“Optical Measurements”

Master Degree in Engineering

Automation-, Electronics-, Physics-, Telecommunication- Engineering

Optical Velocimeters

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Summary

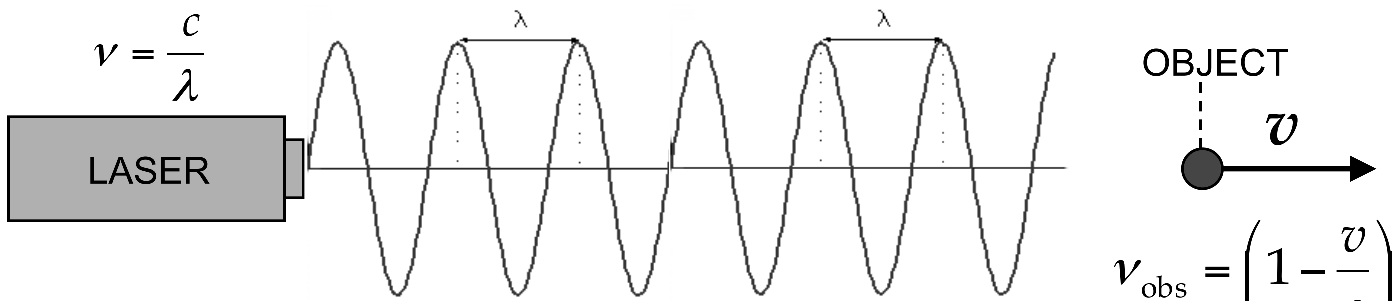
- **Measurement principles and application**
  Doppler effect (on laser beams)
  Heterodyne method for velocimetry (laser Doppler)

- **Velocity measurements in fluids**
  LDV (Laser Doppler Velocimetry)
  PIV (Particle Image Velocimetry)

- **Autovelox**
  - optical barrier
  - tele-laser (time of flight and Doppler)

Doppler effect (on laser beams)

$\nu = \dfrac{c}{\lambda}$



$$\nu_{obs} = \left(1 - \frac{v}{c}\right) \cdot \nu$$

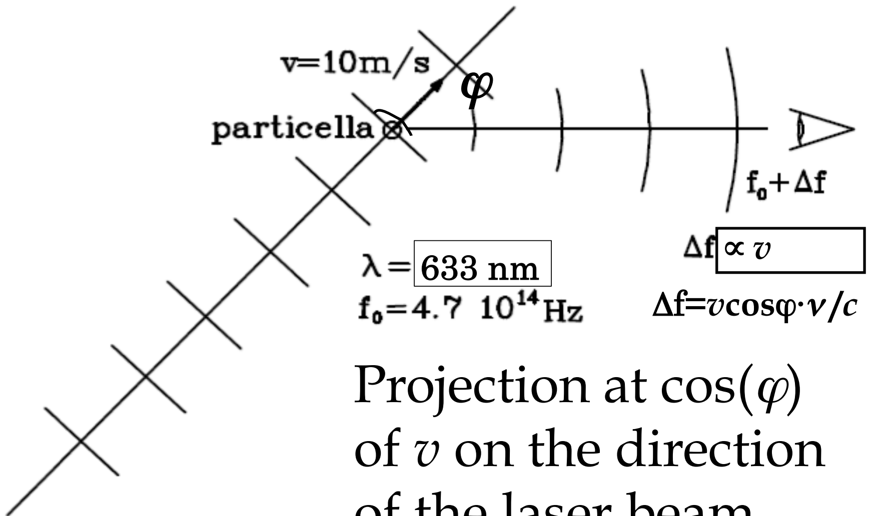
The observed optical frequency (ν_{obs}) is smaller than the one emitted by the laser (ν) when the object moves farer ($\nu_{obs} > \nu$ when object gets closer)

Considering a velocity $v << c$, the **Doppler shift**

$$\boldsymbol{\Delta\nu = (\nu - \nu_{obs}) = (v/c) \cdot \nu \ << \ \nu}$$

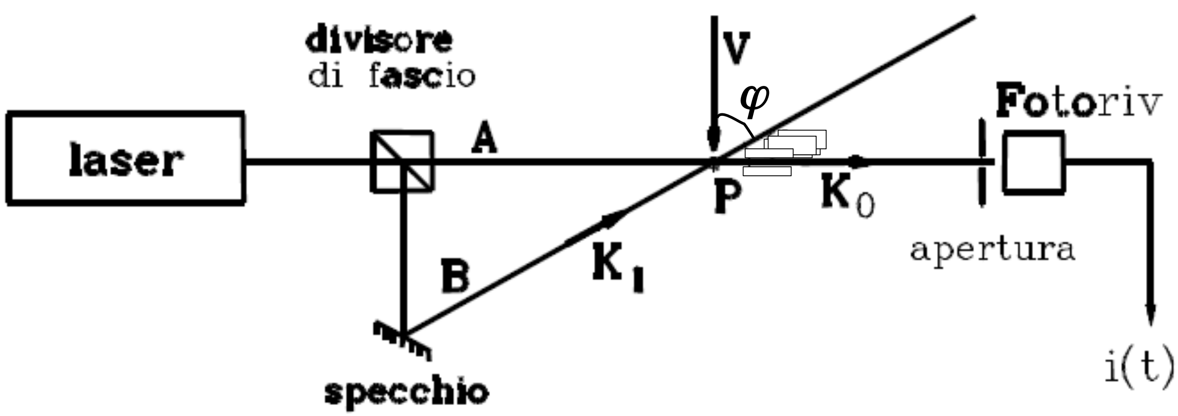
is much smaller then the optical frequency
[for λ=0.6 μm (ν =500 THz), v=1 m/s → $\Delta\nu \cong$1.7 MHz, $\Delta\nu / \nu \cong 3.3\times10^{-9} \approx$3 ppb!]

