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Introduction aux techniques non intrusives pour la caractérisation des écoulements à bulles

Prof. Maria Rosaria Vetrano

Introduction

- Very broad topic
- Different sizes, different shapes, embedded in transparent/opaque fluids.
- A large variety of applications and conditions (temperature, pressure,…)
- Techniques often developed cases-by-case

Article | Open access | Published: 22 May 2018

Characterization of different bubble formulations for blood-brain barrier opening using a focused ultrasound system with acoustic feedback control

Chenchen Bing, Yu Hong, Christopher Hernandez, Megan Rich, Bingbing Cheng, Imalka Munaweera, Debra Szczepanski, Yin Xi, Mark Bolding, Agata Exner & Rajiv Chopra

Scientific Reports **8**, Article number: 7986 (2018) | Cite this article

Home > Journal of Hydrodynamics > Article

Measurement and characterization of bulk nanobubbles by nanoparticle tracking analysis method

Articles | Published: 14 December 2022

Volume 34, pages 1121–1133, (2022) Cite this article

Home > Experiments in Fluids > Article

In situ measurements of void fractions and bubble size distributions in bubble curtains

Research Article | Open access | Published: 24 January 2023

Volume 64, article number 31, (2023) Cite this article

Characterization of a chemical reaction in a bubble column using wire-mesh sensor and ultrafast X-ray CT

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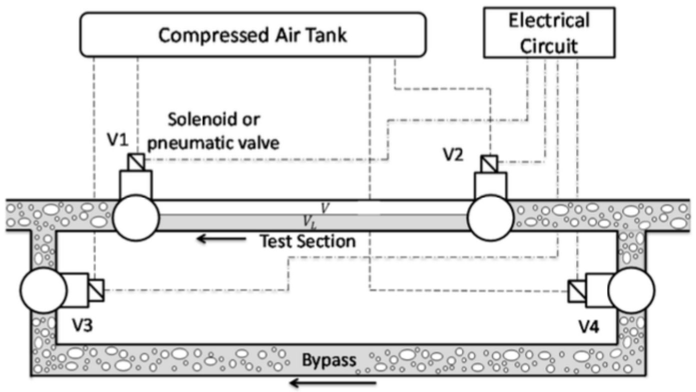
Void fraction

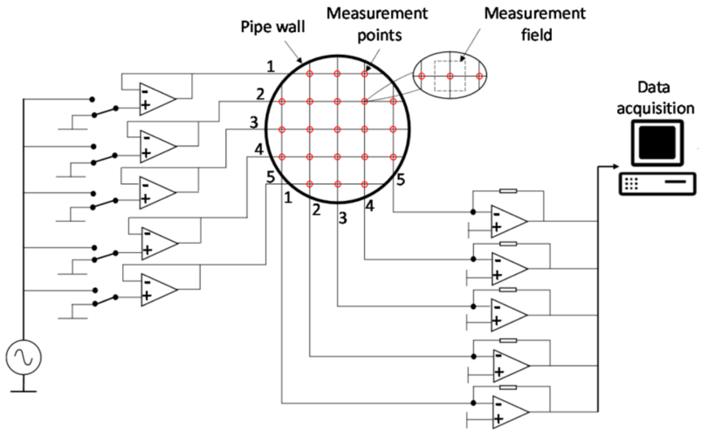
Sampling

Quick-Closing Valves

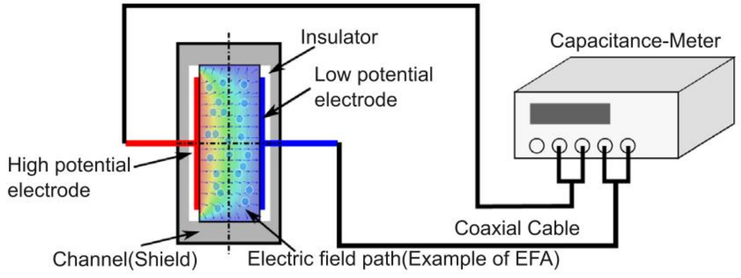


Intrusive

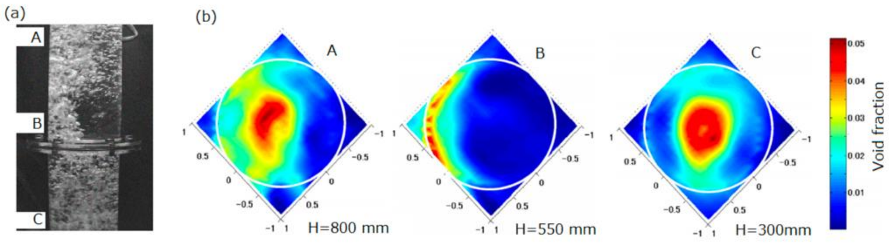
Wire-Mesh



Capacity sensors



Ultrasonic sensors



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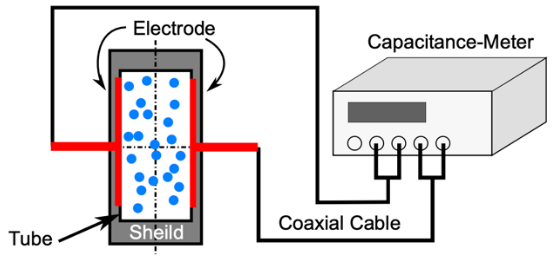
Capacitive sensor

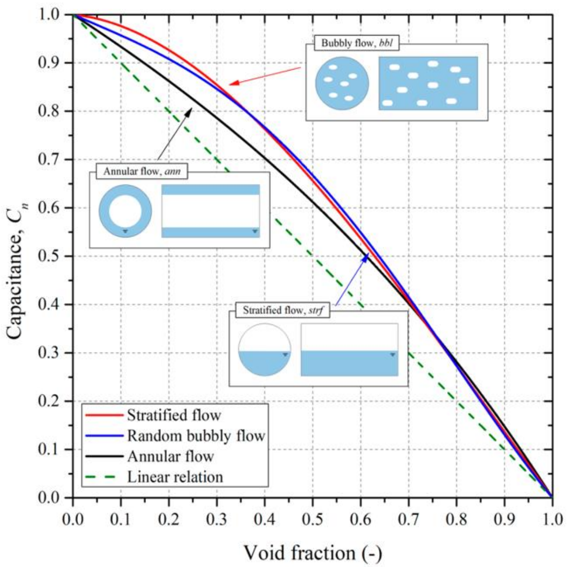


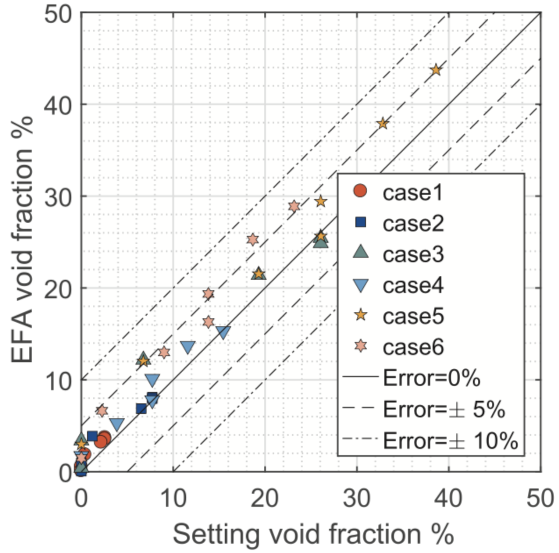
Principle

- The void fraction is calculated by the measured capacitance, which changes due to the gas/liquid volume ratio.
- The liquid dielectric constant is larger than the gas one, so the capacitance increases with liquid volume.
- Finite element method-based simulations (Electric Filed Analysis) to calibrate.
- The design of the sensor should be optimized for the liquid and its temperature

$$\alpha = \frac{C_L - C_M}{C_L - C_G} \times 100[\%]$$

C_L is capacitance at the liquid phase,
C_G is capacitance at the gaseous phase
C_M is measured capacitance





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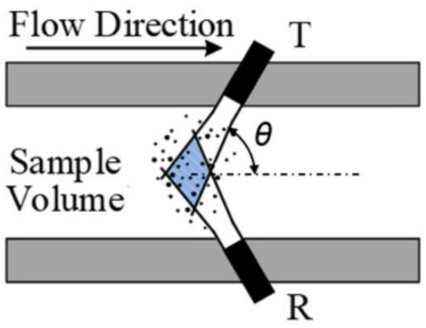
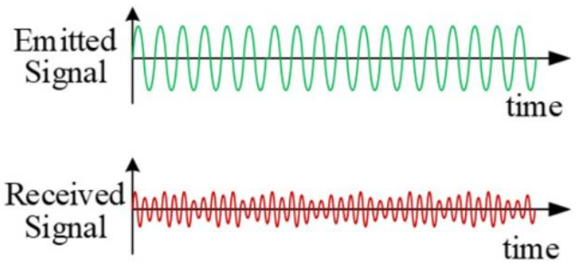
Ultrasonic sensor

