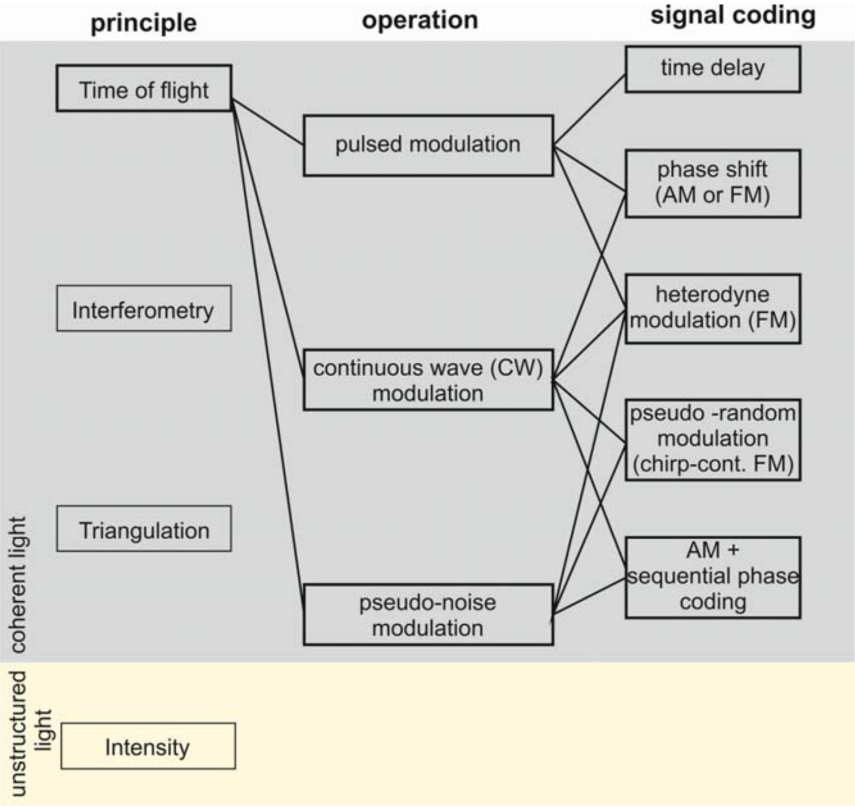
$$\phi = a\tan\left[\frac{x_3 - x_1}{x_4 - x_2}\right]$$

distance measurement error due noise after summed n periods

$$\Delta D = \frac{c}{2}\cdot\frac{T\cdot\sqrt{B}}{4\cdot A'\cdot\sqrt{2\cdot n}}$$

D = distance to be measured
c = wave propagation speed
B = noise level
A = amplitude emitter
A' = amplitude sensor
Δt = time delay
ϕ = phase shift
T = time period

ToF - Methods



principle
operation
signal coding

coherent light

Time of flight
Interferometry
Triangulation

pulsed modulation
continuous wave (CW) modulation
pseudo-noise modulation

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unstructured light

Intensity

Time of Flight (ToF) -features

Important impact parameters

- propagation speed c: c_{air}=350m/s , $c_{EM\text{-}waves}$=3.10^8m/s

Quality aspects

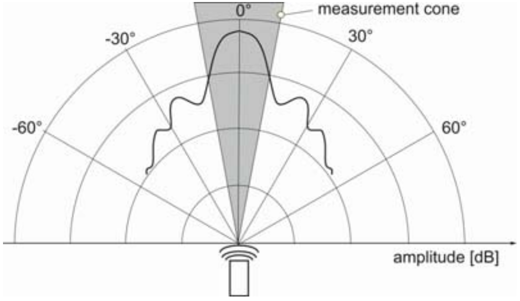
- **accuracies** of **time measurement, sensor acceptance**
- **opening angle** of transmitted beam (especially ultrasonic range sensors)
- interaction with target (surface properties(absorption), specular/multiple reflections)
- **variation** of **propagation speed** (sound=f(temperature))
- **speed target** (shape)

Ultra-Sound range sensors

- piezoelectric emitter/sensor
- ranges (cm→m).

- piezoelectric emitter/sensor, opening angle 15°
- ranges (air cm→m), accuracy ~1mm, 40-180kHz

https://www.electrodragon.com/product/ultrasonic-proximity-sensor/ 20th march 2019, 1.15€/pcs

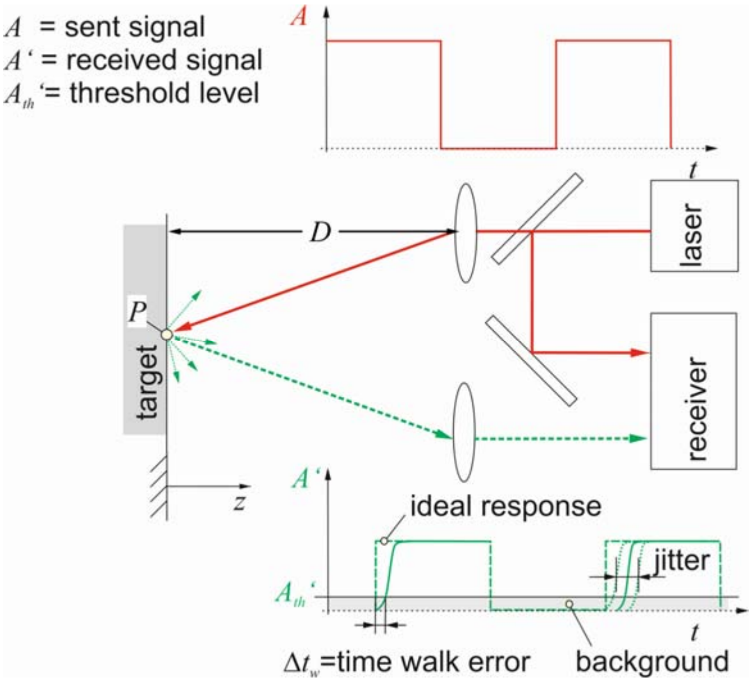


Applications

- distance measurement also for transparent media
- collision detection (remote handling)

Time of Flight (ToF) -light

- same principle& drawbacks as ultrasound, but larger propagation speed c
- **LiDAR** (LADAR) =***Li***ght ***D***etection ***A***nd ***R***anging (**time delay principle Δt**)



error sources for sent signal

- shot noise (signal),
- jitter
- nonlinearity receiver sensor

error sources received signal *:

- shot noise (background)
- timing walk (due to amplitude, shape variations)
- jitter (leading edge acquisition)
- nonlinearity receiver sensor
- sensor drift .

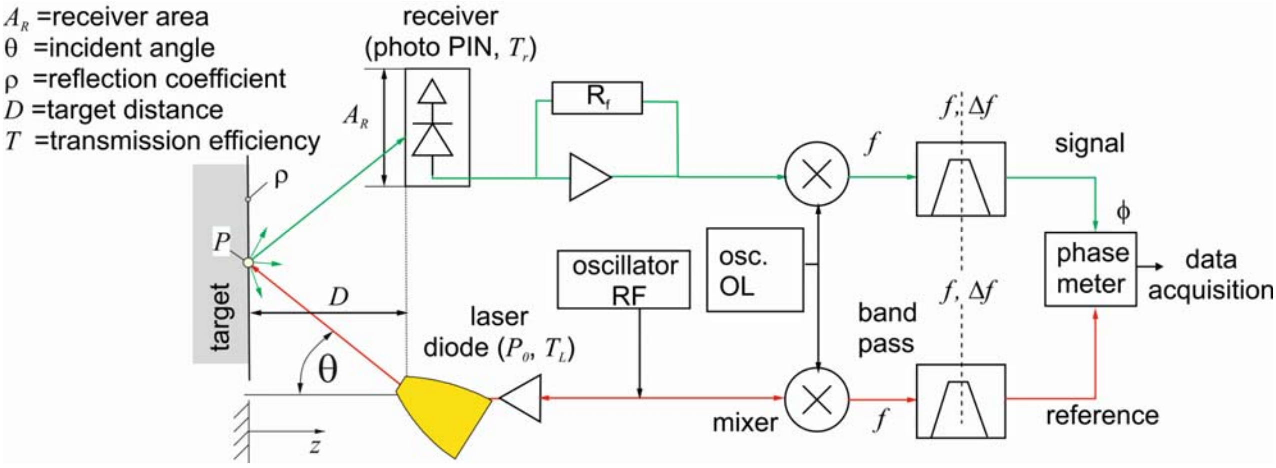
system errors

- speckle phase noise (induced by target roughness/surface)
- system setup vibrations