Heterodyne method for velocimetry



Projection at cos(φ) of v on the direction of the laser beam

To detect Δf of a few MHz on the optical beam at ≈500THz we can not use a monochromator or OSA but much better (being $\Delta f/f_0=\Delta\nu/\nu<<1$) to measure the "heterodyne" beat signal with a reference laser beam



Laser Doppler Velocimetry (LDV)

- **LDV** was **invented in 1964** and is still today a great success of optical measurements, to *contactless* detect a **wide range of velocities in moving fluids**

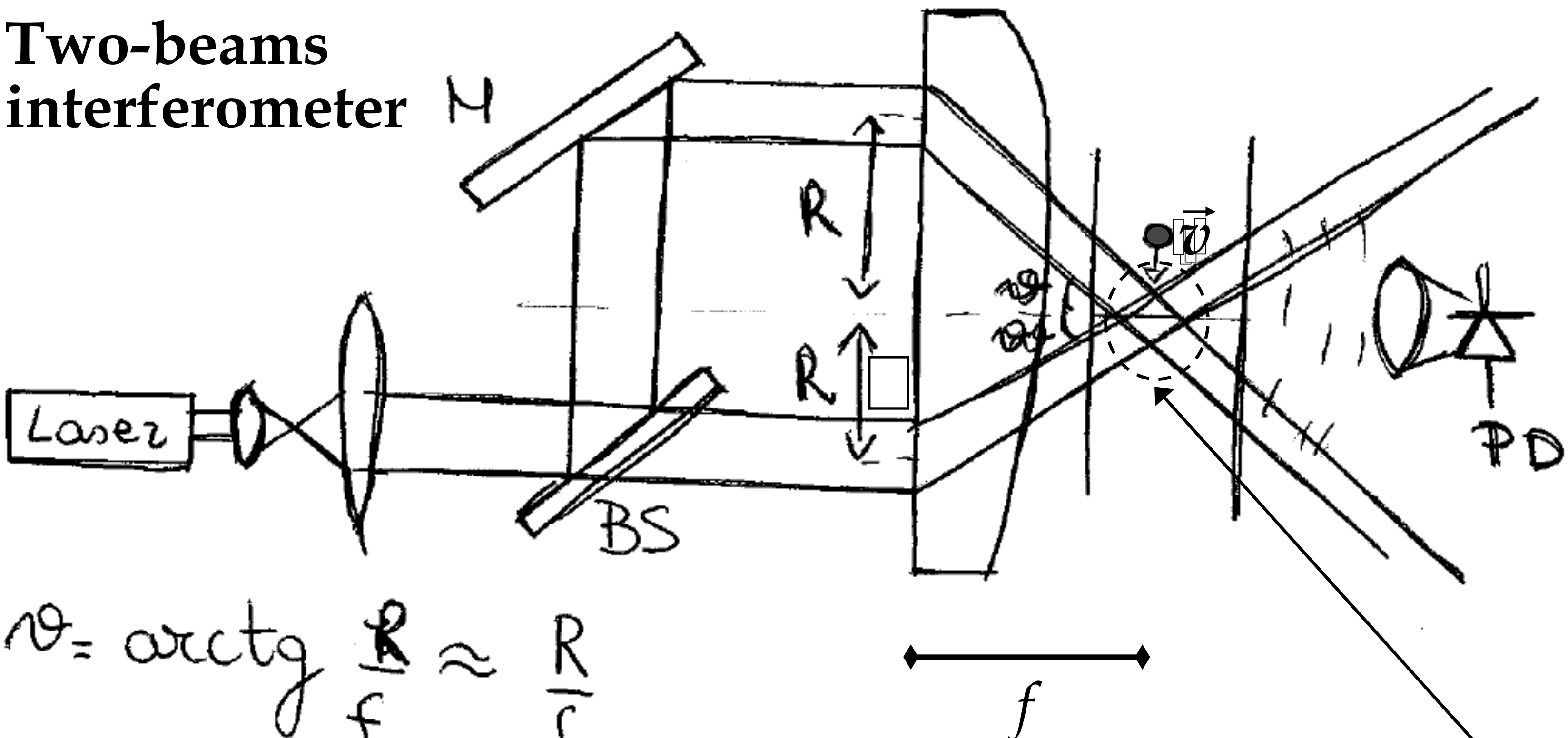
  The **LDV techniques** are used **to measure velocity of fluids** (liquids / gases) **carrying diffusing (scattering) particles**, naturally present or artificially "inseminated" in the fluid

- The diffusion, or ***scattering***, due to interaction of the e.m. field and the particle can be divided into two types:
  - **Rayleigh** ($r << \lambda$) $\alpha_s \propto r/\lambda^4$ $f(\theta)$ constant with the angle
  - **Mie** ($r \approx> \lambda$) $\alpha_s \approx$ cost. $f(\theta)$ max. for $\theta = 0$ (*forward scatt.*)

- The **measurement signal** can be seen as due to:
  - **fringe** crossings ←
  - **Doppler** effect
  - **interferometric** phase shift