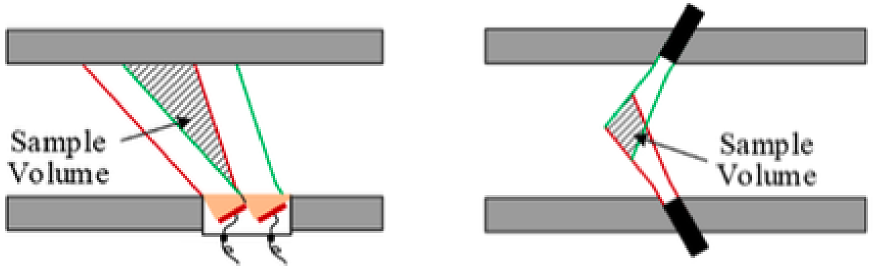
Continuous-wave ultrasonic Doppler (CWUD)



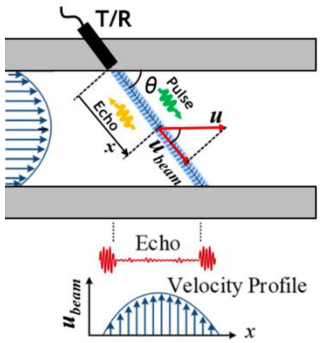


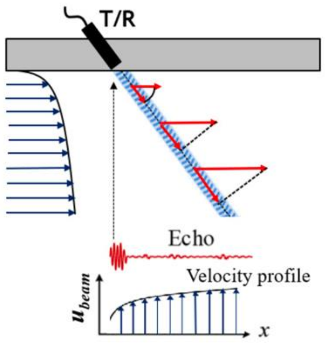
Principle velocity measurement

- Transducer T emits ultrasonic waves of frequency f_0 to the fluid
- Transducer R receives the waves with a frequency modulated according to the Doppler effect $f_d = \frac{2u \cos\theta}{c} f_0$
- When multiple bubbles are present in the sample volume, an average Doppler frequency $\langle f_d \rangle$ and an average velocity is calculated $\langle u_{Dop} \rangle$



Pulsed-wave ultrasonic Doppler (PWUD)





Principle velocity measurement

- One transducer emits and receives pulsed ultrasound waves.
- The measurement position x from which the pulse is reflected $x = \frac{c\,\Delta t}{2}$, varying Δt one varies the measurement volume position
- The phase shift obtained from the echo give de bubble velocity

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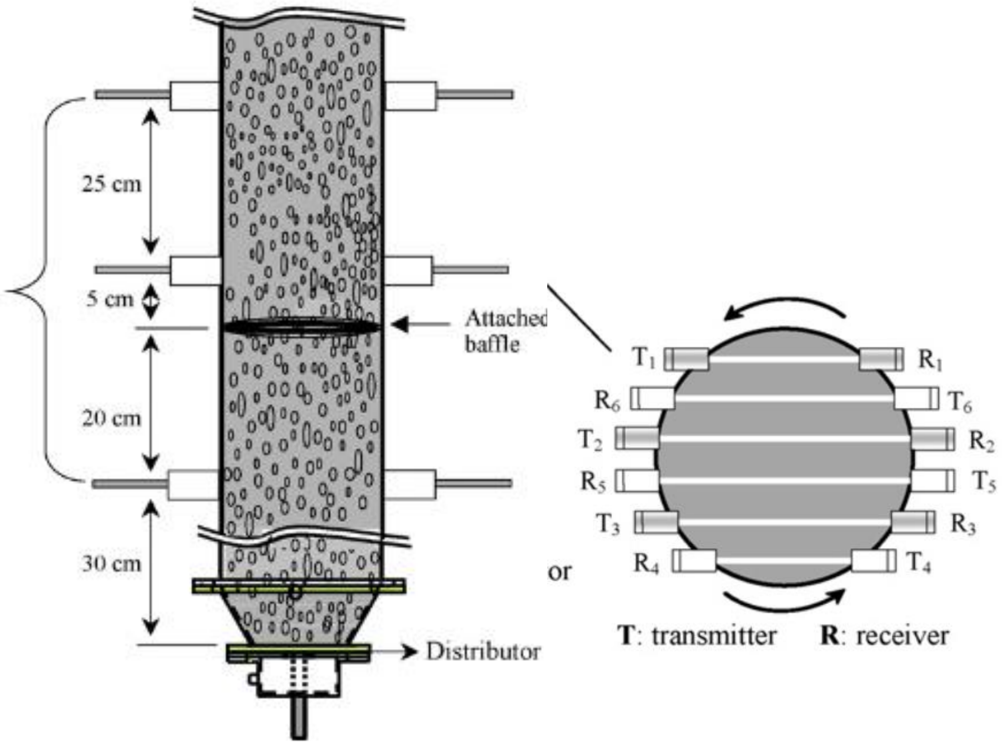
Ultrasonic computed tomography

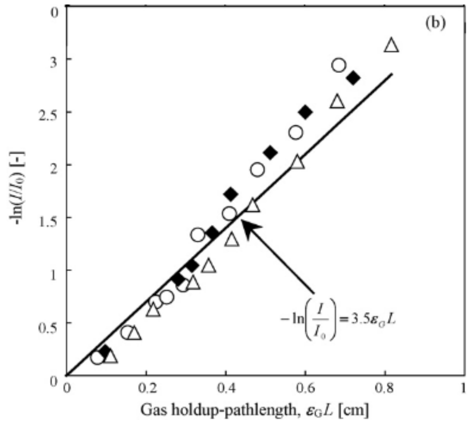
Example of void fraction field reconstruction

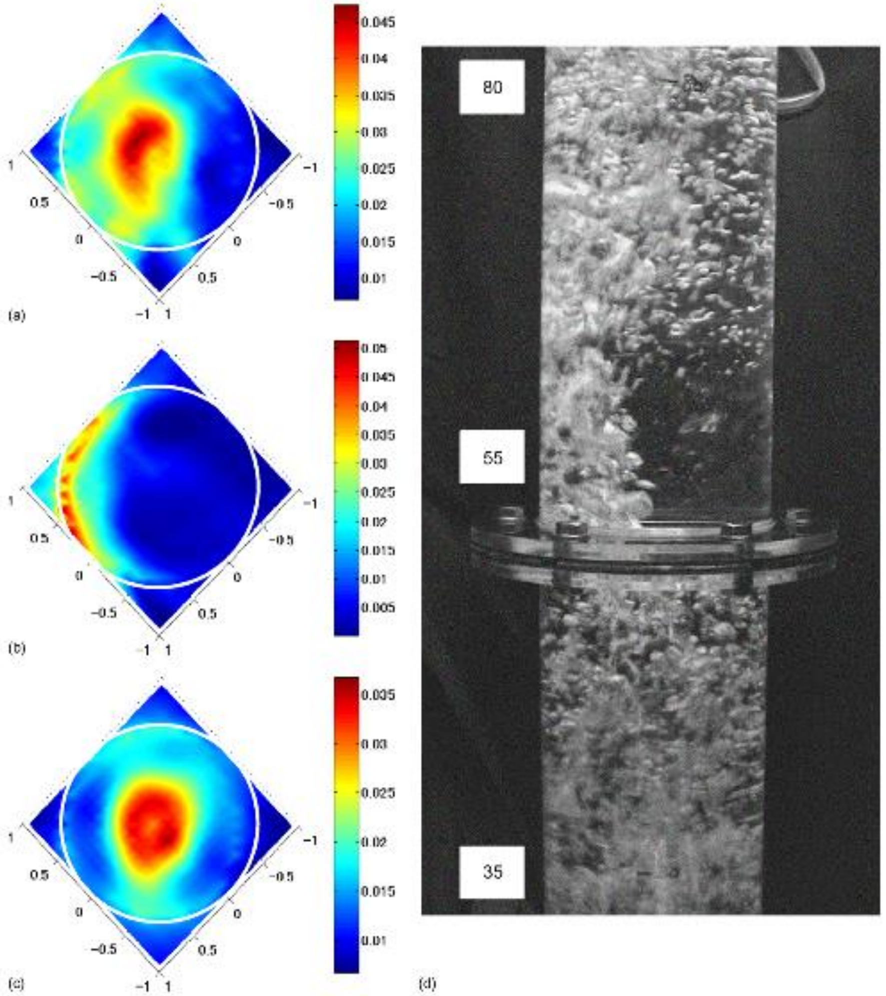
Principle void fraction (holdup) measurement

- Based on the attenuation of the sound waves
- Needs preliminary calibration
- Use Filtered Back Projection (FBP) to reconstruct 3D field



Preliminary calibration





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Bubble size/velocity

- Allows for accurate size, shape measurement, and velocity.
- They require transparent media and can have limited resolution for very small bubbles.
- They can fail if the void fraction is increased.

