DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF SCIENCE

Bangalore-560012

Experimental Methods

Jaywant H. Arakeri

Fluid Mechanics Laboratory,
Department of Mechanical Engineering,
Indian Institute of Science, Bangalore, India-560012

Shashikant S Pawar
Visakh
Navneet

Contents

- Laser doppler velocimeter (LDV)
- Particle Image velocimetry (PIV)
- Concentration measurement
- Thermal imaging

Principles of

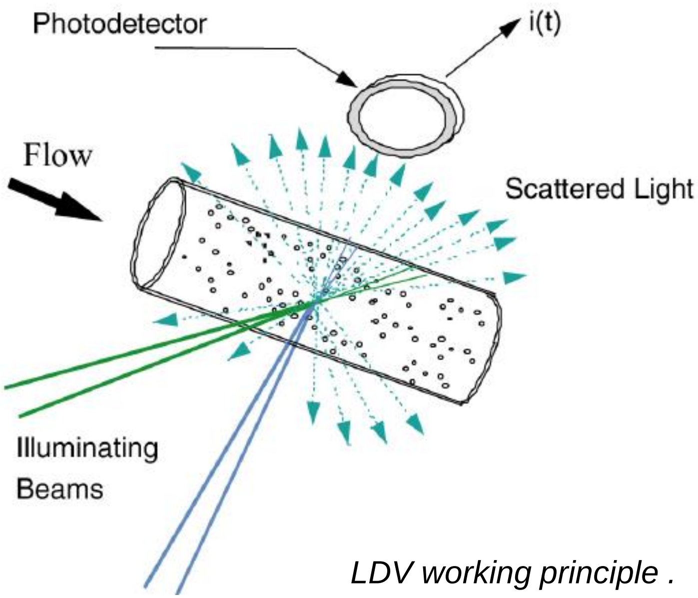
Laser Doppler Velocimetry (LDV)

Introduction

- LDV - Optical measuring technique to determine velocity of a fluid with high temporal resolution
- Velocity measured virtually at one single point – Measurement Volume (MV)

The method:

- Flow is seeded with small tracer particles
- Use one or more coherent, polarized laser beams to form a MV
- Receive scattered light from particles passing through the MV
- Resulting scattered light intensity is measured, which is related to the particle velocity



LDV working principle .
Ref: TSI User manual

Benefits

- Non-invasive measuring technique
- High accuracy
- No calibration required
- High data rates
- High spatial and temporal resolution
- Can be used in environments unsuitable for conventional techniques

Limitations

- Need transparent fluid and transparent walls
- Expensive equipment
- Needs to be seeded with particles
- Single point measurement
- Difficult to collect data near the walls