LDV: measurement *set-up*

Two-beams interferometer

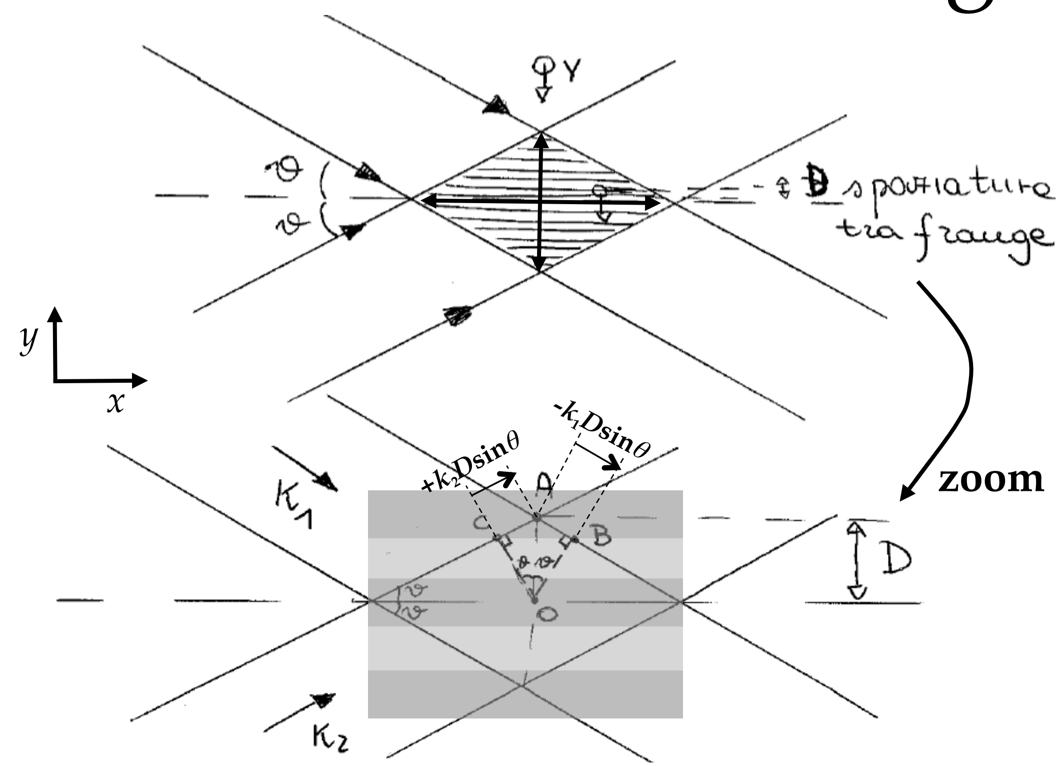


$$\vartheta = \text{arctg}\,\frac{R}{f} \approx \frac{R}{f}$$

The two collimated beams impinge off-axis on the lens and are focused at distance *f* from the lens in an **interference region**

example: *R*=0.5cm and *f*=250mm → θ≅20mrad=1.15°≈1°

LDV: interference fringes



collimated beams → wavefronts approx. plane with width $\pm w_0$

the interaction zone is wide
$\Delta X = \pm 2 w_0 \cdot \cos\theta$
$\Delta Y = \pm 2 w_0 \cdot \sin\theta$

$\Delta\boldsymbol{\Phi}_{(O\rightarrow A)} = [\boldsymbol{\Phi}_2 - \boldsymbol{\Phi}_1]_{(O)} - [\boldsymbol{\Phi}_2 - \boldsymbol{\Phi}_1]_{(A)} = 2\pi$ **fringe spacing** ***D*** dark/dark

From O to A: $\Delta\boldsymbol{\Phi}_2 = \boldsymbol{\Phi}_{2(O\rightarrow C)} + \boldsymbol{\Phi}_{2(C\rightarrow A)}$ and $\Delta\boldsymbol{\Phi}_1 = \boldsymbol{\Phi}_{1(O\rightarrow B)} + \boldsymbol{\Phi}_{1(B\rightarrow A)}$ $\Delta\boldsymbol{\Phi}_2 = (0 + k_2\underline{CA}) = +(2\pi/\lambda) D\sin\theta$ and $\Delta\boldsymbol{\Phi}_1 = (0 - k_1\underline{BA}) = -(2\pi/\lambda) D\sin\theta$

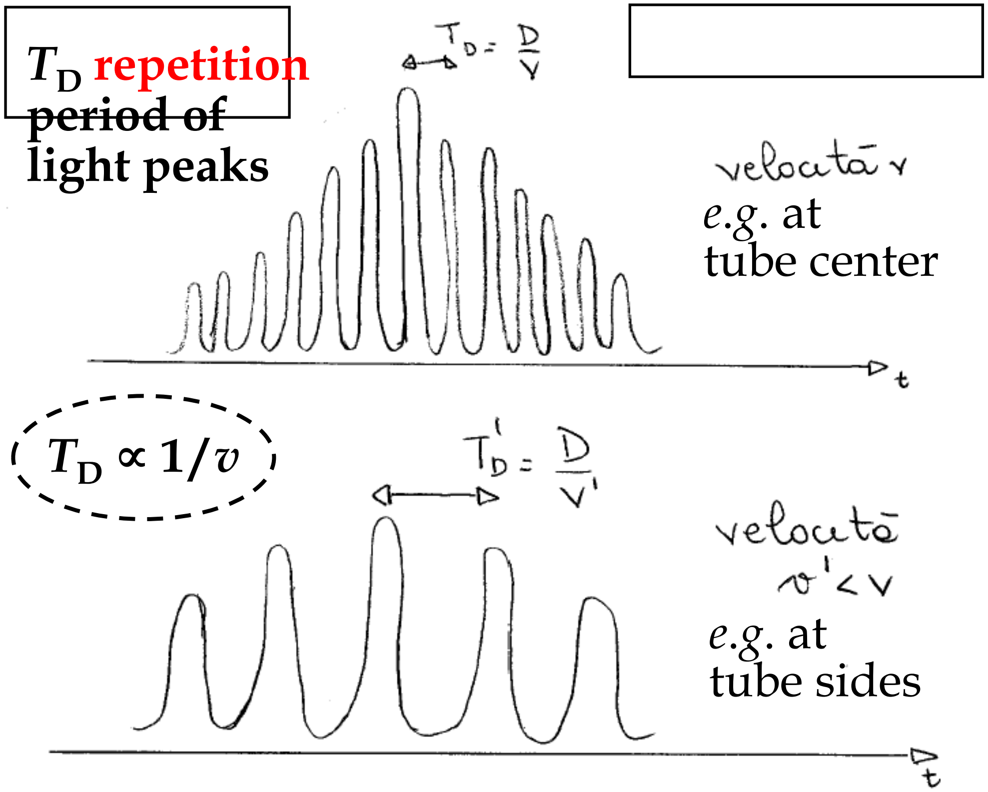
$\boldsymbol{D\sin\theta = \lambda/2}$

$\Delta\boldsymbol{\Phi}_{(O\rightarrow A)} = \Delta\boldsymbol{\Phi}_2 - \Delta\boldsymbol{\Phi}_1 = 2\cdot(2\pi/\lambda) D\sin\theta = 2\pi \Rightarrow$

$$D = \frac{\lambda}{2\sin\theta}$$

Light peaks repeated at distance *D* (⊥ a *v*)