- **Phase Detection Probes**
- **Backlighting/Shadowgraphy**
- **Laser Diffraction Systems**
- **Laser/Phase Doppler Anemometry**
- **Glare points (GPVS)/ Glare Circles**
- **ILIDS**
- **CARS**

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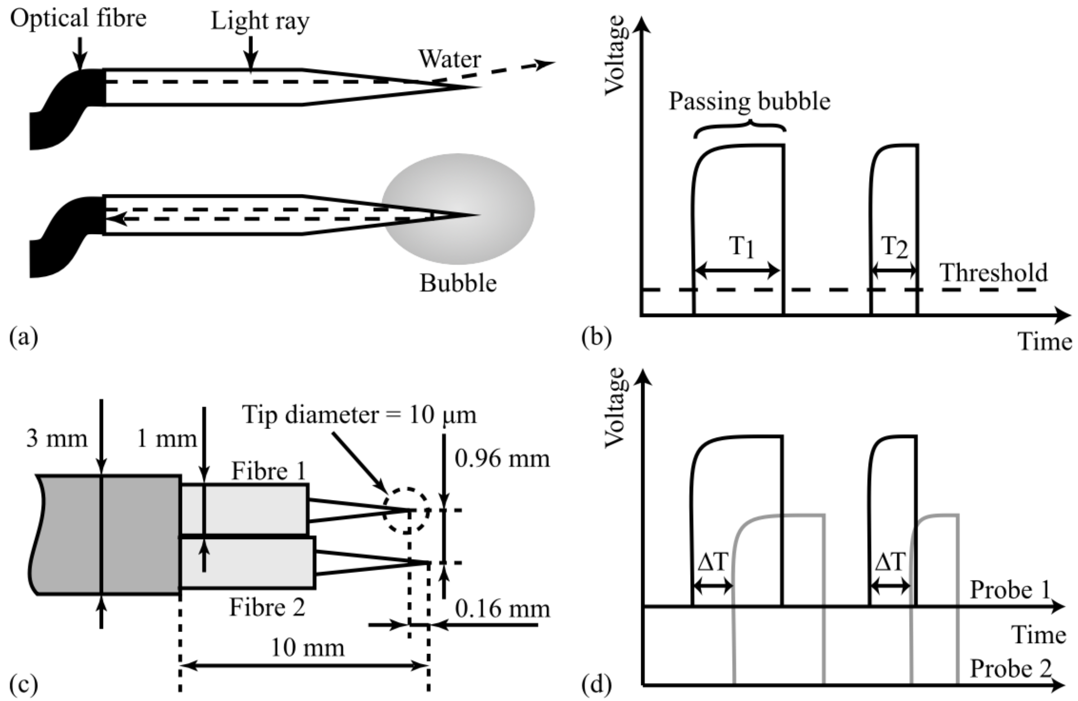
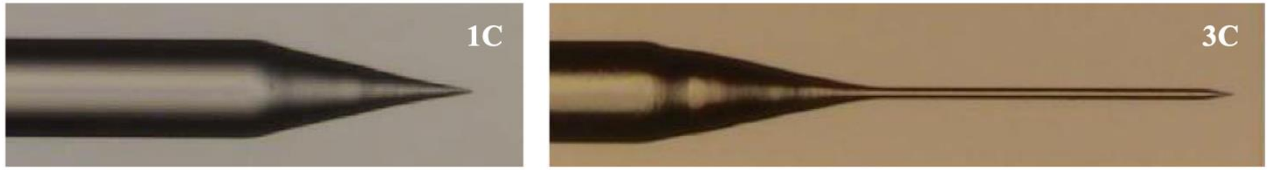
Phase Detection Probes



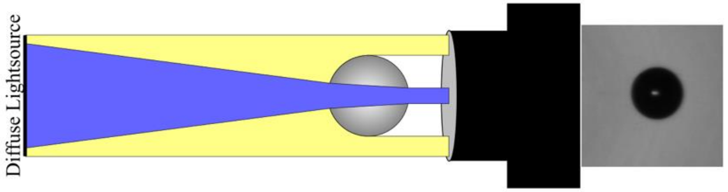
Principle

- When a bubble passes by, it causes the tip to pierce the surface, leading to total reflection of the light ray at the fiber-air interface due to the significant difference in refractive index.
- Using two tip configuration the velocity and size of the bubble can be determined.



Recent development of Optical-Fiber Doppler Probe (OFDP)

Backlighting



Principle

- Bubble illuminated by a diffused light source
- Images recorded by a camera (resolution is important)
- Processing of these backlighting images via a computer algorithm to detect circles/ellipses (fitting procedure).

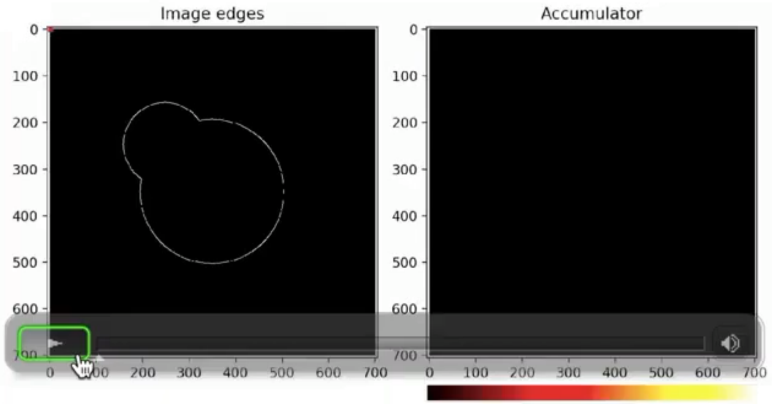
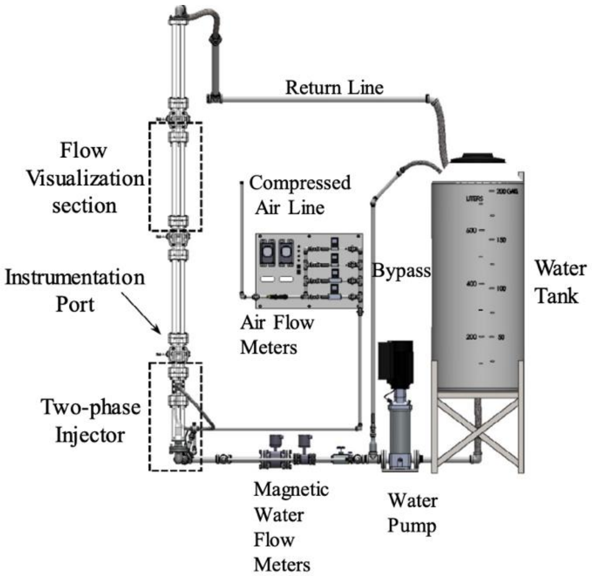
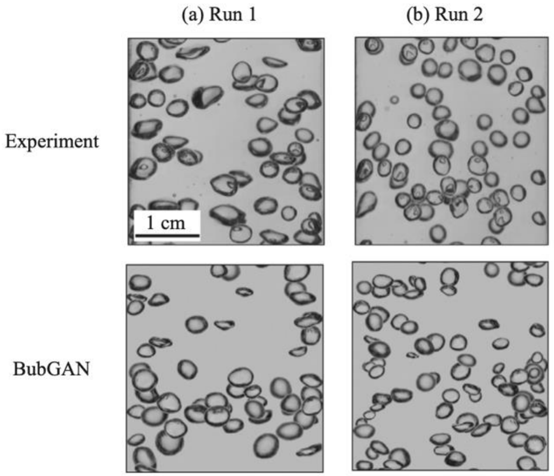
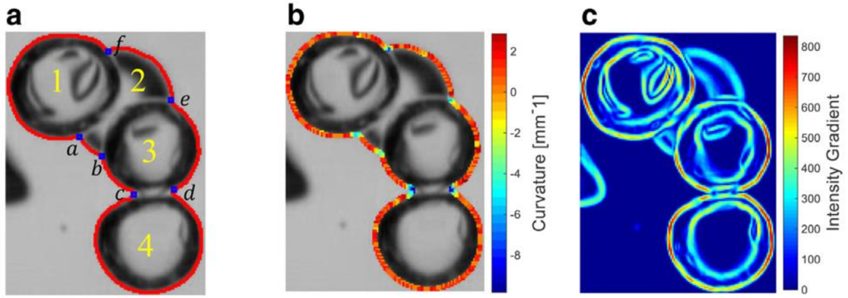


Image processing challenges

- Circle/Ellipse/Gen. Hough Transform –> high storage and computational cost
- High bubble number concentration –> bubble overlap
- Breakpoint method for bubble clusters
- Topology analysis (Watershed transform, bubble skeleton, and adaptive threshold)
- Deep learning approaches (BubGAN)
  - Bubbly flow image synthesis