Some key aspects of LDV

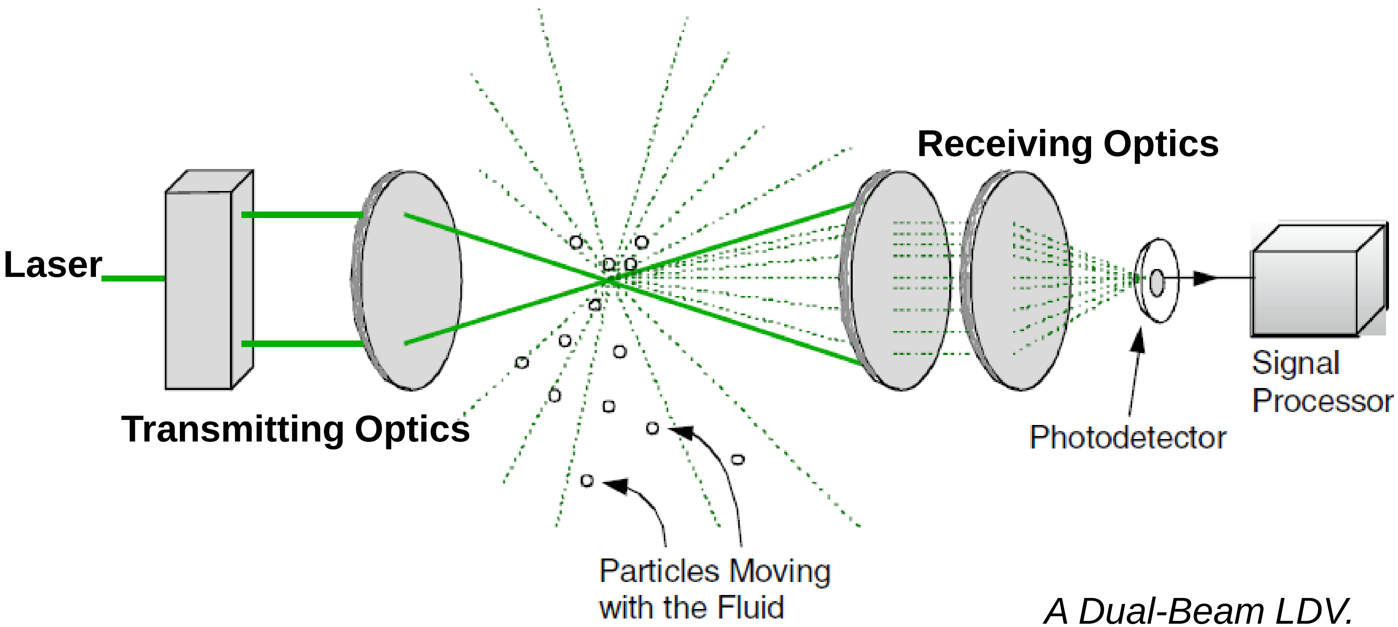
- Measurement is independent of the property of the medium
- Desired component of velocity can be measured by suitably orienting the laser beams – up to 3 components can be measured
- Signal is discontinuous, since it exists only when a detectable particle is in the measurement volume

Applications

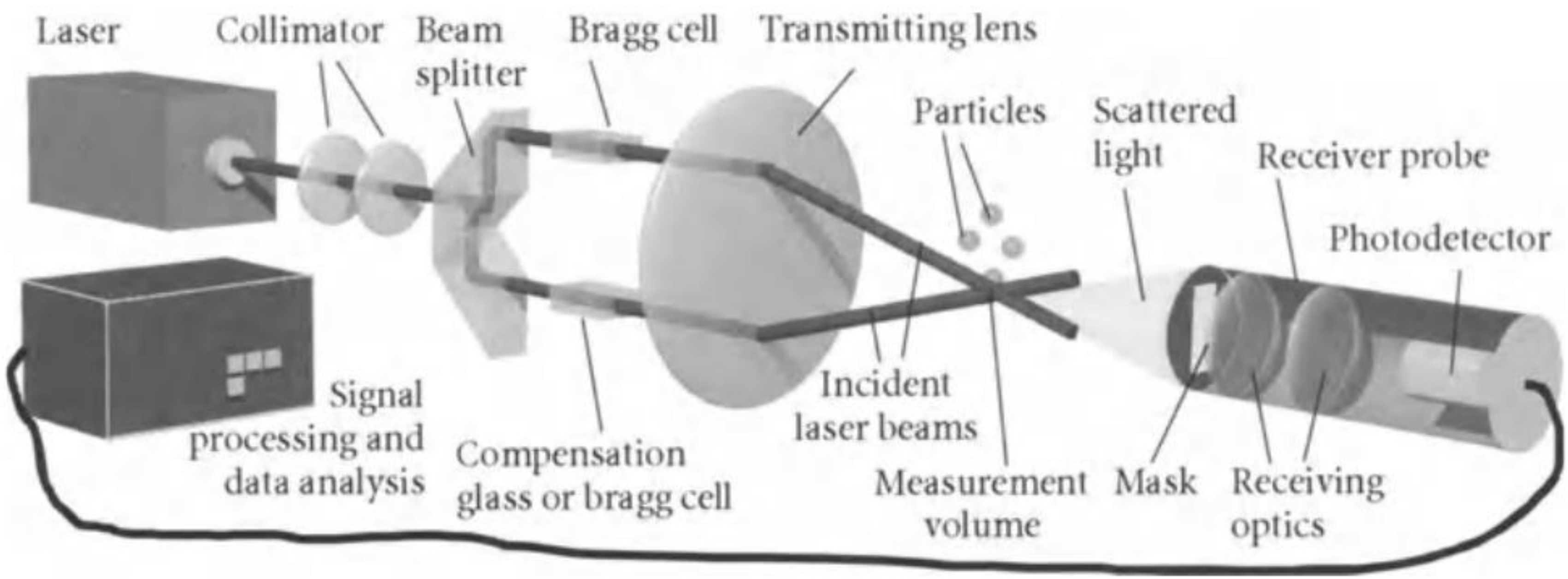
- Turbulent flow research
- Atmospheric turbulence
- Internal combustion engines, Turbines, etc
- Aerodynamics, Supersonic flows, etc
- Medical, biophysical, etc
- Can be upgraded to PDPA for measuring droplet, spray size and velocities