LDV: relation velocity→frequency

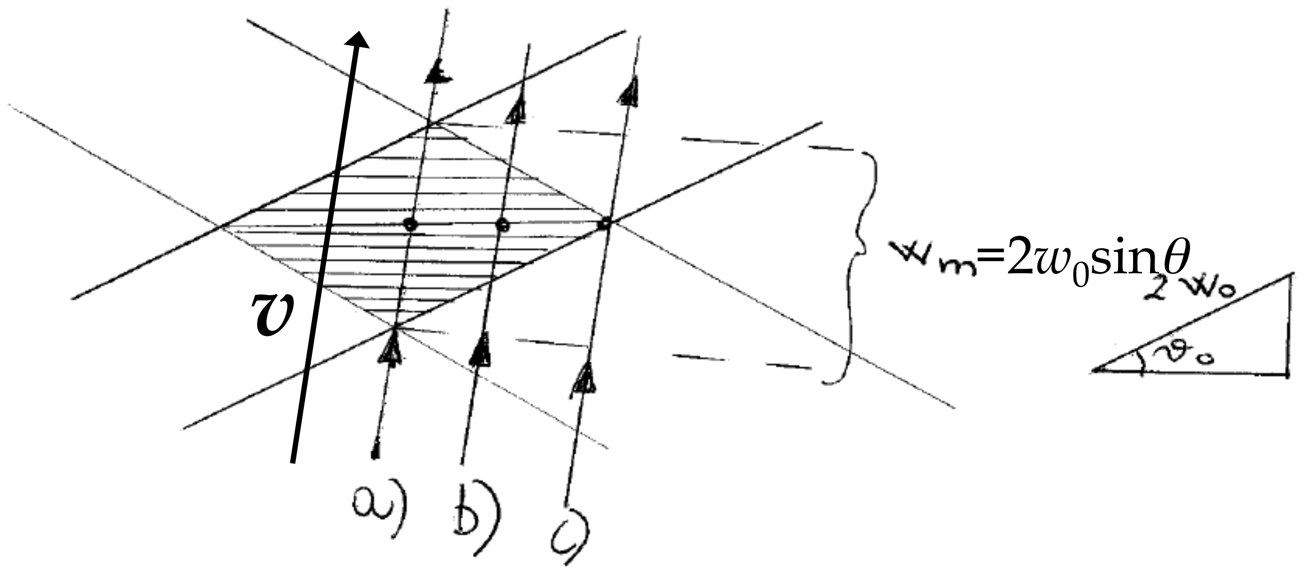


Thickness of crossing zone changes with position of crossing line (in the lit zone) but **light-light distance remains constantly *D*** in orthogonal direction to the interference zone.

On a time axis the distance T_D between light peaks depends on velocity v

The optical beam profile, crossed by particles, is Gaussian and hence diffused light intensity profile varies with position.
<u>The frequency of alternating light-dark-light depends on the fringe distance and particle/fluid velocity</u> $f_D = 1/T_D \propto v$

LDV: signal period and frequency



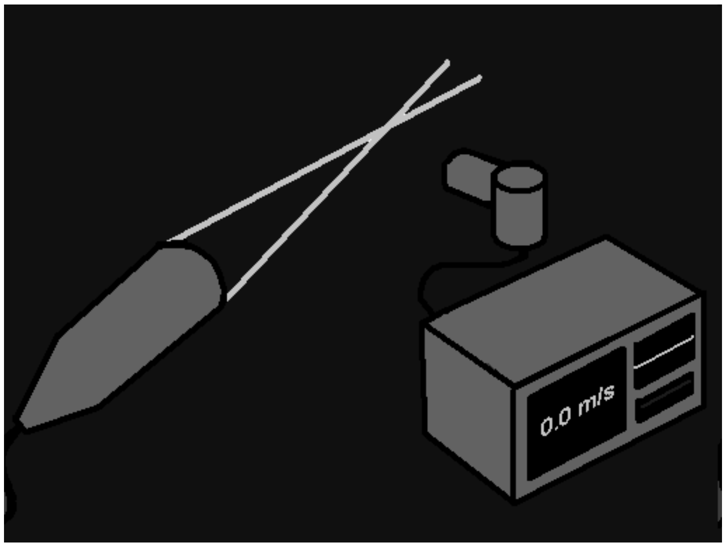
$T_D = D/v$ period of diffused light signal (light-dark-light)

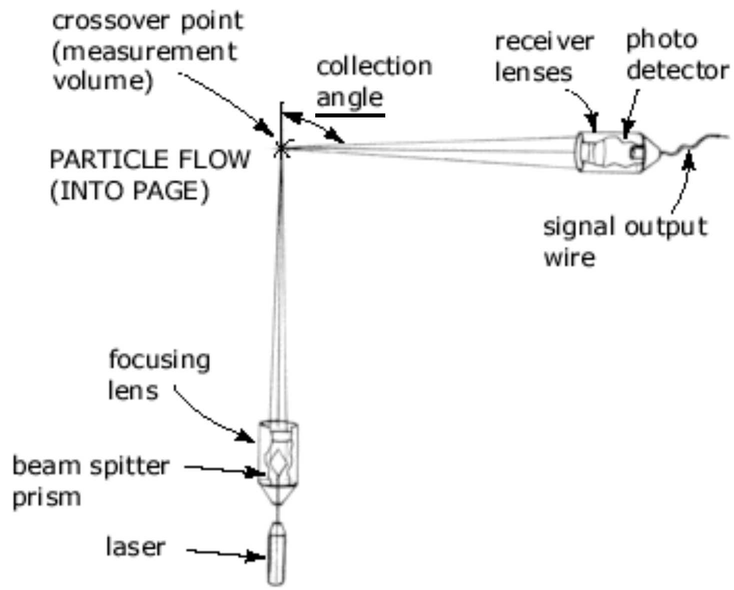
$$\Rightarrow \quad f_D = \frac{1}{T_D} = \frac{v}{D} = \frac{2\sin\theta}{\lambda} v \propto v \quad \Leftarrow$$