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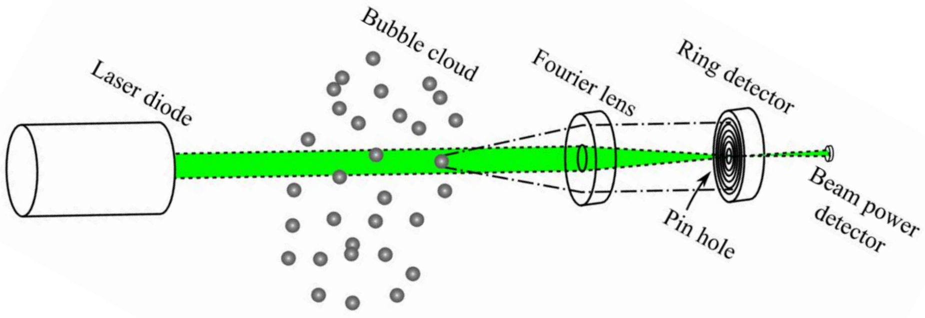
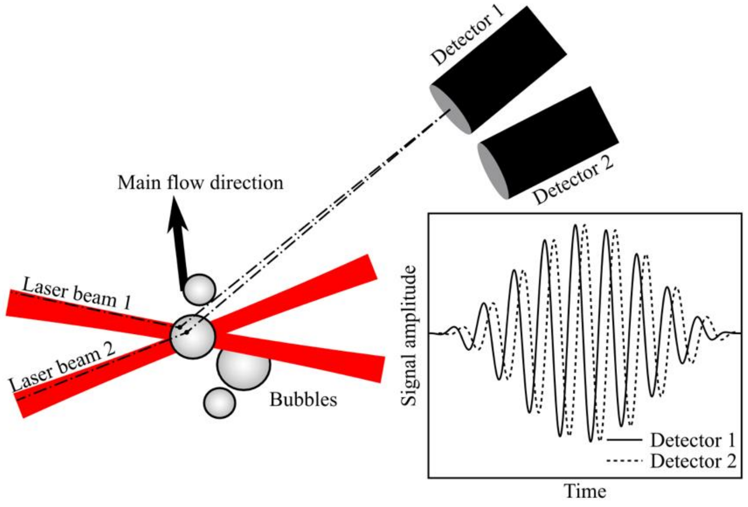
Laser Diffraction systems



Principle

- Bubbles illuminated by a collimated laser.
- A Fraunhofer diffraction pattern is created, resulting in the original laser beam surrounded by concentric rings in the far-field light intensity.
- Since the radius of the rings is linked to particle diameter, a diameter distribution (averaged along the beam's line of sight) can be determined from the intensity at various radial distances.
- It is a line-of-sight technique.
- It can measure very small bubbles but the fringe intensity can be low.

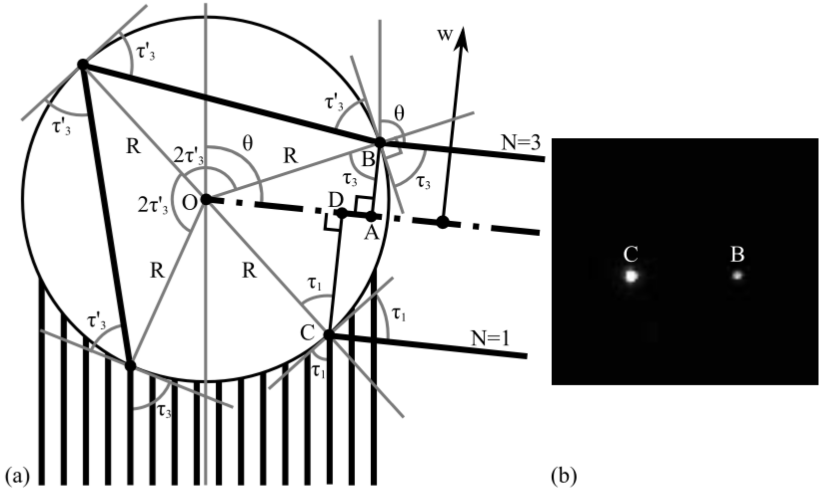
Laser/Phase Doppler Anemometry



Principle

- In a PDA, a laser Doppler anemometer (LDA) creates a probe volume where two laser beams intersect, forming interference fringes.
- When particles pass through this area, they scatter light.
- Detectors placed at different angles capture the scattered light.
    - **Particle Size Measurement** from the phase shift. By measuring this shift, the PDA can determine the particle's diameter.
    - **Velocity Measurement** from the Doppler shift.

Interaction of a laser with a spherical bubble



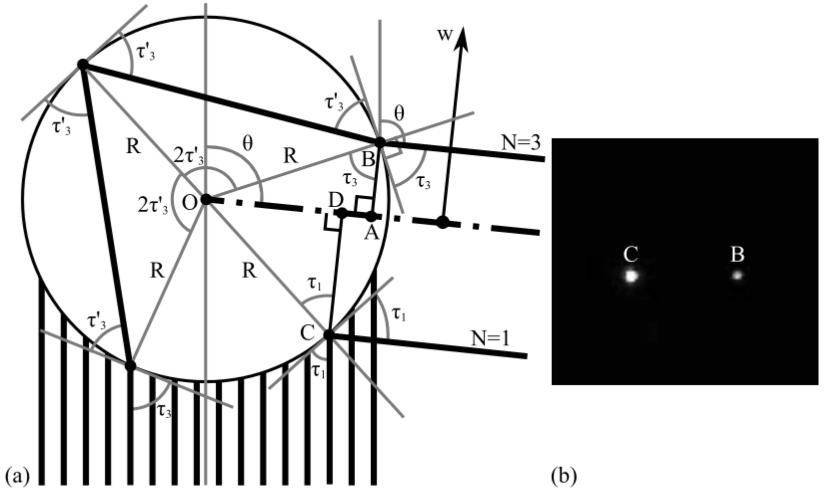
Principle

- A laser beam thinner than bubble diameter
- When light rays hit the bubble’s surface –> reflected or refracted.
    - **Ray 1**: Reflected directly by the bubble (N=1 interaction).
    - **Ray 2**: Undergoes three interactions within the bubble (N=3).
- Both rays exit the bubble at an angle (θ), known as the **observation or scattering angle**
- Since all incoming rays are parallel, they exit at various angles.
- If a camera is positioned far from the bubble at the angle θ relative to the laser, only certain rays (those shown) will reach the camera.
- This creates **high-intensity glare points** at points B and C, where these rays meet the camera view.

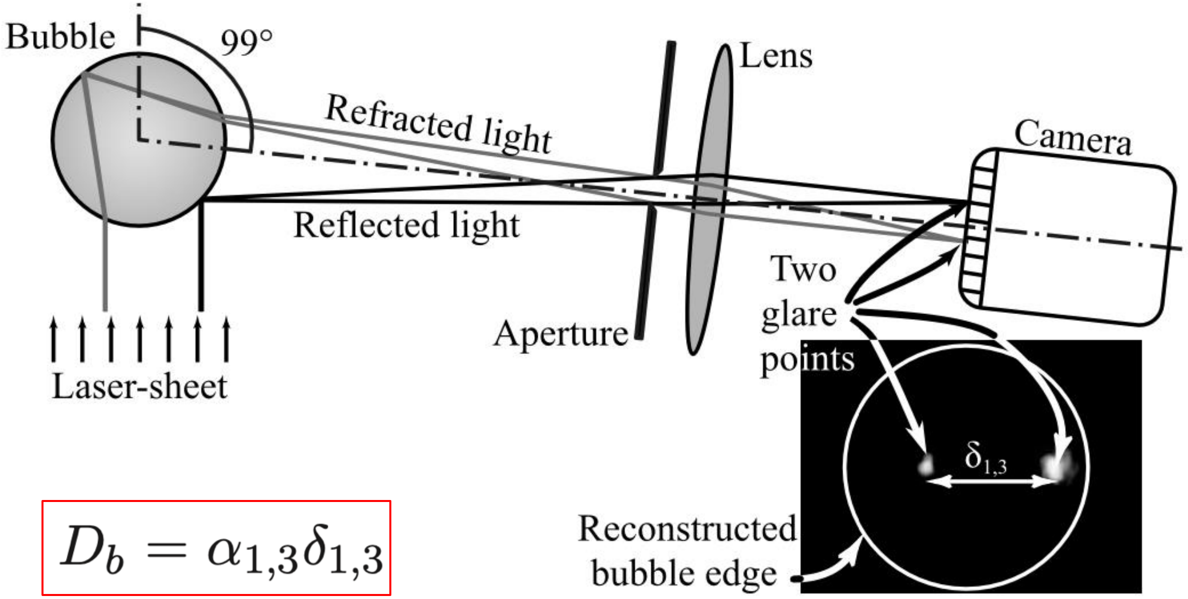
The distance between these two high-intensity glare points is proportional to the bubble diameter

$$\boxed{D_b = \alpha\delta}$$

Glare point location. Bubble diameter & velocity



$$\begin{aligned} \theta &= 2\tau_N - 2(N-1)\tau'_N \\ n_{air}\cos(\tau'_N) &= n_{liq}\cos(\tau_N) \\ |AB| &= R\cos(\tau_3) \\ |CD| &= R\cos(\tau_1) \end{aligned}$$



$$\boxed{D_b = \alpha_{1,3}\delta_{1,3}}$$

$$\alpha_{1,3,water} = \frac{2}{\cos\left(\frac{\theta}{2}\right) + \cos\tau_3}$$