Components of an LDV system

- Laser — Monochromatic light source, provides coherent, collimated beam
- Transmitting optics
- Receiving Optics, Detector
- Signal processor, Data Analysis system



A Dual-Beam LDV.
Image courtesy : TSI User manual



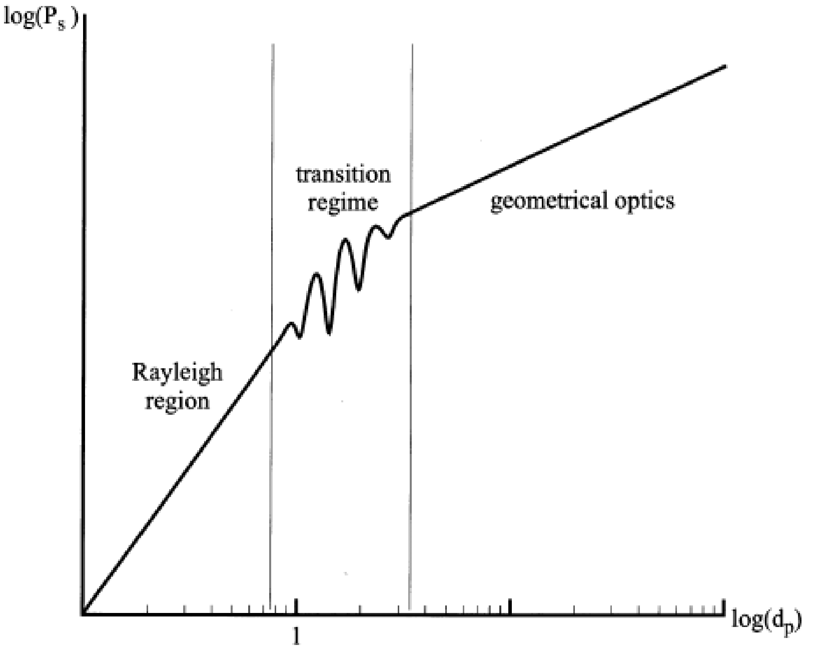
Dual-beam Laser Doppler Anemometer (LDV)

Ref: H.-E. Albrecht, M. Borys, N. Damaschke, C. Tropea, Laser Doppler and Phase Doppler Measurement Techniques (Springer, Berlin, Heidelberg 2003)