*Baumann et al., Speckle phase noise in coherent laser ranging: fundamental precision limitations, Opt. Lett. 39, 2014

Time of Flight (ToF) -light

- LiDAR (LADAR) =***Li***ght ***D***etection ***A***nd ***R***anging (**phase shift ϕ**)
  - modulation of optical power with constant frequency f (c=$\lambda \cdot f$, typ. operation freq. MHz range).
  - after target reflection photodiode collects a part of the laser beam.
  - unambiguous distance Λ measurement given by Λ=(c / f)
  - two mixers outputs are filtered by a passband circuit tuned on f (bandwidth Δf)



- received signal power P_r $$P_r = T_r \cdot T_L \cdot \frac{\rho}{\pi} \cdot P_0 \cdot \cos\theta \, \frac{A_R}{D^2}$$

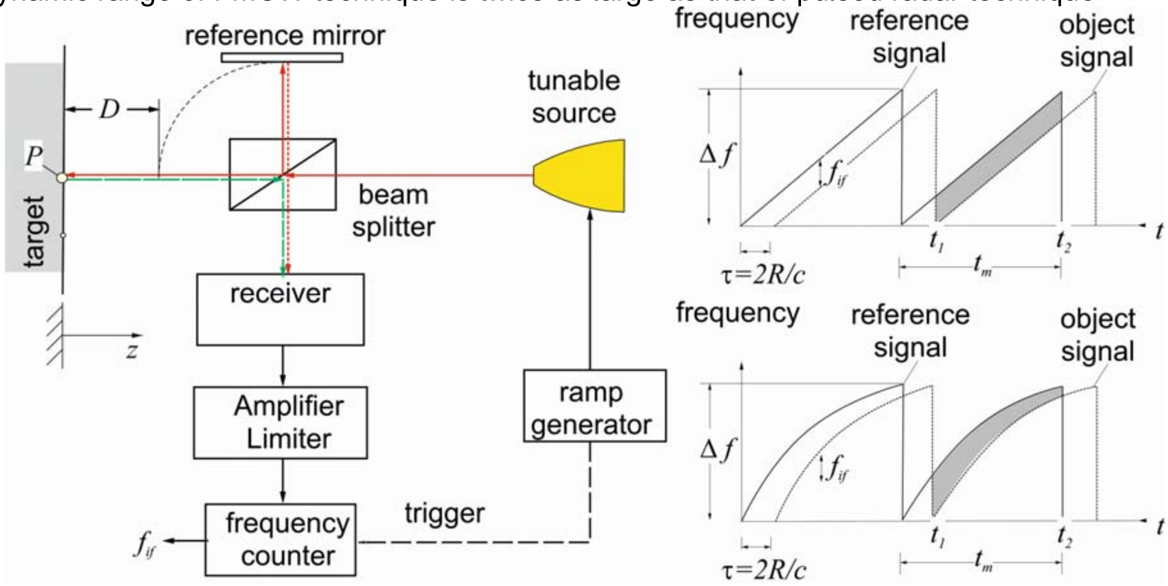
But

- only „**Lambert reflection“** part can be used (if ρ>0.8-0.9 **no signal is obtained**)
- problematic for laser (beam size ≈ target shape amplitude), good for HF waves (beam spot>>target contour fluctuations‘)

Time of Flight (ToF) –radar (light or HF)

- FMCW technique with periodic and linear frequency chirp
- superposition of target and reference mirror reflections in receiver
- main ac component of mixed signals occurs at frequency difference f_{if}
- Intermediate frequency f_{if} of reflected signal is measured by frequency counter
- due to mixing of both signal amplitudes f_{if} ~ amplitudes (of both target + reference)

➡dynamic range of FMCW technique is twice as large as that of pulsed radar technique

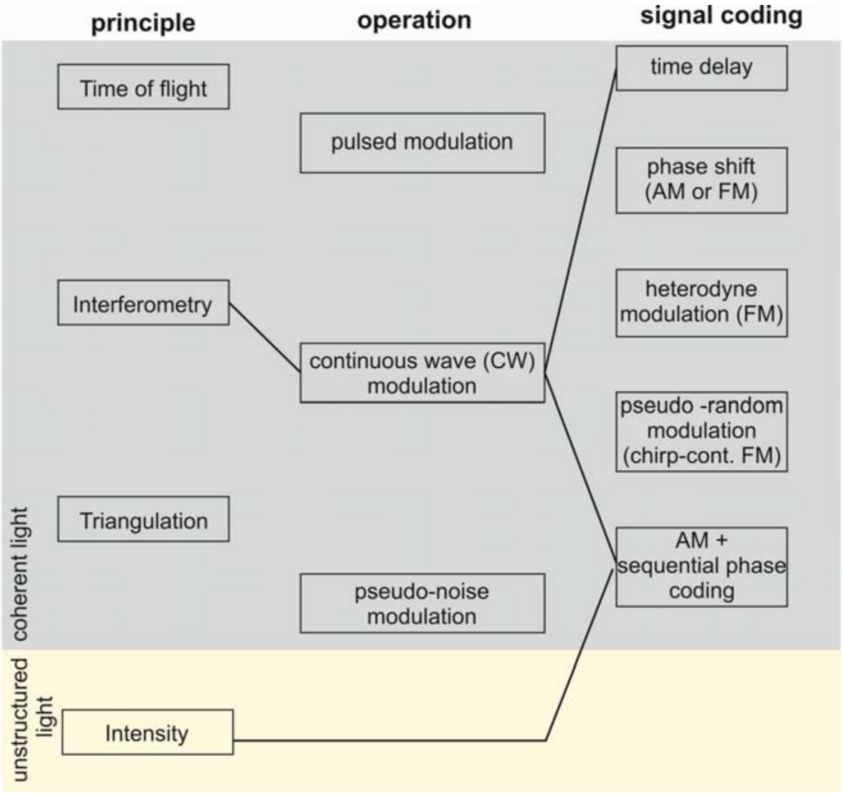


- round trip delay time $\tau = 2D/c$ ➡ intermediate frequency f_{if}

$$f_{if} = \Delta f \cdot \tau / t_m = 2 \cdot \Delta f \cdot R / c\, t_m$$

FMCM=frequency modulated continuous wave
t_m = ramp period (0.1-1ms)
c = propagation speed ligth