Bubble velocity –> tracking of the Glare Points displacement

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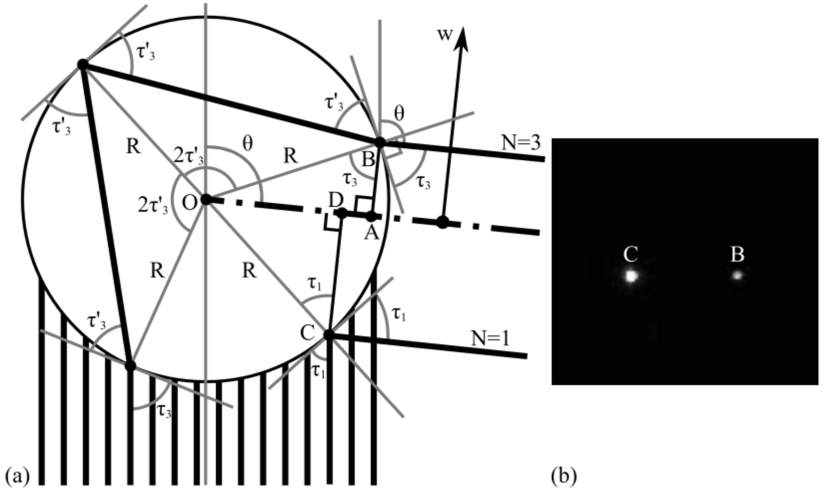
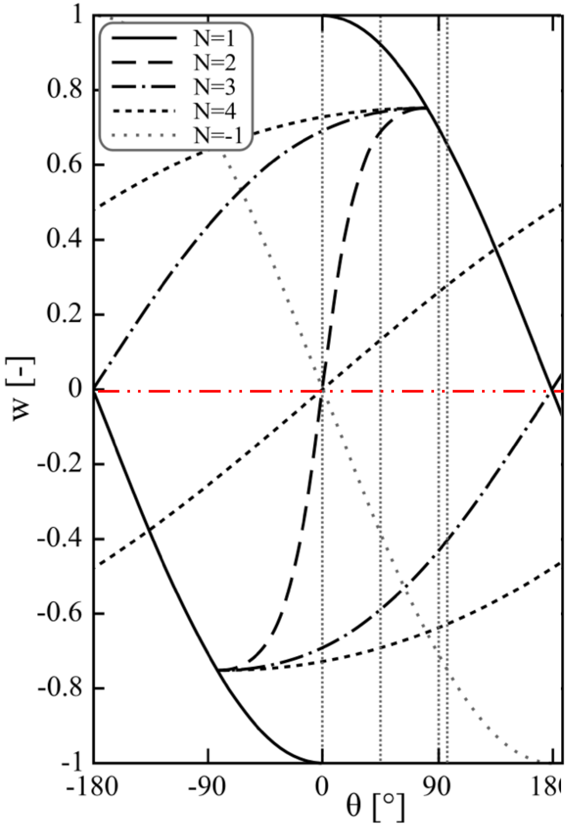
Observation angle for air bubble in water

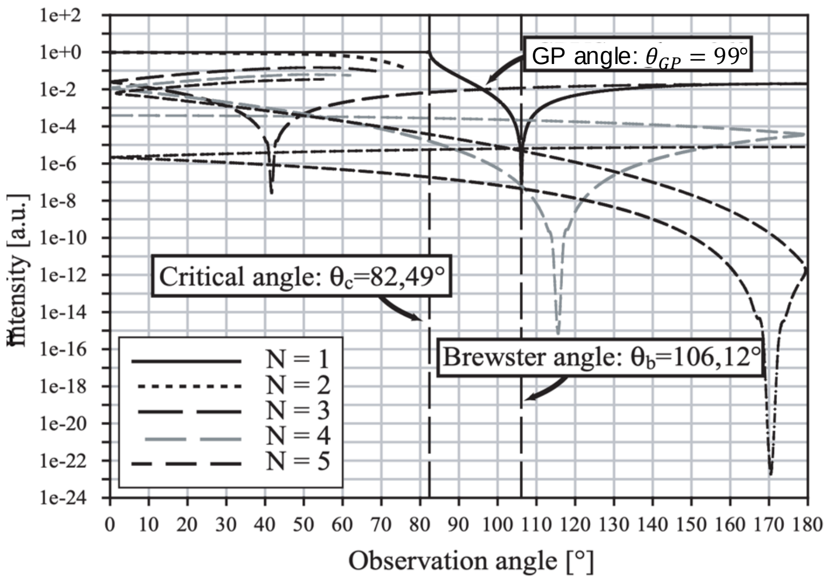


w= distance of the glare point from the middle centerline

$n_{H_2O} = 1.33, n_{air} = 1$



Glare points intensity for parallel polarised laser light



Glare points coming from N=1 or N=3 have similar intensity at $\theta \cong 99°$

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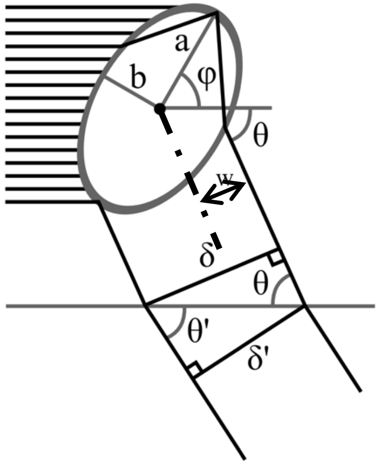
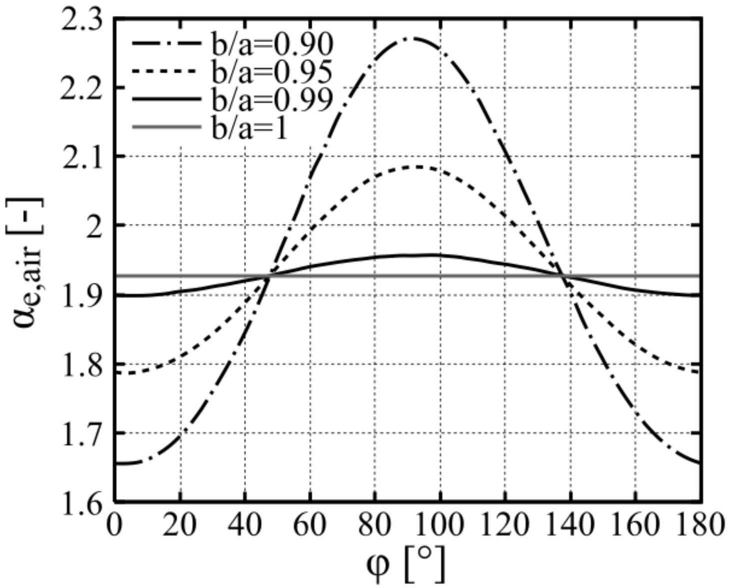
Effect of sphericity, container walls and depth of field



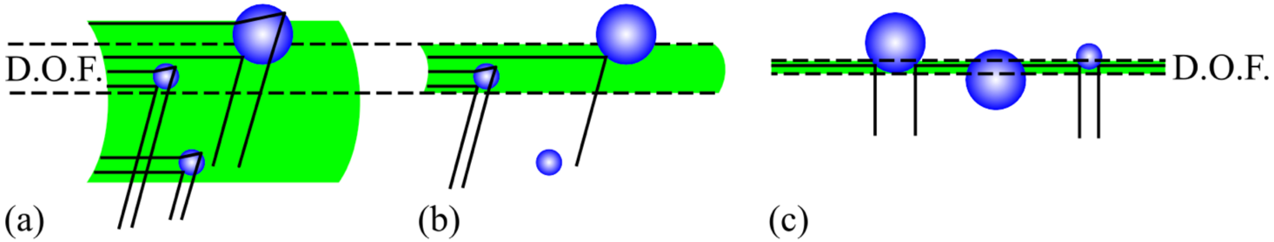
- Non sphericity plays an important role
- Sphericity cannot be measured, but the presence of non-spherical bubbles can be detected



$$\delta' = \frac{\sin\theta'}{\sin\theta}\delta$$

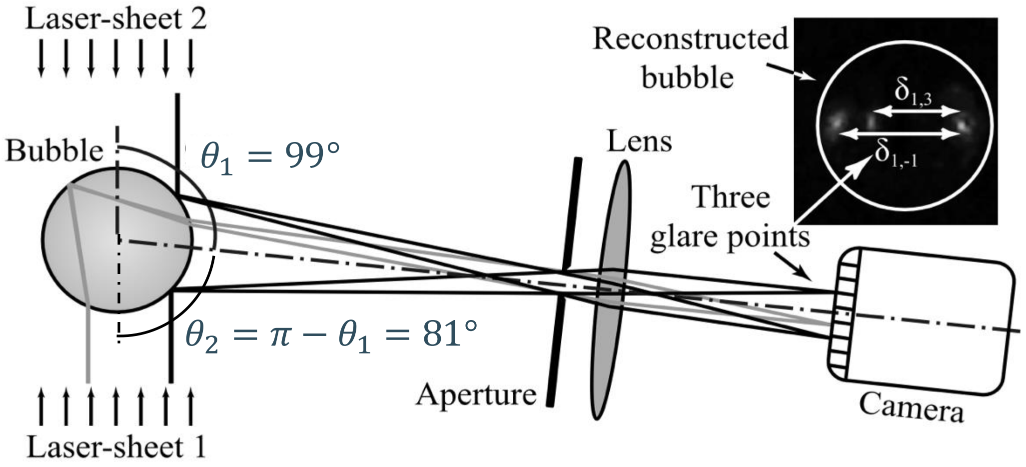
$$\alpha_{1,3} = \frac{2}{\cos\left(\frac{\theta}{2}\right) + \cos\tau_3}\frac{\sin\theta}{\sin\theta'}$$

$$\boxed{D_b = \alpha_{1,3}\delta_{1,3}}$$



- This is a 2D approach! The light ray is not allowed to leave the incident plane.
- Hence, the non-sphericity can only be studied when two principal axes lie within this plane.