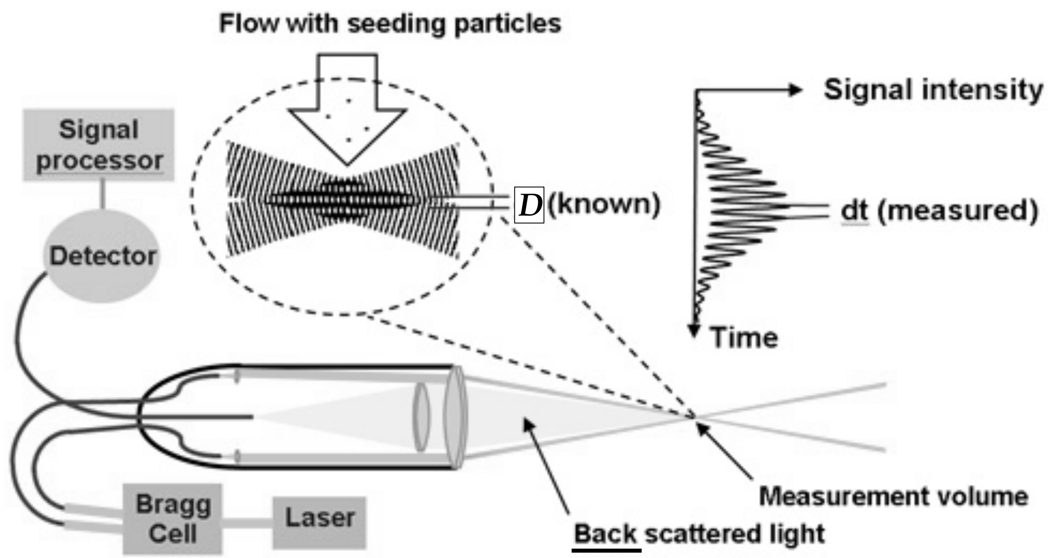
MEASURE SENSITIVITY: $S_{f\leftarrow v} = \Delta f / \Delta v = 2\sin\theta/\lambda$ **(Hz/ms^{-1})**

Measure of f_D: 1) counter; 2) electron. AS; 3) correlation

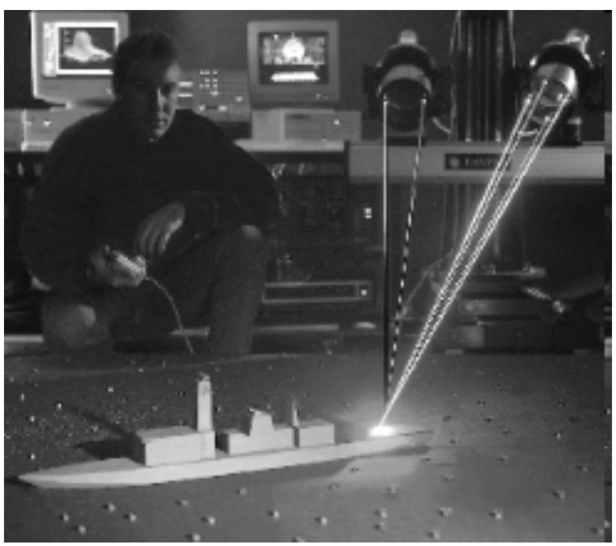
LDV: schemes (*angle_scatt./back_scatt.*)

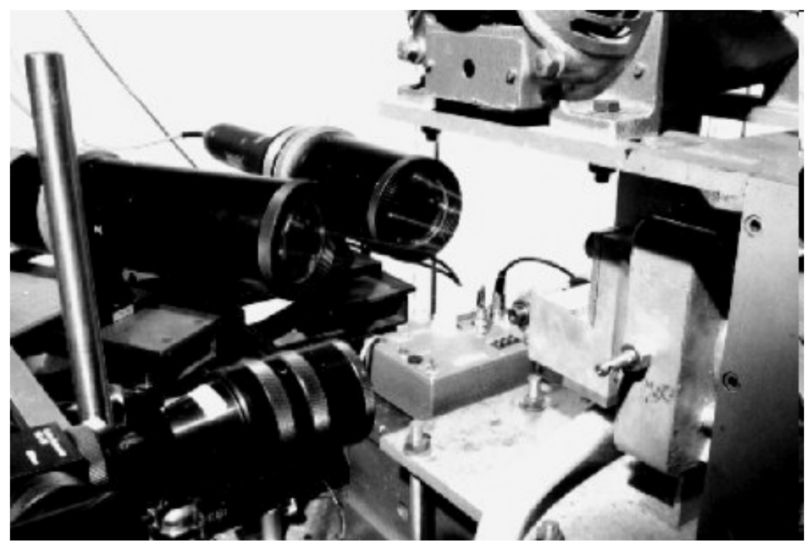






LDV: photos of 3D LDVs





LDV: practical example

$\lambda = 532\ nm$ (Nd:YAG duplicato)

$\vartheta_1 = 3°$ (~ 0.05 rad) $\Rightarrow S_{1,v \to f} \cong 200 \frac{KHz}{m/s}$

$\vartheta_2 = 20°$ (~ 0.35 rad) $\Rightarrow S_{2,v \to f} \simeq 1.3 \frac{MHz}{m/s}$

Se si misura una velocità $v = 500 \frac{m}{s}$

$f_{D,1} = 100\ MHz$

$f_{D,2} = 650\ MHz$

$$S = \frac{\Delta f_D}{\Delta v} = \frac{2 \sin\theta}{\lambda}$$

La misura diviene critica per alte velocità del fluido ($v > 100\ m/s$) mentre risulta agevole e molto sensibile per misure di basse velocità.

con $\vartheta = 0.5$ rad (~32°) $\Rightarrow S_{v \to f} \cong 2 \frac{MHz}{m/s}$

e f_D è per $v = 1\ mm/s \Rightarrow f_D = 2\ kHz$.

Agevolmente misurabile dopo conversione A/D del segnale di luce diffusa in funzione del tempo.

LDV: properties

$$v = \frac{\lambda}{2\sin\theta} f_D \cong \frac{\lambda}{2\theta} f_D$$

PRESTAZIONI DI MISURA

La sensibilità del velocimetro Doppler è:

$$S_{v\to f} = \frac{2\,\text{sen}\,\vartheta}{\lambda} \approx \frac{2\vartheta}{\lambda} \quad \text{per } \vartheta \ll 1$$

per cui, in termini di incertezza relativa:

$$\frac{u(S)}{S} = \sqrt{\frac{u^2(\vartheta)}{\vartheta^2} + \frac{u^2(\lambda)}{\lambda^2}}$$

e potendo considerare un solo contributo d'incertezza alla volta si ha:

$$\frac{u(S)}{S} \approx \frac{u(\vartheta)}{\vartheta}$$

oppure

$$\frac{u(S)}{S} \approx \frac{u(\lambda)}{\lambda}$$

Solitamente l'incertezza nella lunghezza d'onda non è un problema in quanto si può conoscere λ con incertezza relativa $\frac{u(\lambda)}{\lambda} < 10^{-4}$. Invece essendo

$$\vartheta = \text{arctg}\,\frac{r}{f} \approx \frac{r}{f}$$

r → disassamento del fascio nella lente

f → focale della lente

mentre f può essere creata con incertezza di 10^{-4} il valore di r può essere mantenuto con incertezza relativa di qualche parte per mille (a causa della instabilità a lungo termine dei componenti meccanici).