Mie Scattering

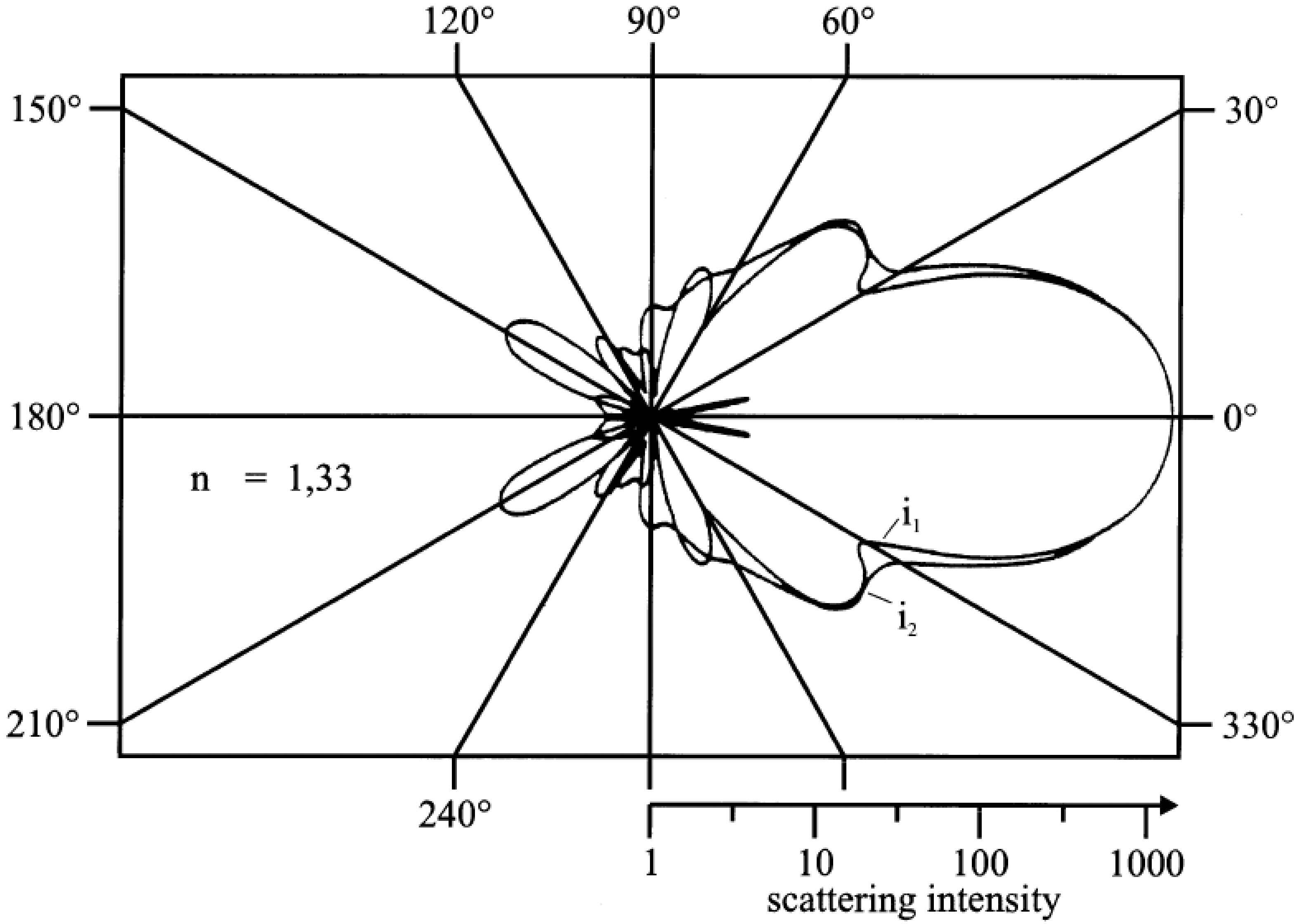
- Measuring principle of LDV is based on the physical effect of Mie scattering.
- Transition regime in which particle diameter is slightly above the illumination wavelength (q>1) is usually used in applications of Mie scattering.

- The intensity of light scattered in forward direction is much larger than in the backward direction.
- The overall intensity increases with increasing diameter of the sphere.
- The characteristics of the intensity distribution as a function of the angle of observation changes strongly.
- The intensity distributions of the two directions of polarizations can be different.



Scattering intensity as a function of normalized particle diameter (ratio of particle diameter and illumination wavelength)
Ref: Optical Measurements- Techniques and Applications [Franz Mayinger, Oliver Feldmann]