Extended Glare Point Velocimetry and Sizing



Principle

- Illumination of the bubble on two opposite sides
- With respect to this second illumination, the scattering angle is $\theta_2 = \pi - \theta_1 = 81°$

- Only a third Glare Point appears (N=-1)
- The fourth Glare Point (N=-3) intensity is too weak

$\delta_{1,-1}$does not depend anymore on the refractive index of the liquid

$$\alpha_{1,-1} = \frac{2}{\left|\sin\left(\frac{\theta}{2}\right)\right| + \left|\cos\left(\frac{\theta}{2}\right)\right|} \frac{\sin\theta}{\sin\theta'}$$

Spericity condition $D_{1,3} = D_{1,-1}$

$$\frac{\delta_{1,3}}{\delta_{1,-1}} = \frac{\alpha_{1,-1}}{\alpha_{1,3}}$$

[SD2]

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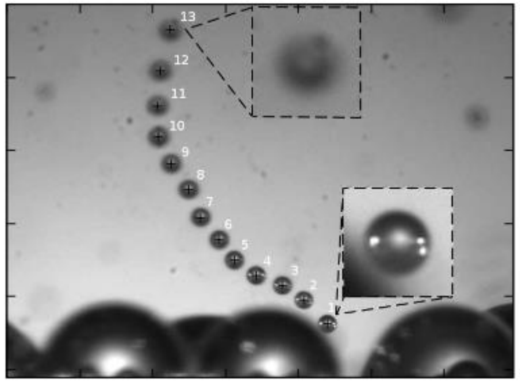
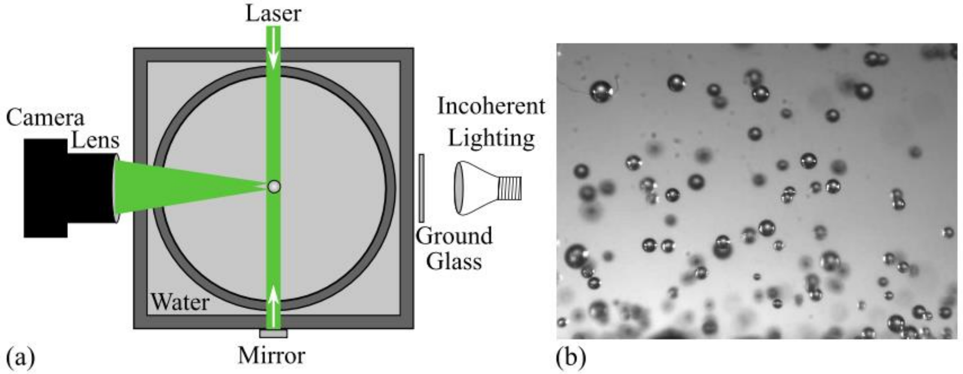
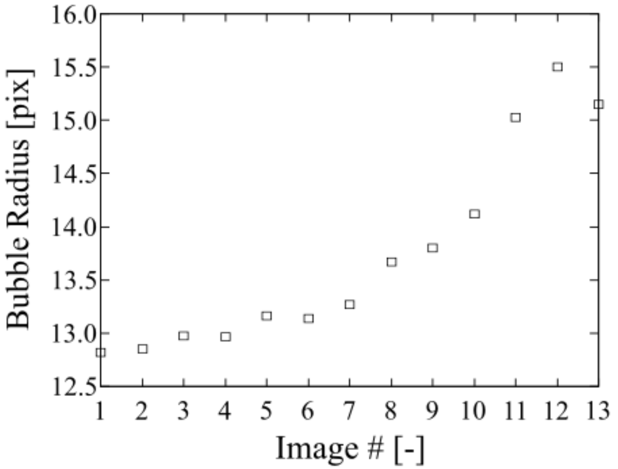
GPVS combined with Backlighting

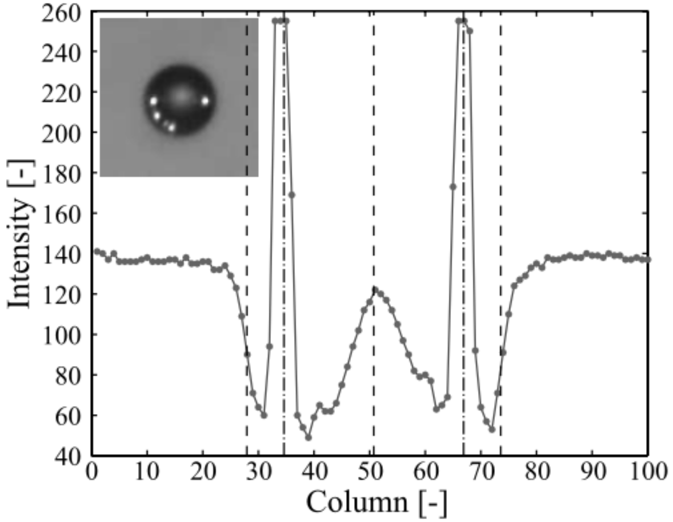


Principle

- Illuminate bubbles with laser and diffused light
- Only the bubbles with glare points should be sized as they are well-focused
- Bubbles without glare points can be located closer to or further away from the lens, inevitably leading to sizing errors.







Procedure

- Circle detection (Circle Hough transform).
- Verify the presence of the two Glare Points

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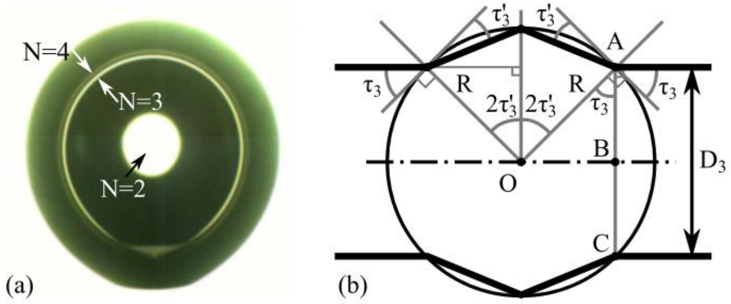
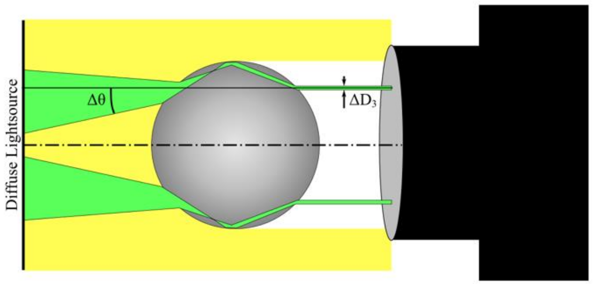
Glare Circles





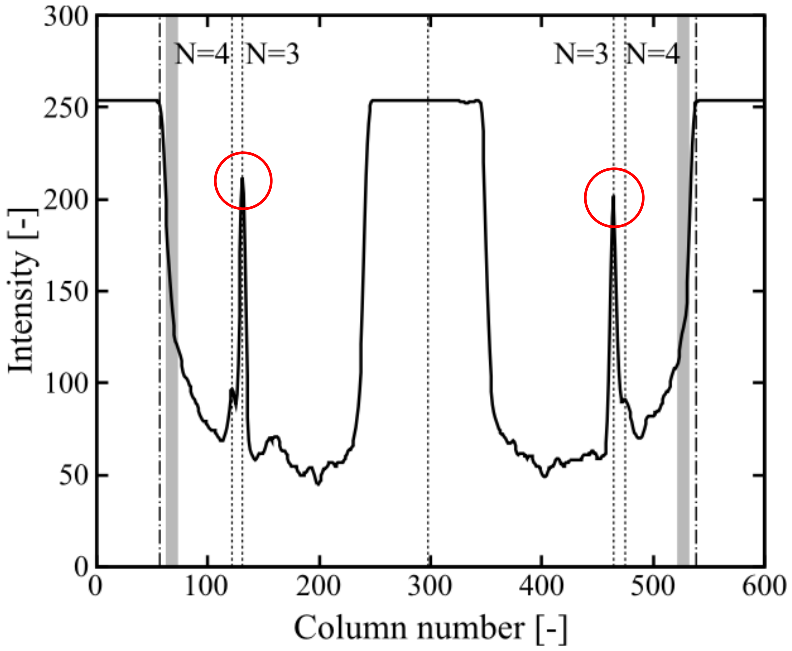
Principle

- Line-in-sight observation of bubbles illuminate by diffused lightt
- Glare points become circles
- Glare circle diameter proportional to bubble diameter
- The glare circle diameter can be estimated with better precision than using Backlight
- Ratio between Glare and Backlight diameter proportional to refractive index

$$D_3 = \frac{1+\sqrt{1+8n_{liq}^2}}{4n_{liq}^2} D_b$$

Intensity along the diameter of a bubble illuminated by laser and diffused light

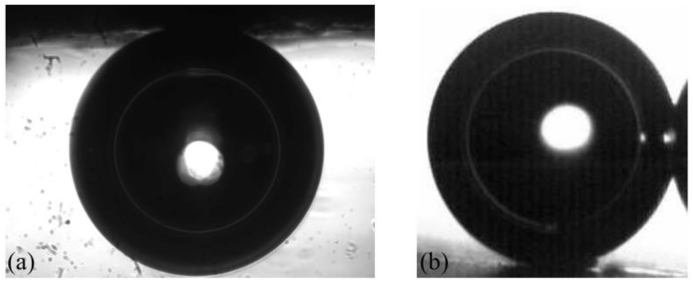
- Backlight gradient ≈ 30 pix
- Glare circle peaks ≈ 8 pix



$$\eta = D_3 \big/ D_b \quad \Rightarrow \quad n_{liq} = \sqrt{\frac{1+\eta}{2\eta^2}}$$