Pertanto un limite di accuratezza nel coefficiente di sensibilità, e naturalmente sulla conseguente misura di velocità, può essere nell'ordine di 10^{-3}.

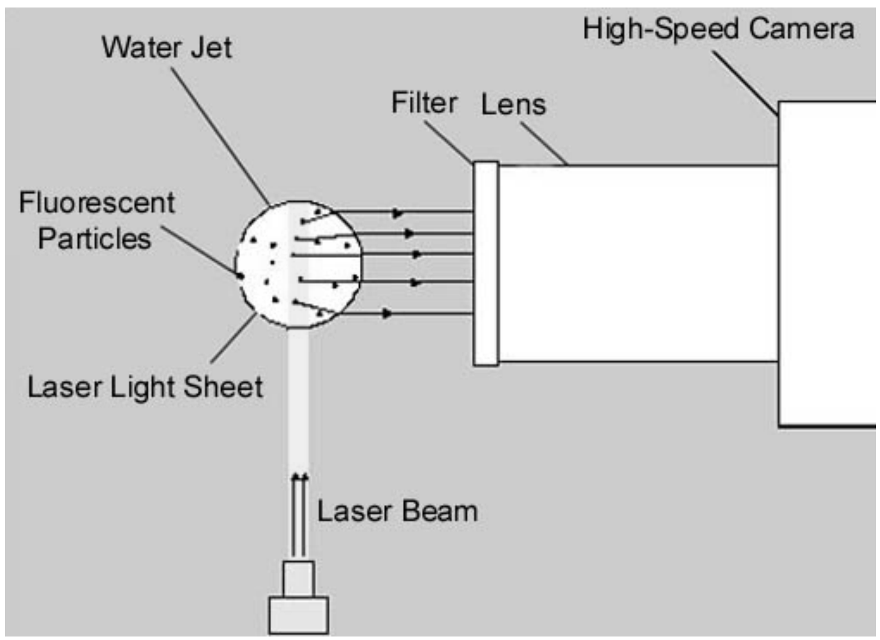
La misura della frequenza f_D naturalmente si può fare con incertezza anche minore di 10^{-6}

(12) (13)

for the Doppler analysis of LDV signal see the Text Book (Prof. Donati)

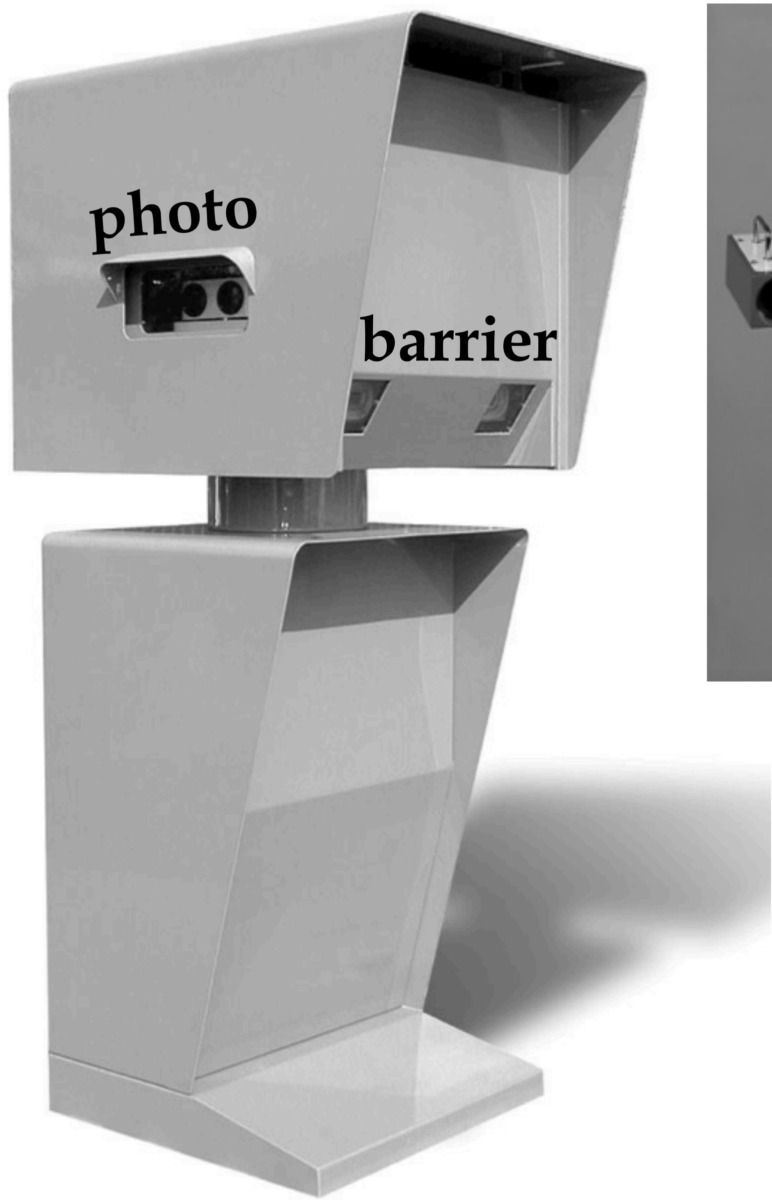
PIV (only measurement "principle")

The velocity measurement of the particles in the fluid is done "lighting" the investigation zone, with laser light (or with fast light flashes and using a multi-exposure slow camera)