Mie Scattering

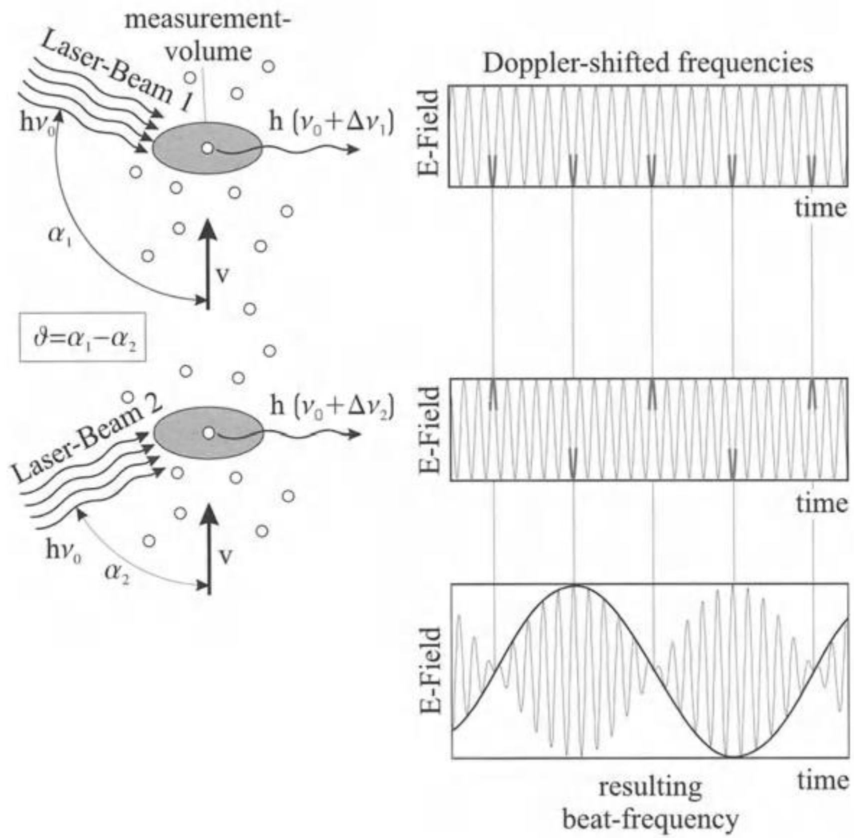


Mie-scattering intensity polar diagram of a water droplet (1µm diameter, refractive index n=1.33) illuminated by linearly polarized light. Intensity I is given in dependence of the polarization of the scattered light: $i_1=q^2I_\perp$, $i_2=q^2I_\parallel$.
Ref: Optical Measurements- Techniques and Applications [Franz Mayinger, Oliver Feldmann]

Theory of LDV

Based on *Doppler effect*: Light scattered by a moving particle w.r.t a light source shows a frequency shift in comparison to the light source

- Dual-beam differential system: most common LDV technique – coherent laser beam split equally.
- Resulting two beams forms the Measuring Volume (MV) at a focused crossing
- A particle traversing the MV scatters light from the two light beams, Doppler shifting each of them.
- The amount of Doppler shift depends on the velocity of the scattering particles, as well as the direction of the light beam. Since the two beams are not parallel, the corresponding Doppler shifts are different.



Measuring principle of LDV
Image courtesy: Optical Measurements- Techniques and Applications [Franz Mayinger, Oliver Feldmann]

Theory of LDV, contd..

- A photo-detector receives scattered light from the MV.
- Superposition of the two Doppler-shifted components results in a beat that is captures by the photo detector.
- The velocity of the particle v can be determined from the beat frequency f_d as:

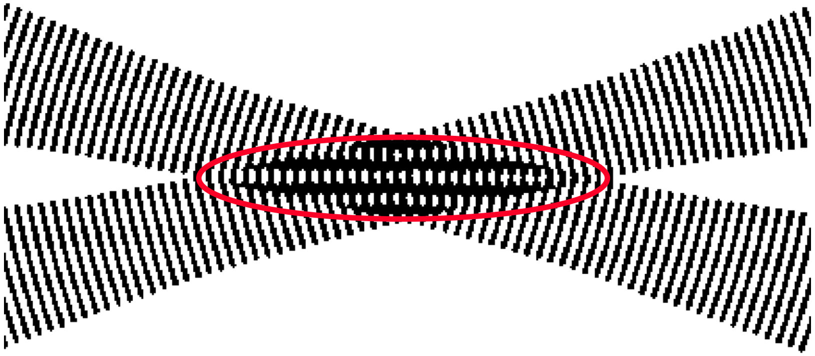
$$v = \frac{f_d \, \lambda}{2 \sin(\frac{\vartheta}{2})}$$

Here, λ is the beam wavelength and ϑ is the angle between the beams.