Interferometry-various approaches



principle
Time of flight
Interferometry
Triangulation
Intensity

operation
pulsed modulation
continuous wave (CW) modulation
pseudo-noise modulation

signal coding
time delay
phase shift (AM or FM)
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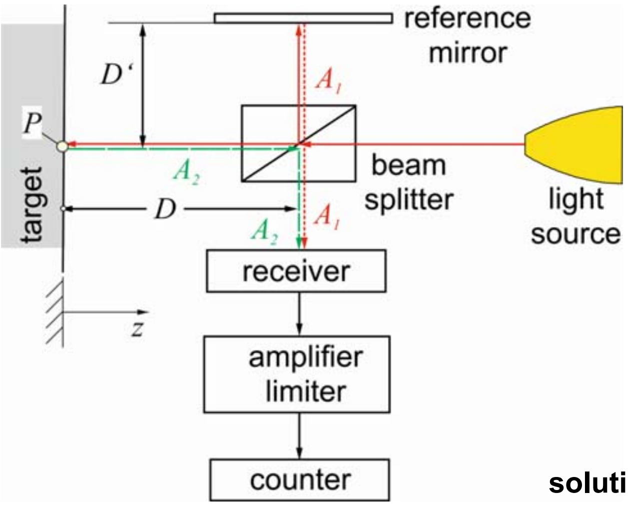
coherent light
unstructured light

Interferometry -principle

- Interference based technology (constructive for λ/2, destructive for λ/4)

functionality

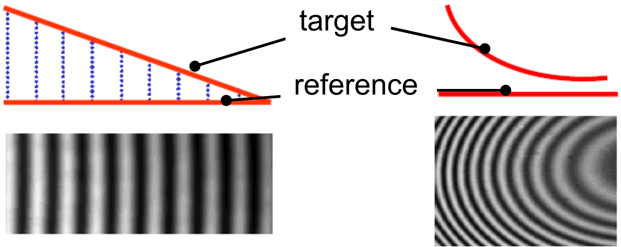
- intensity peak each time the object position changes by λ/2
- counting number of minimum-maximum transitions in interference pattern
- over time, when the object moves, the distance of movement can be incrementally
- determined at an accuracy of O(λ)



D= distance of target
D'=distance reference object
A_i=Amplitude beam i
I_i = Intensity beam i
λ= wave length

features

- Intensity $I = I_1 + I_2 + 2\sqrt{I_1 \cdot I_2} \cdot \cos\left(\frac{2\pi(2D-2D')}{\lambda}\right)$
- **no directional information**
- **no absolute information**

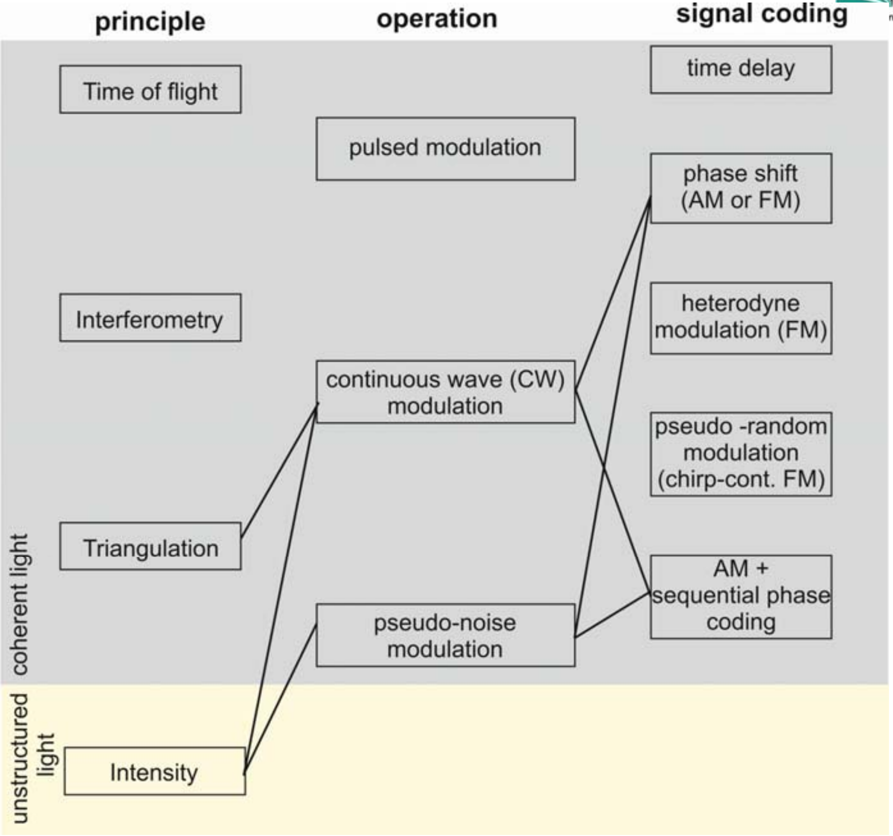


© https://cmi.epfl.ch/metrology/files/Wyko/Interferometery_Basics.pdf, 2016

solution to overcome drawbacks

- multi – λ-Interferometry
- light polarisation (additional information of ϕ)
- white-light interferometers (low coherence length)
- acousto-optic modulation

Triangulation –various approaches



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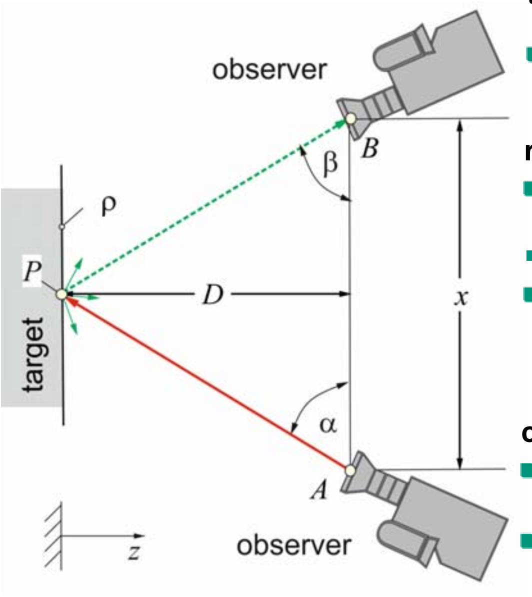
Triangulation – passive

- pure geometric approach (stereovision, photogrammetry, theodolite)

principle

- observation of target point from two different sites A and B of known distance x
- measurement of viewing angles α and β with respect to the base AB



target distance *D*

- geometric relation $$D = \frac{x}{\frac{1}{\tan\alpha} + \frac{1}{\tan\beta}}$$

requirements

- each **point** to measure must be **identified** from both observers A and B **unambiguously**,
- ➡ **require** a scene with **high contrast**
- application of **reconstruction techniques** (in both observer image typical object features are found and compared. From position of each feature's centroid in both separate images, angles α and β are obtained)

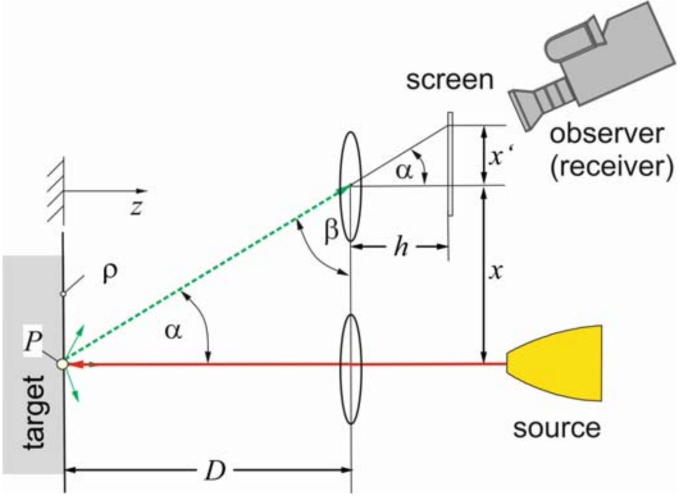
challenges

- **shadowing effects** (solution more cameras- multivision systems- but leading to increased computational effort)
- **auto-calibration** (required for both cameras to account for motion of camera) must be precise
- high precision **pixel resolution** (to determine centroid)