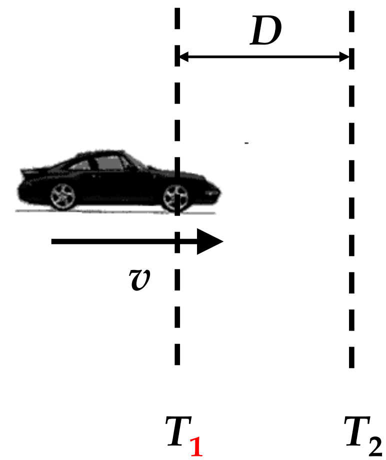
Images of the particles as a function of time are detected with a fast CCD camera, from which one can reconstruct the entire spatial profile (field) of velocities: $v_i = \Delta l_i / \Delta t$

Autovelox with optical barrier (e.g. 104 C2)



optical barrier

D = 0.5 m



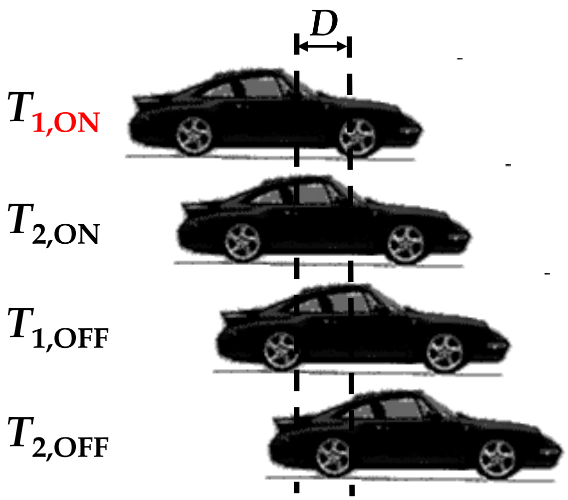
v=$D/(T_2$-$T_1)$=$\boldsymbol{D/\tau_{21}}$

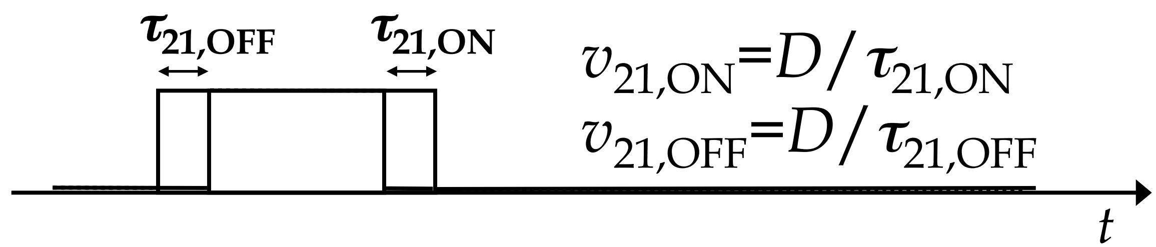
E.g. for v=150 km/h τ_{21}=12 ms

$\Delta\tau_{21}\cong$10 μs Δv=-$D/(\tau_{21})^2\cdot\Delta\tau_{21}\cong$0.1 km/h

Detection with NIR laser (Class 1)
No interception/countermeasures
PLATE imaging by photo/video

Autovelox with optical barrier (e.g. 104 C2)





$v_{21,ON} = D / \tau_{21,ON}$

$v_{21,OFF} = D / \tau_{21,OFF}$

Measurement independent from vehicle profile and double-detection ($v_{21,IN} \cong v_{21,OFF}$ within 1 km/h) allows discarding fake readings and meas. errors

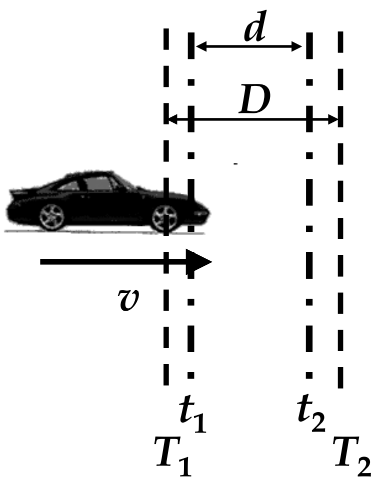
The target is hit by the laser and retro-diffused light is detected

Autovelox with optical barrier (e.g. 104 C2)

Co-planarity ($\theta_{Orizz.} = \theta = 0$) of the optical barrier with the road is important and instrument **calibration** is mandatory by law every year

horizontal vs. inclined

$$\boldsymbol{d = D \cdot \cos\theta < D}$$



The horizontal instrument measures

$v = v_{21} = D/(T_2 - T_1) = \boldsymbol{D/\tau_{21}}$

but if inclined by θ the measure is

$\tau_{21}^* = (t_2 - t_1) = d/v < \tau_{21}$ and hence

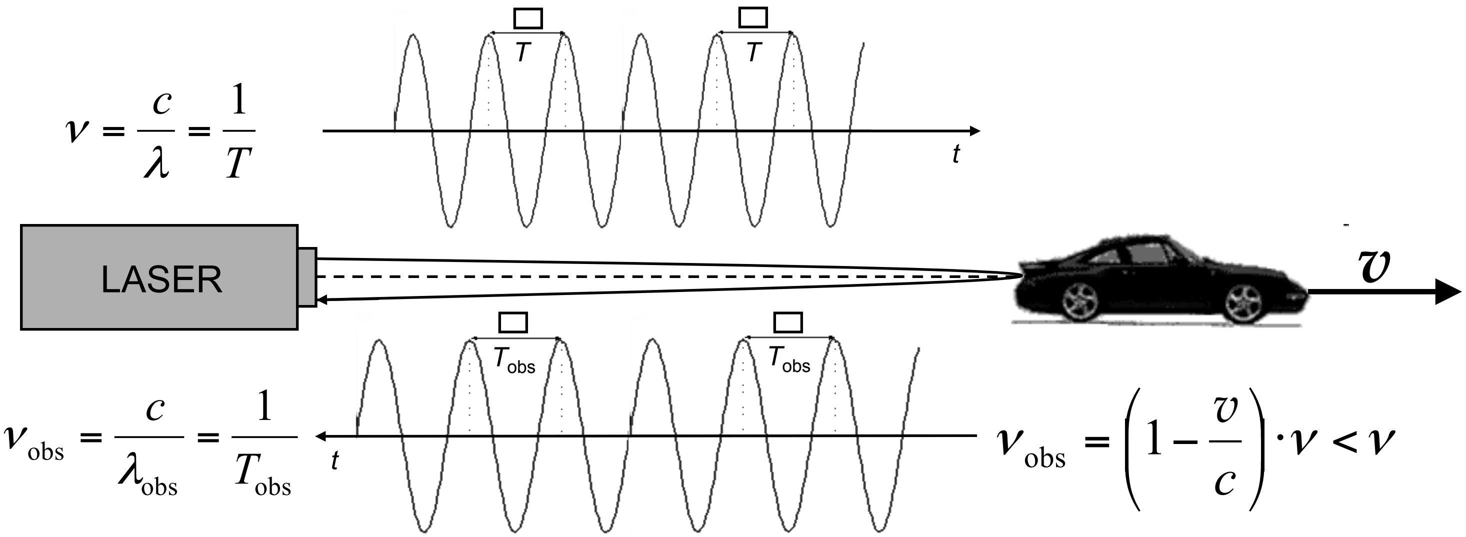
$$\boldsymbol{v^* = D/\tau_{21}^* = v \cdot D/d = v/\cos\theta > v}$$