- However, detected frequency *f* and hence calculated velocity *v* are not dependent on the sign (direction) of the velocity component of the particle, only the magnitude. To overcome this, frequency of one of the beams is shifted by a frequency f_0. Thus, a particle moving in the positive direction causes Doppler bursts of a higher frequency than shift, and vice versa. The resulting velocity is calculated as:

$$v = \frac{(f_d - f_0) \, \lambda}{2 \sin(\frac{\vartheta}{2})}$$

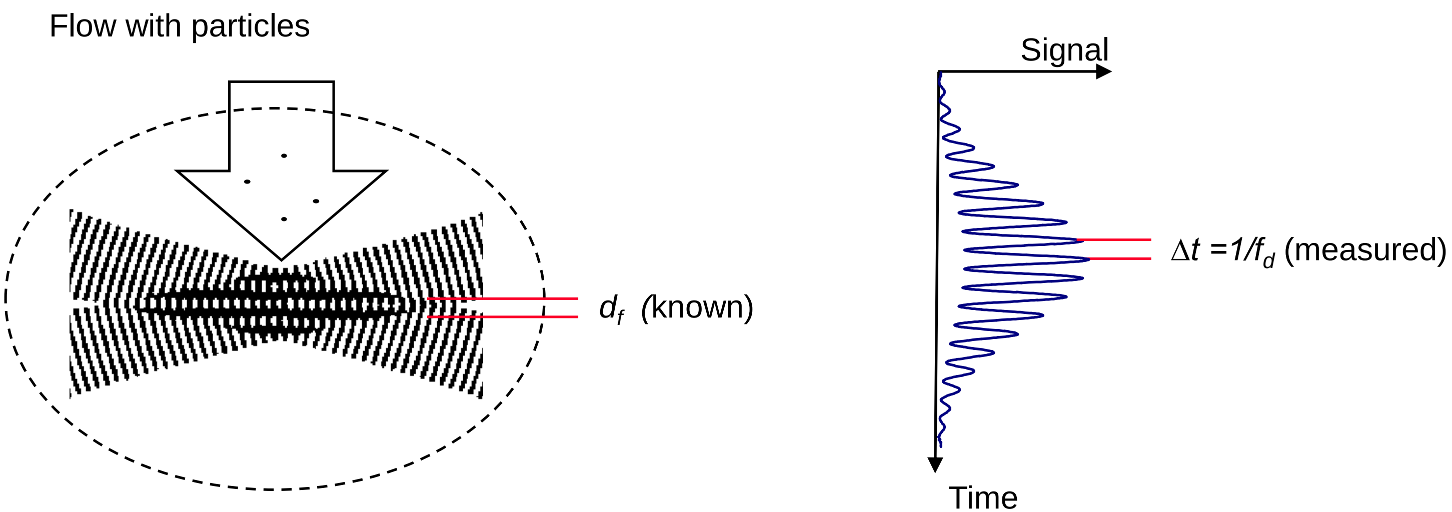
Fringe interference description
(Alternate explanation)



Fringe pattern in the MV
Image courtesy : Dantec Dynamics

- Incident pair of laser beams form a fringe pattern (dark and bright planes) at the Measurement Volume due to interference of their planar wave fronts.
- Fringe planes are oriented parallel to the optical axis and perpendicular to the plane defined by the two incident beams.
- A particle passing through the MV scatters light proportional to the intensity of the light there. i.e, high in the bright zones and low in the dark zones.
- When the particle traverses this fringe pattern, the scattered light fluctuates in intensity with a frequency equal to the velocity of the particle (component perpendicular to the fringe planes) divided by the fringe spacing.

Fringe interference description, contd..



Fringe pattern and signal burst
Image courtesy: Dantec Dynamics

- The photo-detector records a signal burst whose amplitude is modulated by the fringe pattern. The frequency of the modulation is the Doppler frequency.
- Particle velocity $v = d_f / \Delta t = d_f \times f_d$, where $d_f = \frac{\lambda}{2\sin(\frac{\vartheta}{2})}$ is the fringe spacing in the MV;

and hence, $v = \frac{f_d \lambda}{2\sin(\frac{\vartheta}{2})}$ (same correlation obtained earlier).

Optics

Laser:

- Ar-ion lasers (3 colors: blue 488nm; green 514.5nm, and purple 476.5nm), power upto 10W for high end applications.
- Others include He-Ne lasers, Nd:YAG laser, laser diodes, etc.
- Laser operated in the TEM_{00} mode, emitting a circular beam (monochrome and linearly polarized) with a Gaussian intensity distribution.
- Ar-ion lasers can be used for 3D LDV systems (3 different wavelengths), and set-ups with difficult optical access (high power).
- LDV optics is specific to type of laser – coating of prisms and filters.