Triangulation – active

principle

- projection of point (or line) to target and observation on screen by detector
- triangulation based on similarity object triangle and image triangle (defined by optical axis of image screen, focal length h and recorded position of point projection x')



challenges- limitations

- **shadowing effects** (δz mean large x causing more shadows !!)
- **auto-calibration** (cameras to account for camera & target motion)
- high precision **pixel resolution**

target distance *D*

- geometric relation $$D = h \cdot \frac{x}{x'}$$
- accuracy δz : $$\delta z = \frac{1}{h} \cdot \frac{D^2}{x} \cdot \delta x'$$
- ➡ high resolution δz requires
  - small D,
  - large triangulation base x and
  - high screen resolution δx

improvement options

- line projection ➡ scanning
- 3D projection ➡ full world image

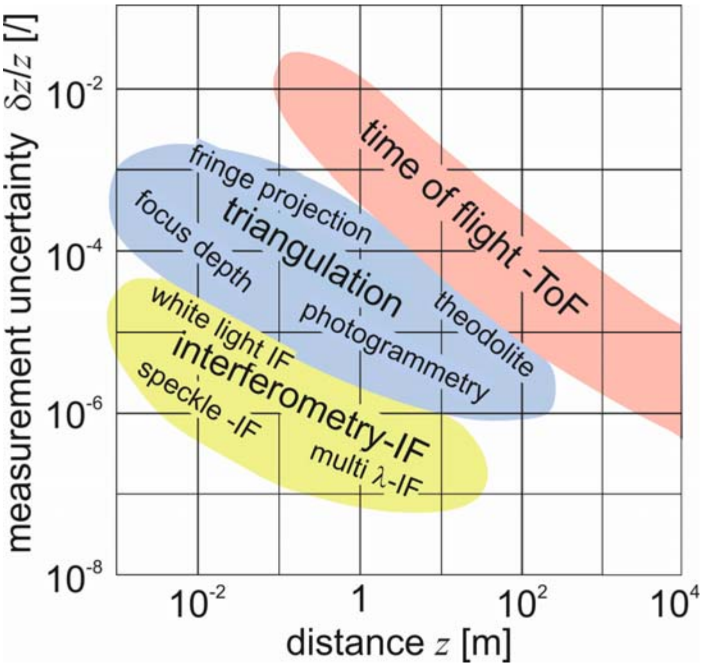
relatives of triangulation techniques

- structured light imagining
  - phase shifted projected
  - gray code approach
  - phase shifted Moire
  - coded patterns
  - random texture
  - colour coded light

Accuracies –US/HF/optics for nuclear applications

summary in theory

- **US limited to milimeter range** resolution requiring dense media (no vacuum)
- **HF/light ToF robust** with sub-milimeter resolution for absolute distance $|\overrightarrow{RP}|$
  - requiring **Lambert type reflection** (easy in HF due to beam expansion, challenging for light)
  - robust with autocalibration
  - many reliable coding options
  - spatial resolution x,y-plane ???
- **triangulation higher resolution** than ToF absolute and in x,y-plane but considerable effort for
  - **re-construction techniques**
  - **auto-calibratrion**
  - **shadowing**
- **interferometry** with highest precision but
  - ambiguity challenge for large D ➡ short target distances
  - fragile against rapid target motion
  - auto-calibration ????



R. Schwarte, 1999, Principles of 3-D Imaging Techniques", in *Handbook Computer Vision and Applications*, Academic Press.

Overview -Techniques

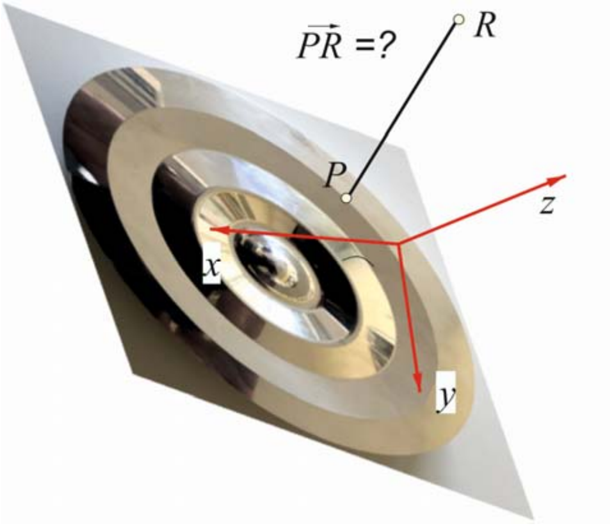
principles	Ultra-Sound	High Frequency	Optic
media transport	air/liquid	any	any
transport velocity	sound speed	light speed	light speed
emitter	piezo	UHF/VHF	laser/coherent light source
modulation freq. ampl.	x no	x x	x x
CW operation	no	yes	yes
beam expansion	10°-30°	5°-15°	0.15°
receiver type	piezo	antenna	photodiode CCD/CMOS
transmission 90° turns	wave guide no	hollow cavity (quasi-optic)	fibre mirror
amplifier	conv. electric	conv. electric	dynodes
radiation hardness	medium	proven	???

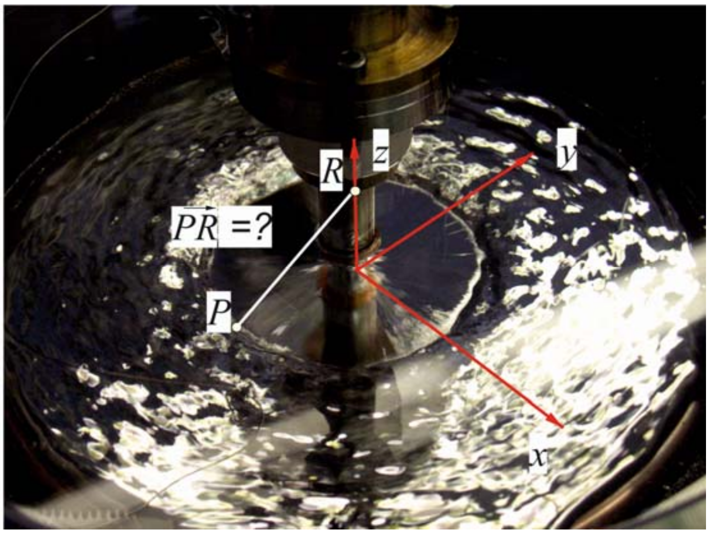
- **application requires adequate functioning for all elements** (source-transmission-acquisition-signal processing @ given boundary conditions

Practical example - Double Layer Projection (DLP)

challenge:

- specular surface in sizeable distance from observer (D~O(m))
- in nuclear environment
- typical motion velocities of O (u=m/s)
- accuracy in vertical direction δz<<1mm, lateral accuracy δx, δy <1mm
- temporal resolution f >50Hz





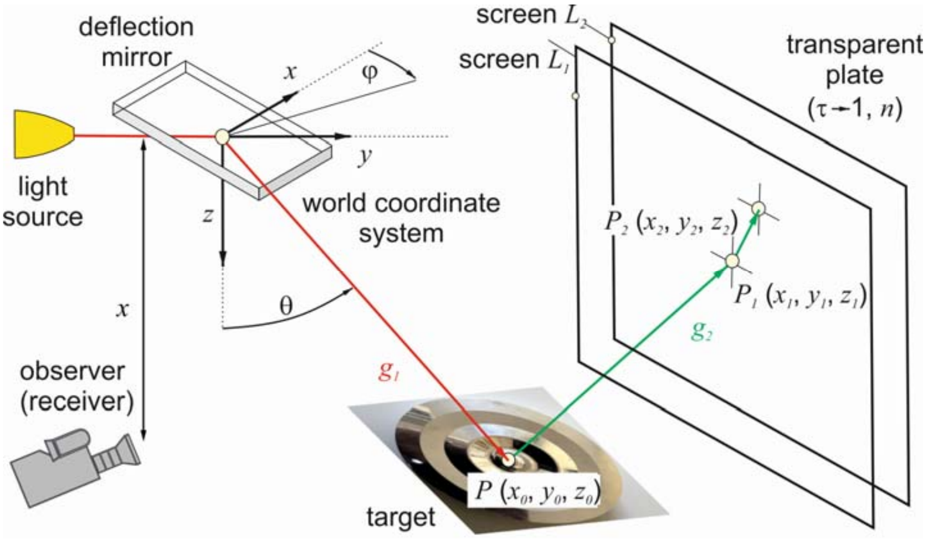
Double Layer Projection (DLP)-functional principle

fundamental idea

- project a focussed laser beam on the specular surface ➡ generation of straight g_1
- record points P_1 and P_2 via a observer camera ➡ calculate g_2
- compute position of P through intersection of $g_1 \cap g_2$

drawbacks

- high sensitivity due to changes of source and receiver (x)
- determination of absolute distance to target (auto-calibration)
- sensitivity to incident beam angle θ