Air/ Silicone oil

Air/ Water



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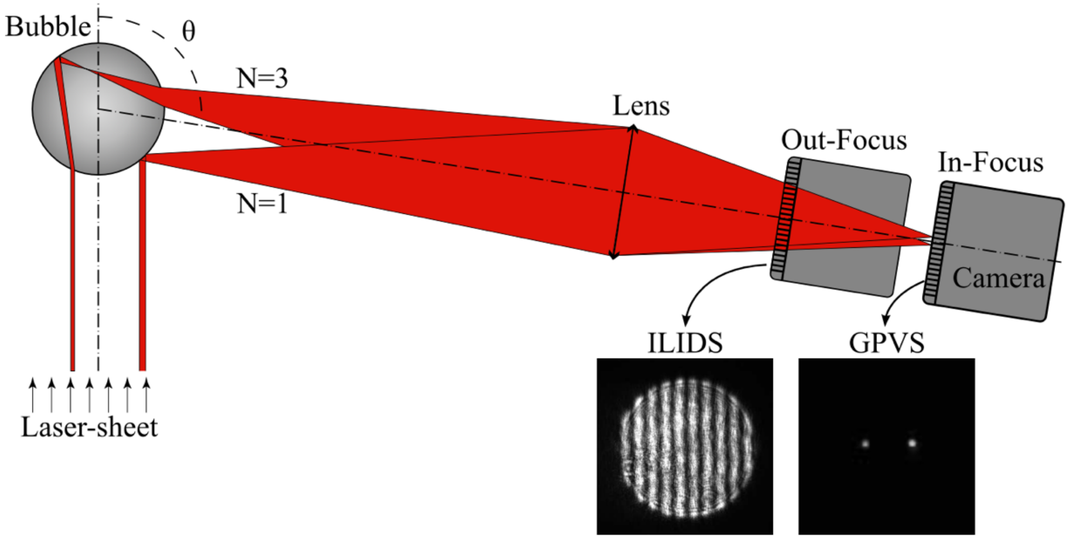
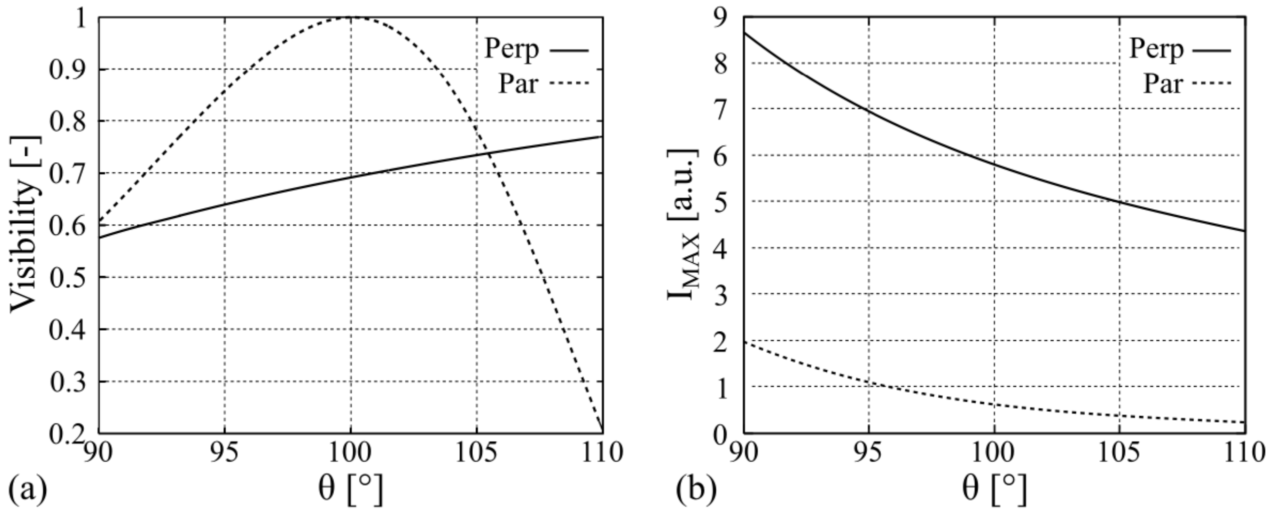


Principle

- Keep geometrical parameters of Glare Points
- Move the optical system out of focus
- Glare points act as coherent point sources → interference
- The diameter of the bubble proportional to the fringe frequency



Choice of observation angle based on fringe visibility and Intensity and light polarization

$$Visibility = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{2\sqrt{I_1 I_3}}{I_1 + I_3}$$

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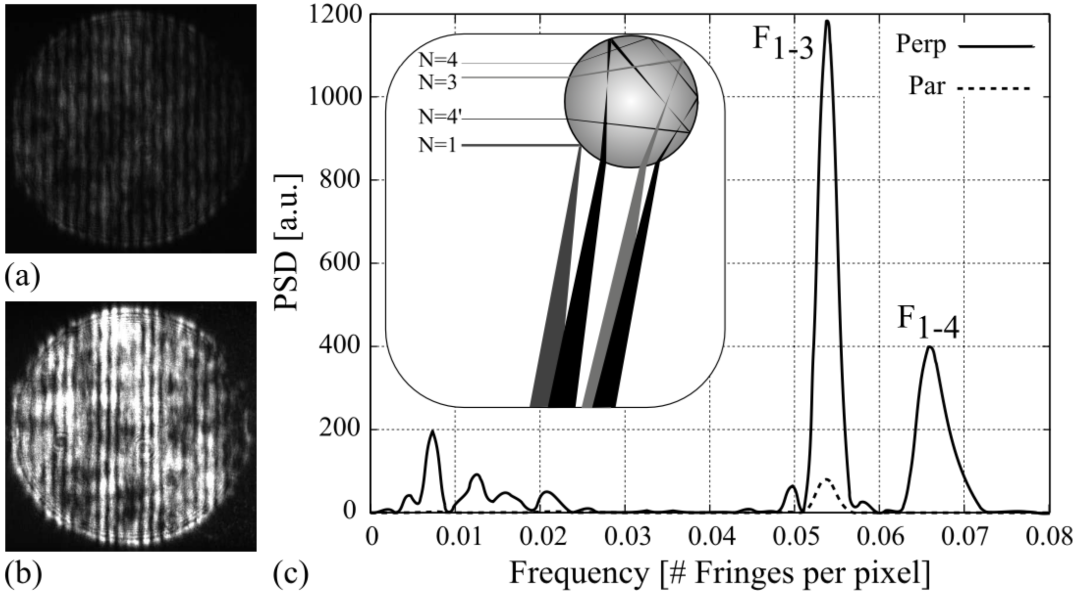
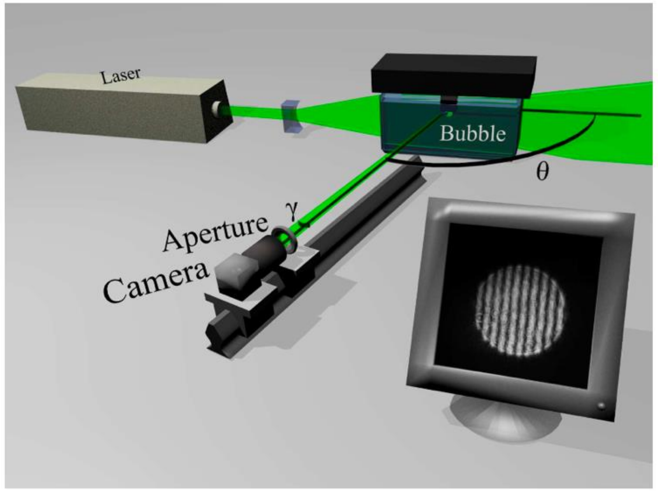
Fringe analysis and bubble diameter



$$D = \lambda\, \alpha_{1-3} F_{1-3}\, C_{pix/rad} = \lambda\, \alpha_{1-4} F_{1-4} C_{pix/rad}$$

If spherical bubble $F_{ratio} = \frac{F_{1-3}}{F_{1-4}} = \alpha_{ratio} = \frac{\alpha_{1-4}}{\alpha_{1-3}}$



How to calculate $C_{pix/rad}$?