<u>the velocity can be "overestimated"</u>

A misalignment barrier-to-road of 10° gives a measurement error of 1.5% (in excess!), corresponding to +2.3 km/h at 150 km/h

If well aligned and calibrated, the instrument can reach accuracy levels well below 1% that – "poor us!" – are more than adequate for the measurement, given with a "tolerance" of 5%

Tele-laser (Doppler velocimeter) "???"



$$\nu = \frac{c}{\lambda} = \frac{1}{T}$$

$$\nu_{\text{obs}} = \frac{c}{\lambda_{\text{obs}}} = \frac{1}{T_{\text{obs}}}$$

$$\nu_{\text{obs}} = \left(1 - \frac{v}{c}\right) \cdot \nu < \nu$$

By beat-note analysis we "could" detect a the **Doppler shift**

$$\Delta\nu_{\text{Doppler}} = (\nu - \nu_{\text{obs}}) = (v/c)\cdot\nu = (1/\lambda)\cdot v$$

[for λ=1 μm (ν =300 THz), v = 108 km/h = 3 m/s → $\Delta\nu$ = 3 MHz]
[for λ=1 μm (ν =300 THz), v = 36 km/h = 1 m/s → $\Delta\nu$ = 1 MHz]
[for λ=1 μm (ν =300 THz), v = 180 km/h = 5 m/s → $\Delta\nu$ = 5 MHz]

Given the high value of $\Delta\nu_{\text{Doppler}}$, T_{Doppler} <1 μs, repeated v_j measurements "could" be averaged in a short time, reducing measurement uncertainty

Tele-laser "pistol" (TOF telemeter)

Technical specs.:

T_{meas}=0.4 s

L-Range=610 m

v-Range=±320 km/h

λ=904 nm

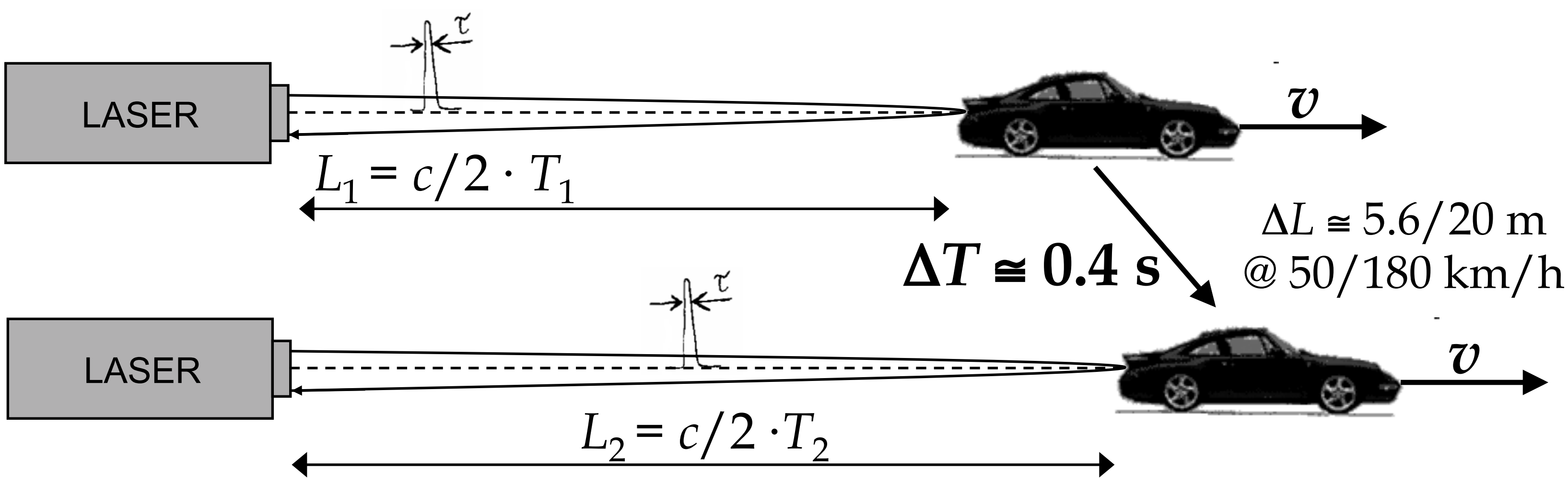
θ_{div}=3 mrad

laser class 1

$u(L)$=15 cm

$u(v)$=2 km/h

Tele-laser (TOF telemeter)



$$v = (L_2\text{-}L_1)/T_{\mathbf{rep}} = c/2 \cdot (T_2\text{-}T_1)/T_{\mathbf{rep}}$$

$T_{rep}=T_{NA}=2L_{NA}/c \approx 4\ \mu s$ (f_{rep}=250 kHz) with $L_{max} \approx L_{NA}$=600 m

Given the high value of f_{rep}, repeated TOF measurements can be averaged in a short time (T_{ave}=10 ms and T_{meas}=0.4 s: average of 40 readings of TOF for L_i meas. and 39 readings of v_j for $v_{ave@400ms}$) reducing measurement uncertainty