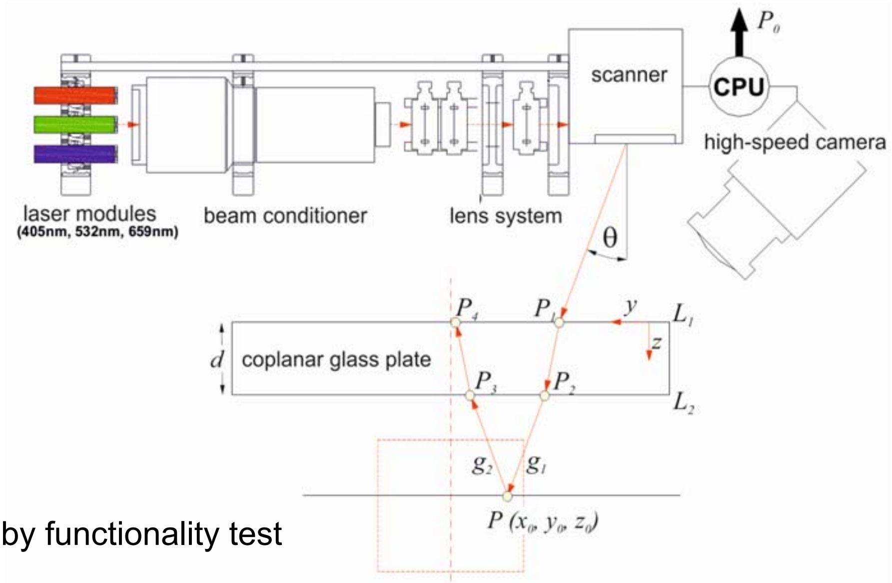
Double Layer Projection (DLP)-technical solution

solution

- (x-problem) record both incoming beam (g_1 by P_1, P_2) and reflected beam (g_2 by P_3, P_4)
- (auto-calibration) use different wave length laser since refractory index $n = f(\lambda)$
- (incident beam angle θ) scanner allows for line (area) tracing but limits θ

sensitive parameters

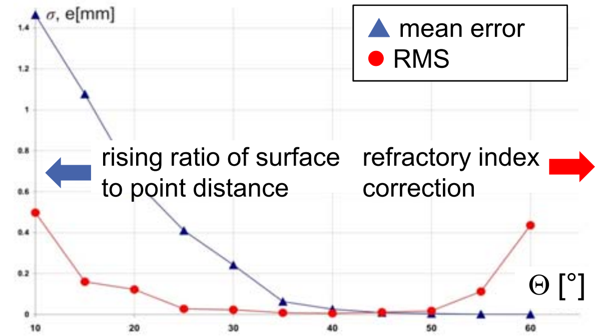
- primary parameters
  - *incident beam angle [θ]*
  - *glass thickness [d]*
  - *target distance [z]*
  - camera focus length [f]
  - target motion speed
  - target shape-curvature
- secondary parameters
  - *illumination time*
  - *wave length [λ]*
  - *camera calibration*



➡ verification & validation by functionality test

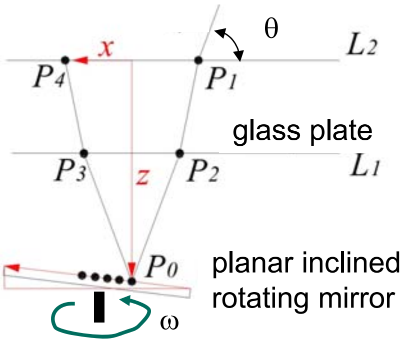
Double Layer Projection (DLP)-technical solution

incidence angle [θ]



rising ratio of surface to point distance

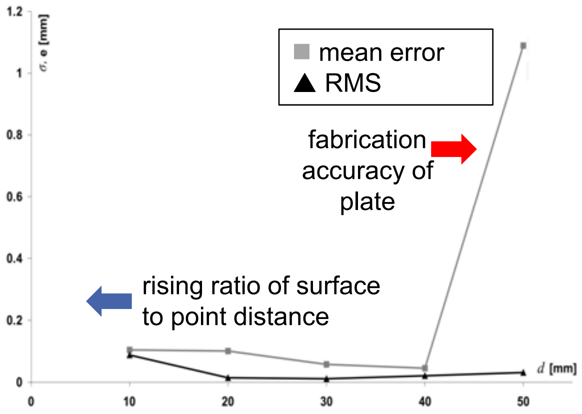
refractory index correction



glass plate

planar inclined rotating mirror

glass thickness [d]

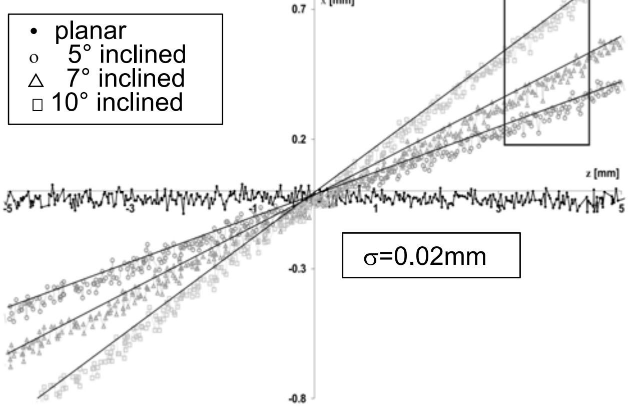


fabrication accuracy of plate

rising ratio of surface to point distance

target distance [z]