Methods	Expression
Semi-Experimental Calibration	$C_{pix/rad} = \frac{\Phi_{pix}}{\gamma}$
Theoretical Calibration	$C_{pix/rad} = \frac{g x_o}{f S_{pix}} = \frac{g}{M S_{pix}}$
Camera Focused at Infinity	$C_{pix/rad} = \frac{f}{S_{pix}}$
Two-Step Calibration	$C_{pix/rad} = \frac{f h}{x_{o,if} S_{pix}} = \frac{M_{if} h}{S_{pix}}$

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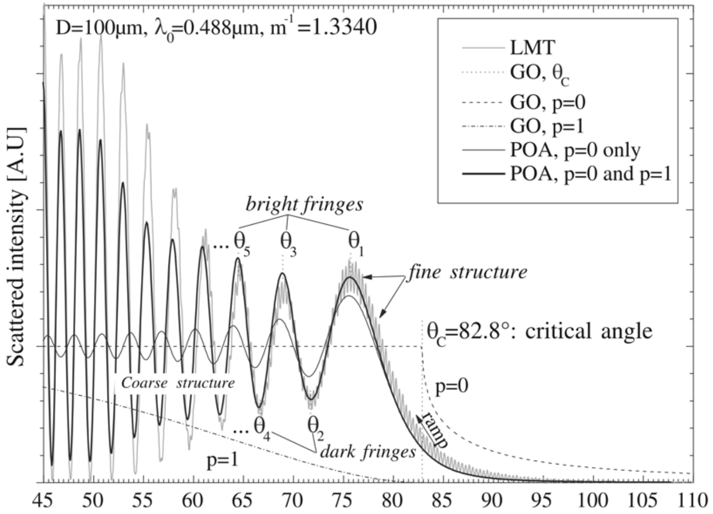
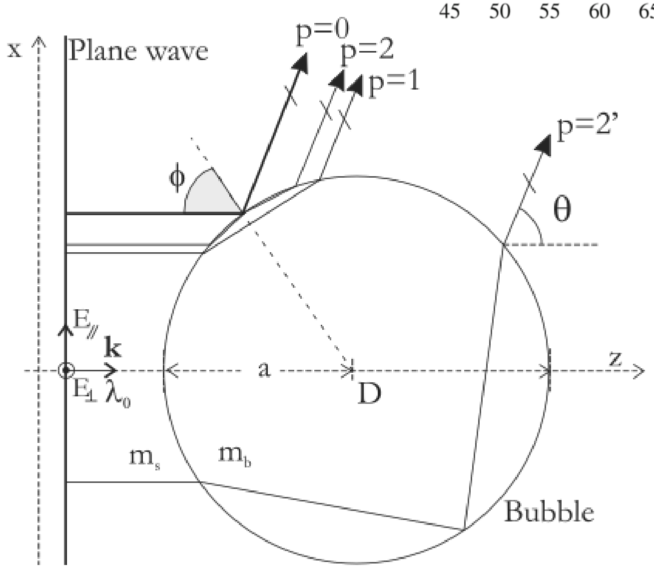
Critical Angle Refractometry and Sizing (CARS)



$p = N - 1$



Principle

- The light scattered by a bubble close to the critical angle possesses the diameter signature.
- Fringes are generated in the region close to the critical angle
- A data inversion algorithm is needed to retrieve from the Scattering pattern the bubbles size.

$I(\theta, D, m, \lambda_0)$ Intensity of the light scattered by a bubble using Lorentz-Mie theory (LMT)

$$I_t(\theta, m, \lambda_0) = N \int_{D_{\min}}^{D_{\max}} I(\theta, D, m, \lambda_0) f(D) \mathrm{d}D = \sum_{j=1}^{M} S_{i,j} F_j \Rightarrow \mathbf{I}_t = \mathbf{S} \cdot \mathbf{F}$$

$$\mathbf{F} = \left(\mathbf{S}^{\mathrm{T}}\mathbf{S}\right)^{-1}\mathbf{S}^{\mathrm{T}}\mathbf{I}_t$$

Solution of an ill-posed problem using regularization techniques (Lawson and Hanson)

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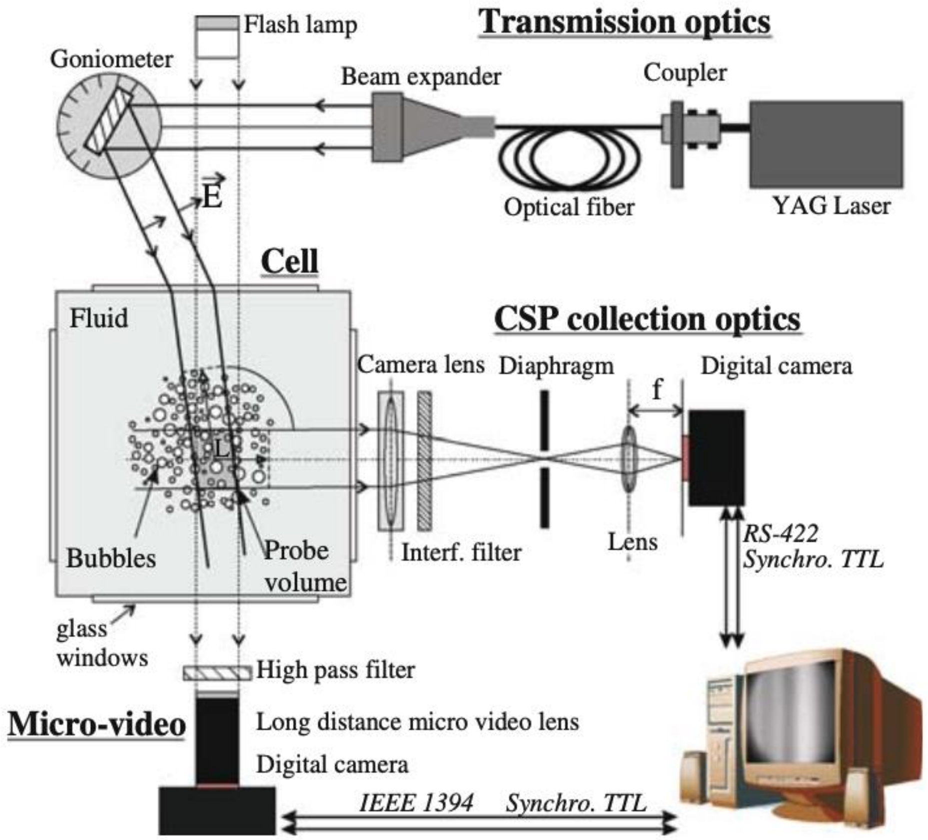
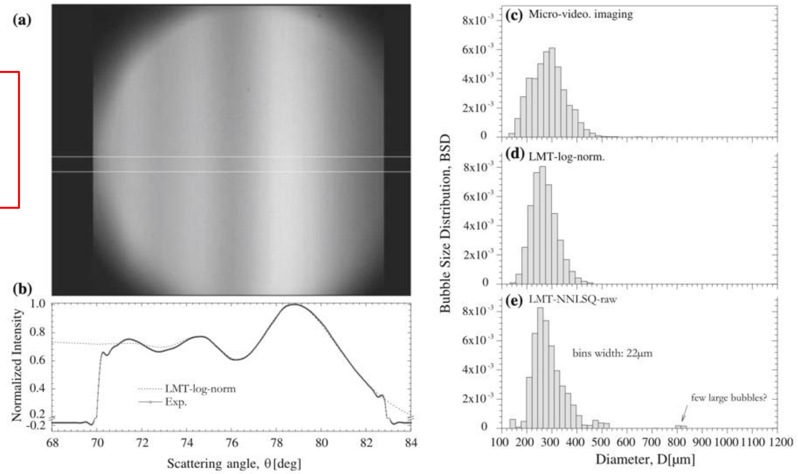
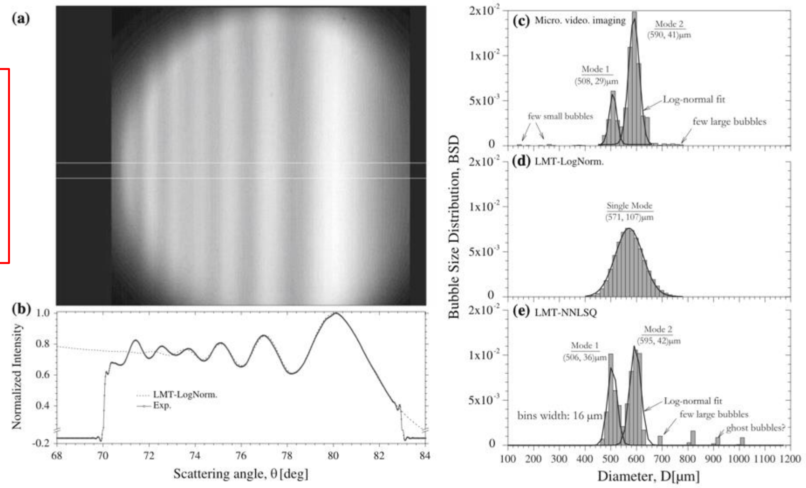


Single peak distribution



Double peak distribution



Conclusions

- Techniques adapted to void fraction measurements often need preliminary calibration but allow measurements in opaque fluids and may give 2D maps.
- Optical techniques
  - Available on the market (Laser diffraction, PDA, Backlighting).
  - To be developed in laboratory, expecially in terms of the data inversion algorithm.
  - Can deliver accurate measurement of bubble size and sometimes refractive index (Temperature!).
  - Often based on light scattering –>limited by multiple scattering and therefore bubble concentration.

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Thank you for your attention

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