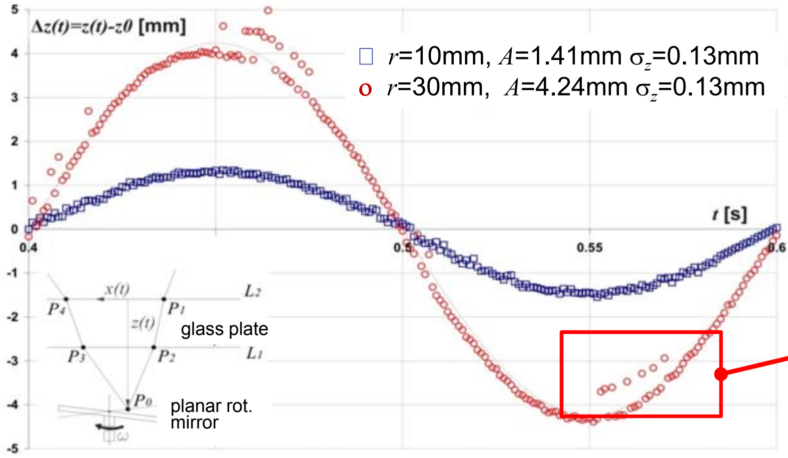
scratches on glass



σ=0.02mm

Double Layer Projection (DLP)-technical solution

- **target motion speed [ω=5Hz] = temporal**



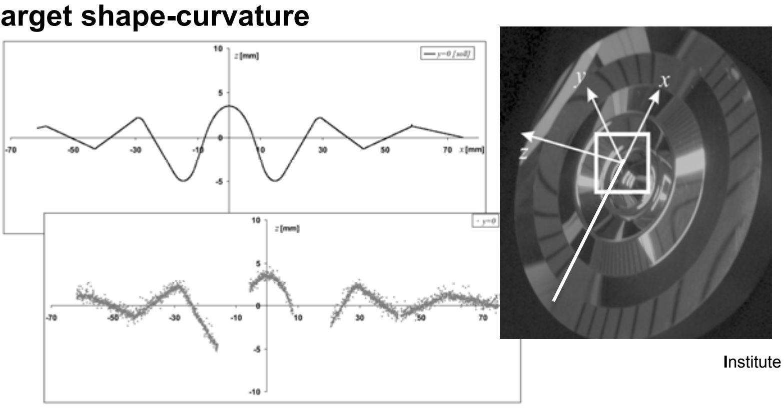
A=Amplitude

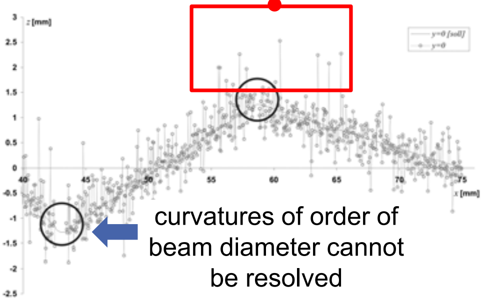
result

- barely dependent of ω
- dependence on absolute velocity

incorrect object assignment

- **target shape-curvature**



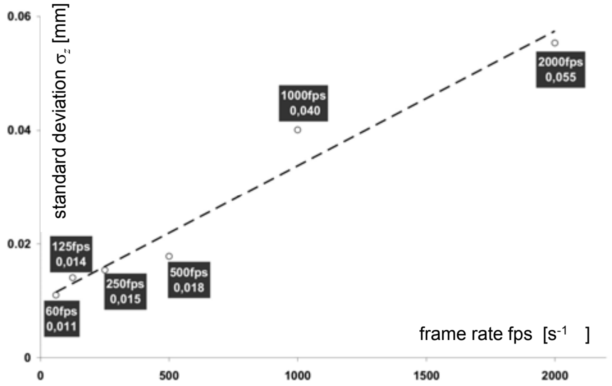


curvatures of order of beam diameter cannot be resolved

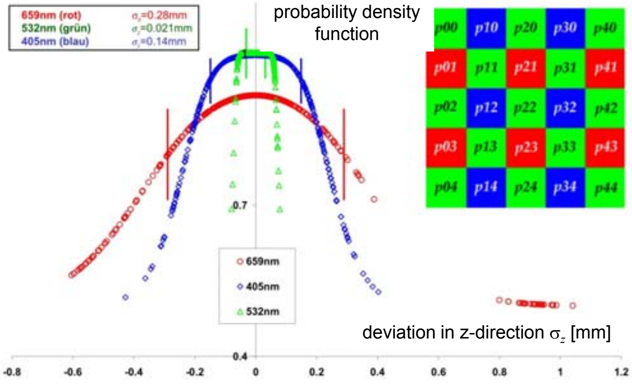
Double Layer Projection (DLP)-pixel assignment

reason for wrong object assignment

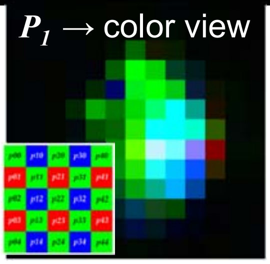
- **illumination time [ω=5Hz] = temporal resolution**

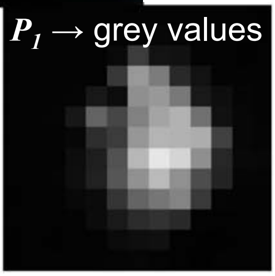


- **impact of wave length λ**

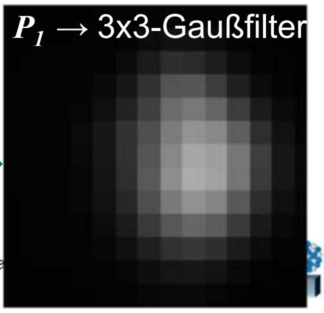


- **What if we go with advanced image processing ?**



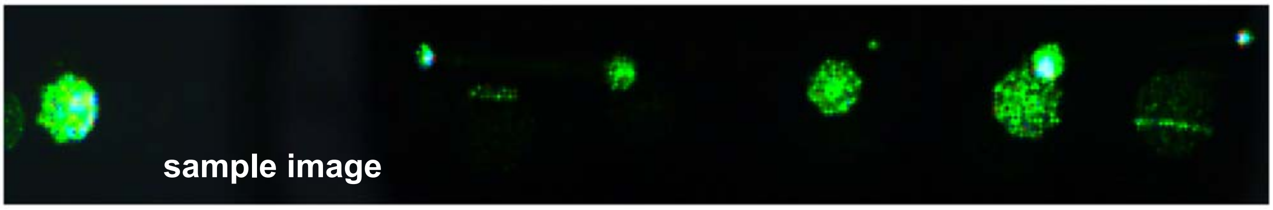


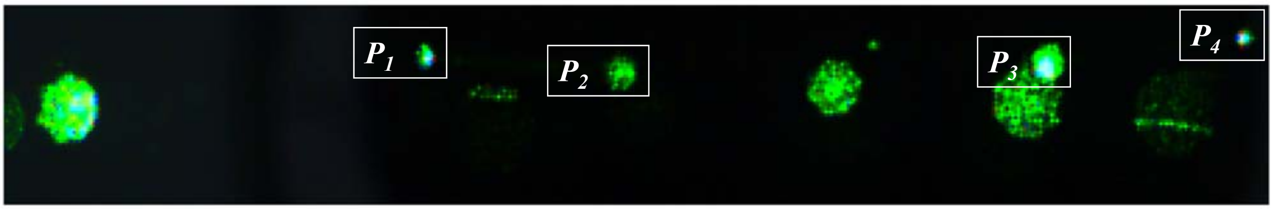
“wrong" colour interpolation can be reduced, but not eliminated

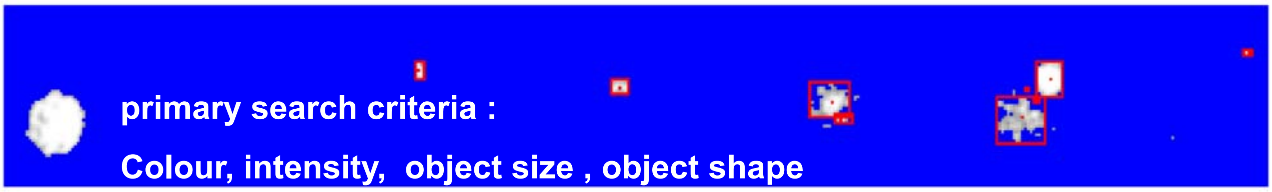


Double Layer Projection (DLP)- image processing

- how to find P1 to P4 in an image ?







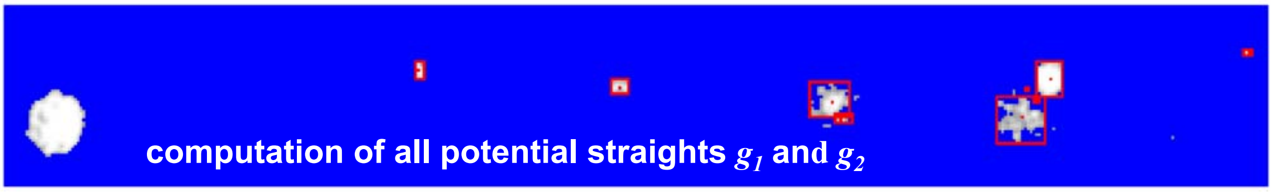
primary search criteria :

Colour, intensity, object size , object shape

➡ more than 4 objects are detected in the image.

Double Layer Projection (DLP)- image processing

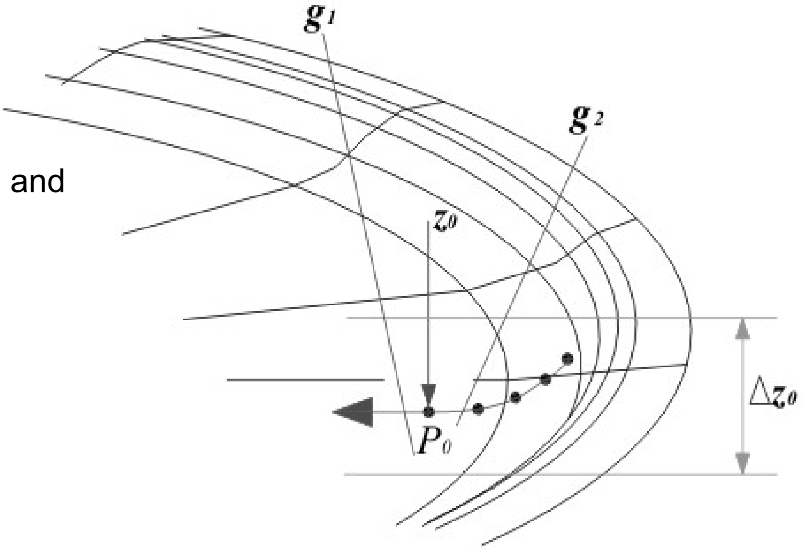
- **implementation of secondary selection criteria**



computation of all potential straights g_1 and g_2

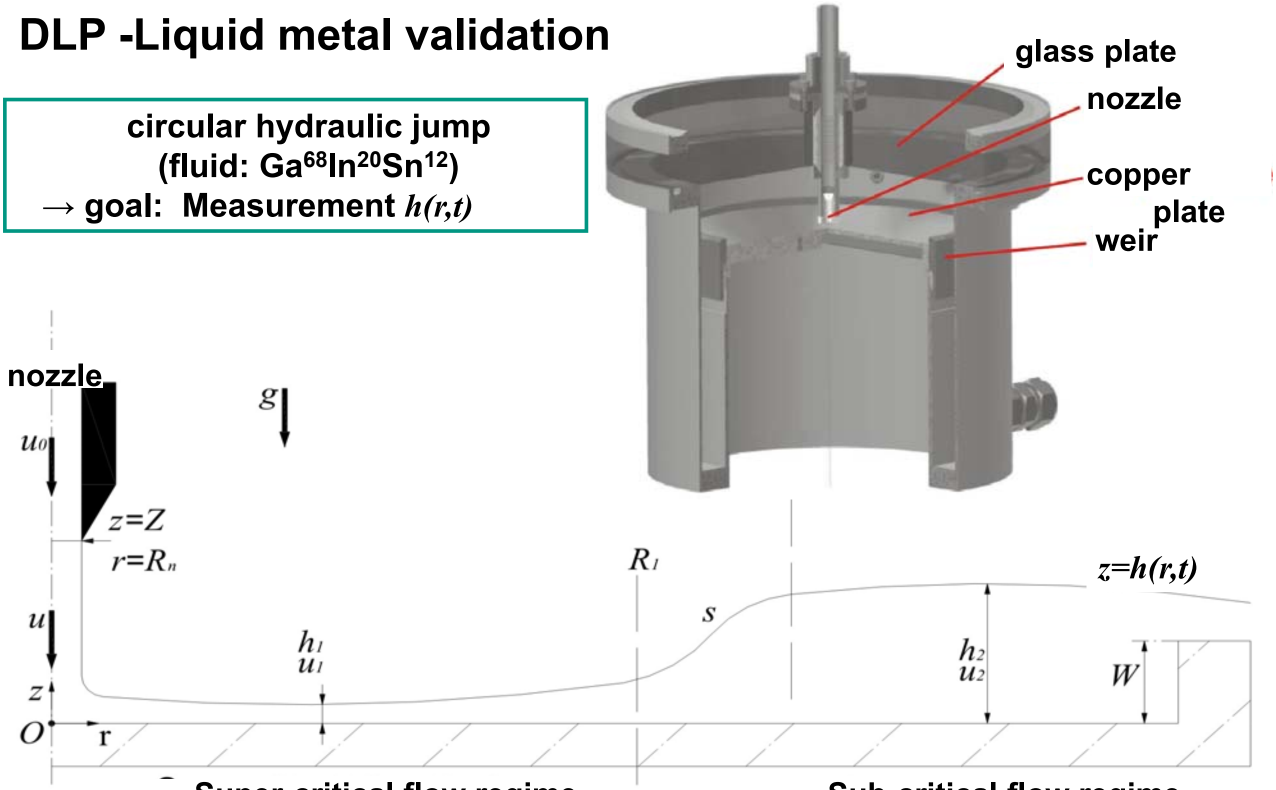
secondary criteria

- straight distance (g_1 by P_1, P_2) and reflected beam (g_2 by P_3, P_4)
- distance to screen z_0
- monotoneous surface shape



DLP -Liquid metal validation

circular hydraulic jump
(fluid: $Ga^{68}In^{20}Sn^{12}$)
→ goal: Measurement $h(r,t)$



Super-critical flow regime

$Fr>1$

Sub-critical flow regime

$Fr<1$

Hillenbrand et al.,Detection of liquid-metal, free-surface flow using the DLP measurement technique, Exp. Fluids, 2012, 52(1),179ff

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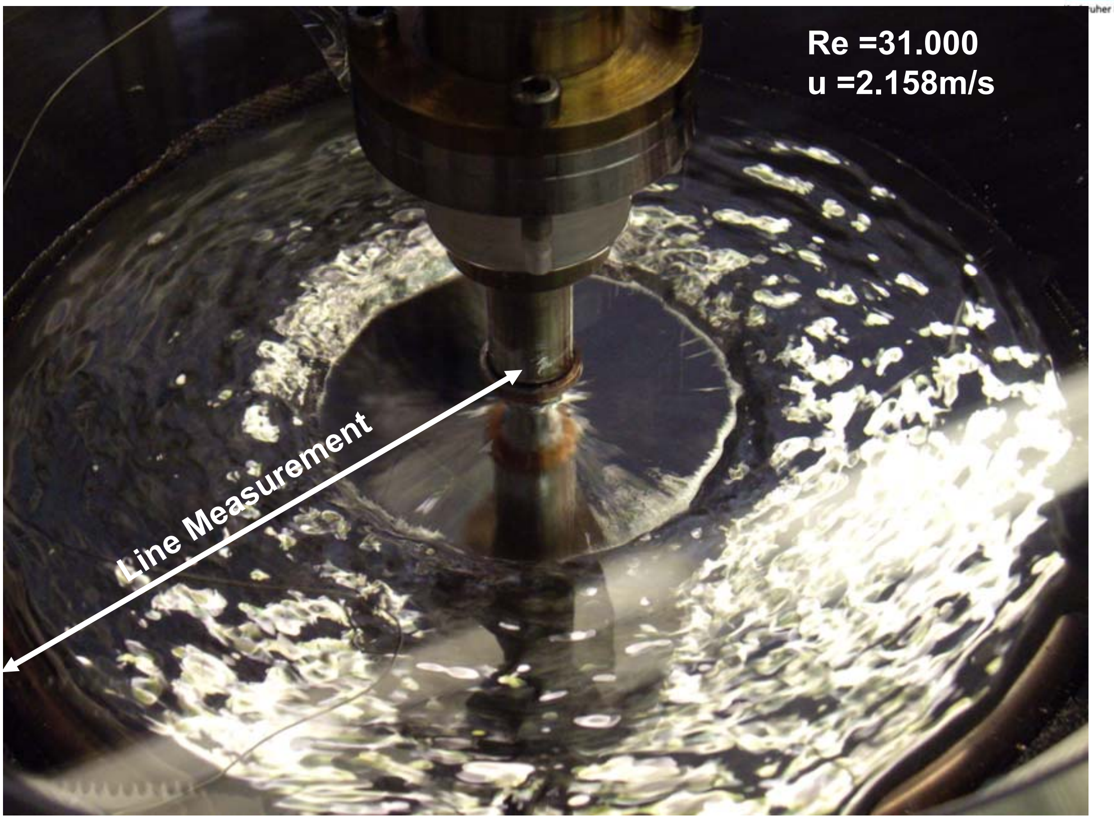
DLP -Liquid metal validation



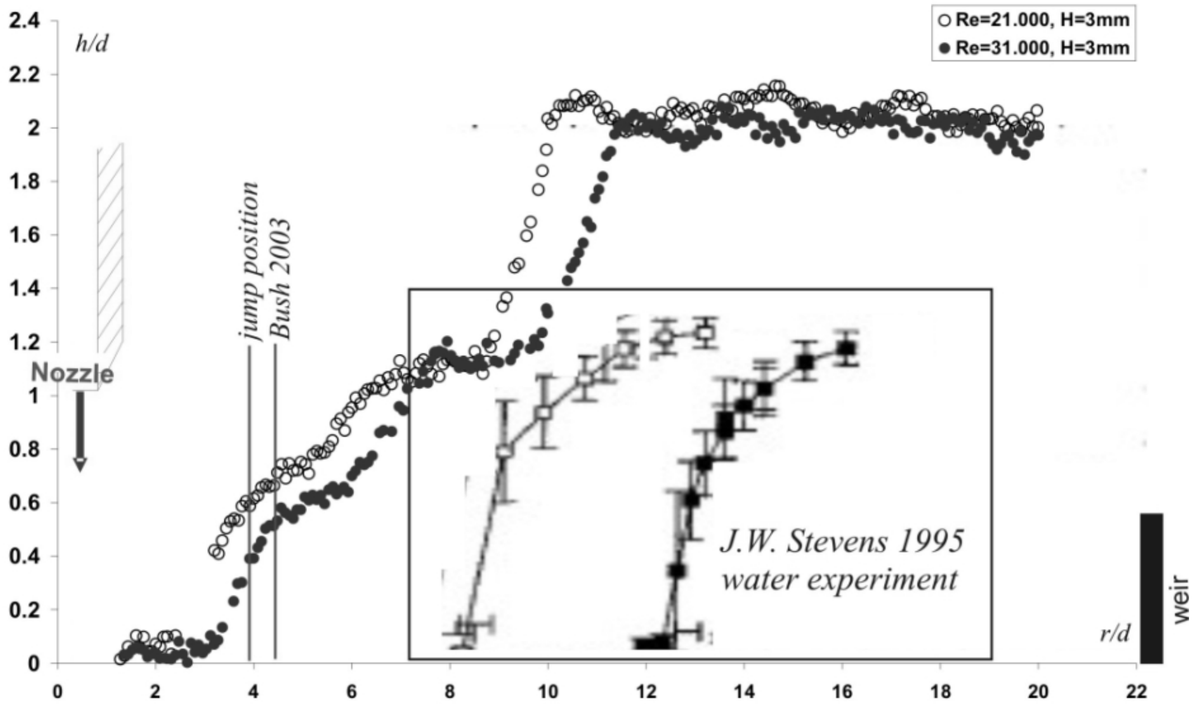
Re =31.000
u =2.158m/s

DLP -Liquid metal validation

- Double step jump
- Surface waves

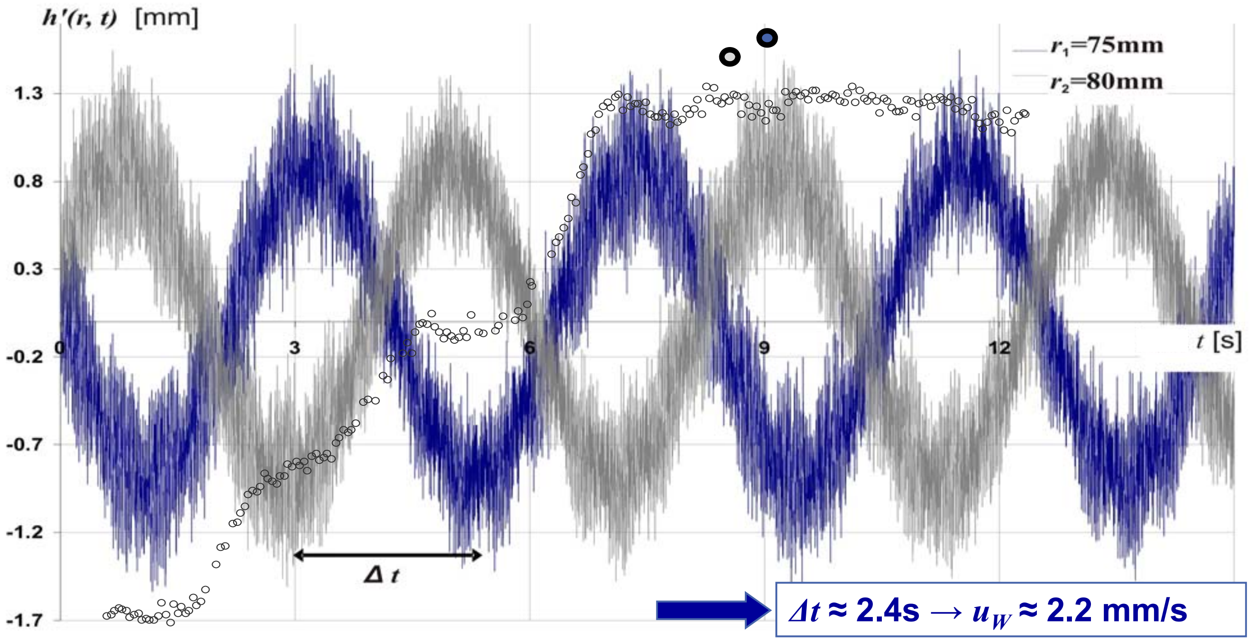
DLP -Liquid metal validation

- shape-resolution→line measurement



DLP -Liquid metal validation

- **spectral behavior**



$\Delta t \approx$ **2.4s** $\rightarrow u_W \approx$ **2.2 mm/s**

SUMMARY

LEVEL METERING

- **traditional** analogue **techniques** are robust,reliable and self-calibrating means (unfortunately intrusive)
- non-intrusive techniques require liquid metal specific **adaptions** (especially for optic devices) of industrially available products➨ **qualification**

SURFACE ACQUISITION (DLP - lessons learnt)

- **no general technique recommendable** (choice dependent on application boundary conditions- e.g. distance from target)
- way to establish a qualified technique **requires exploitation** of vast **parameter range ➨ qualification**
- although quality of technical equipment, AD conversion computational processing capabilities increased
  - verification and validation is indispensable
  - requires lots of preparations and
  - exhibits many (unexpected) surprises
- adaption of a technique and qualification for liquid metal surfaces is quite challenging even if proof of principle has been shown