Optics

Measurement Volume:

- Ellipsoid with Gaussian intensity distribution in all 3 dimensions.

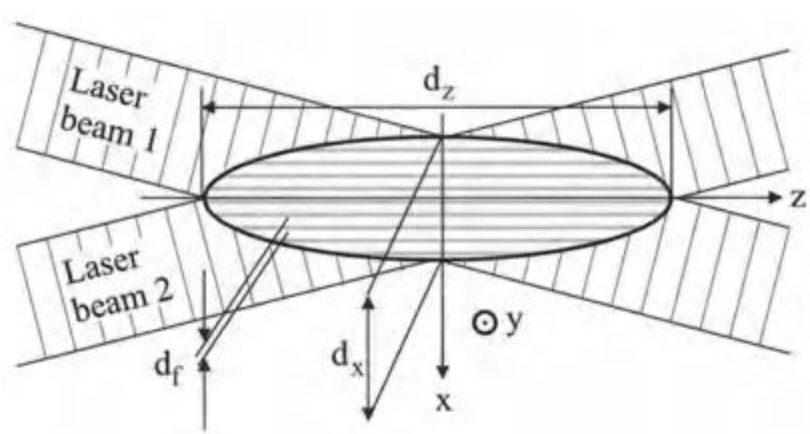
$$d_x = \frac{d_l}{\cos(\frac{\vartheta}{2})}\ ;\ d_y = d_l;\ d_z = \frac{d_l}{\sin(\frac{\vartheta}{2})}$$

d_l is the diameter of the laser beam, defined as:

$$d_l = \frac{4\lambda F}{\pi d_l'};$$

F – focal length of front lens; d_l' - beam waist of unfocussed laser beam

- Fringe separation given by where $d_f = \frac{\lambda}{2\sin(\frac{\vartheta}{2})}$; and
- Number of fringes $N_f = \frac{d_x}{d_f} = \frac{2d_l\tan(\frac{\vartheta}{2})}{\lambda}$



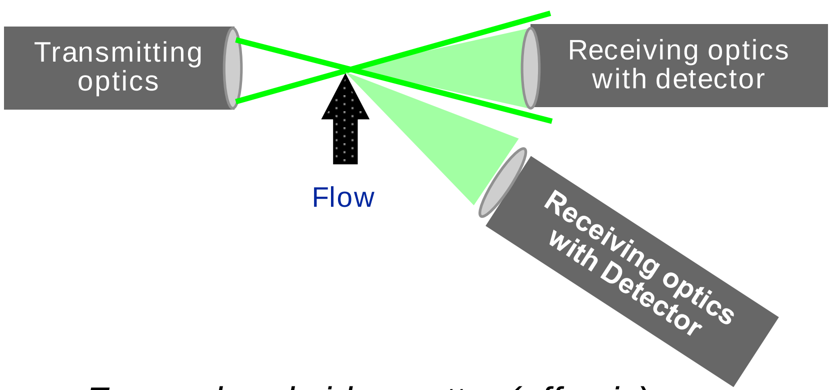
Measurement Volume

Ref: Optical Measurements- Techniques and Applications [Franz Mayinger, Oliver Feldmann]

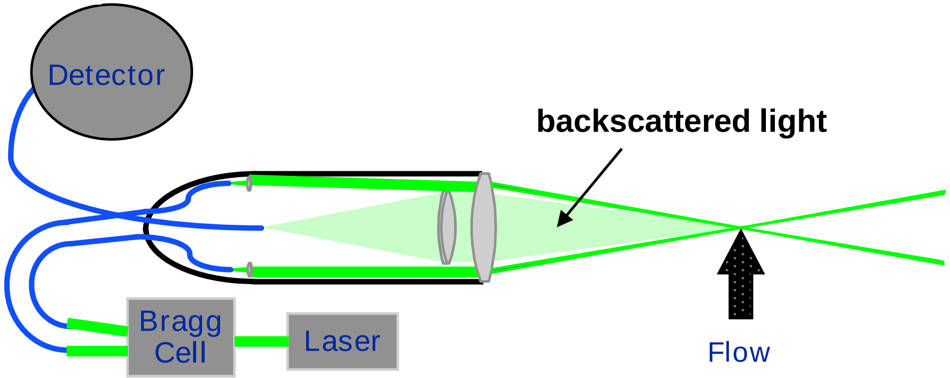
Optics

Receiving Optics:

- Scattered light can be detected by forward, side (off-axis) or back-scatter modes.
- Forward/Side scatter mode:
  - Difficult to align, Optical accessibility from both sides needed, vibration sensitive
  - Intensity of scattered light higher (generally, two orders of magnitude) than that of backscatter mode
- Back scatter mode:
  - Front lens of LDV optics serves as focusing lens
  - Optical accessibility required only from one side
  - No additional adjustment of collector optics necessary, user friendly



Forward and side-scatter (off axis)



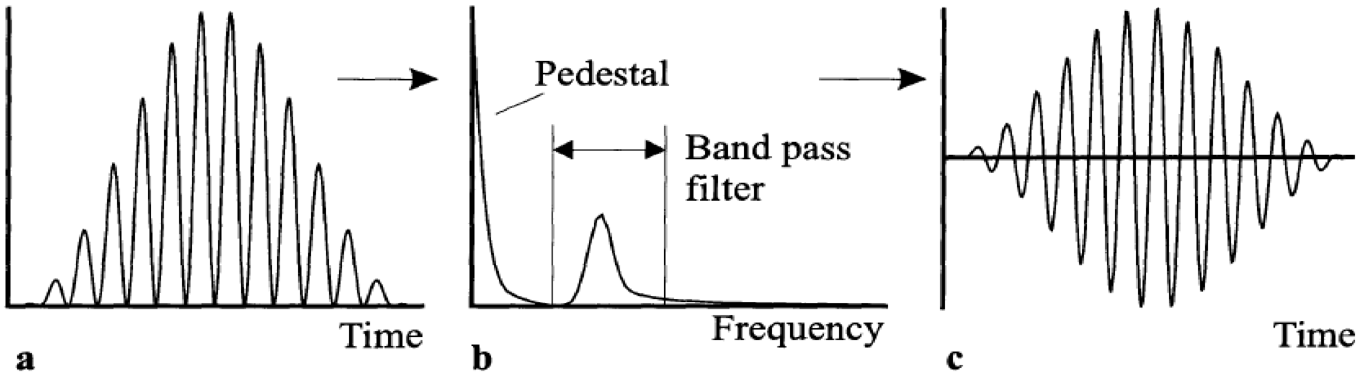
Back-scatter

Image courtesy : Dantec Dynamics

Signal Processing

- Scattered light usually detected by Photomultiplier (PM) which transforms scattered light into electronic signal.
- Signal can be decomposed into: *Low frequency pedestal* (caused by the particle passing through the focused Gaussian-intensity laser beams) + *Doppler frequency* + *spurious noise* which may originate from:
    - Photodetection shot noise
    - Secondary electronic noise and thermal noise from preamplifier circuit
    - Higher order laser modes (optical noise)
    - Light scattered from outside MV and unwanted reflections
- Signal is first transformed into frequency domain and band pass filtered for eliminating the high frequency noise and low frequency pedestal, and converted back to time domain.
- Limits of the band pass filter set before measurement so that all velocities that appear during measurement are determined.
- High velocity ranges – wide band pass filter range – decreased signal-to-noise ratio.

Signal Processing



Recorded Doppler Burst

Transformed to frequency domain

Re-transformed to time domain after band pass filtering

Ref: Optical Measurements- Techniques and Applications [Franz Mayinger, Oliver Feldmann]

Seeding Particles

Desirable properties of seeding particles:

- Follow flow fluctuations faithfully
- Good light scattering property
- Chemically inactive, non-volatile, slow evaporation
- Conveniently generated, inexpensive
- Clean, non-toxic, non-corrosive, non-abrasive

Particle	Fluid	Diameter [μm] 1 kHz	Diameter [μm] 10 kHz
Silicone oil	atmospheric air	2.6	0.8
MgO	methane–air flame, 1800 K	2.6	0.8
TiO_2	oxygen plasma, 2800 K	3.2	0.8
PVC	water	16	5.0

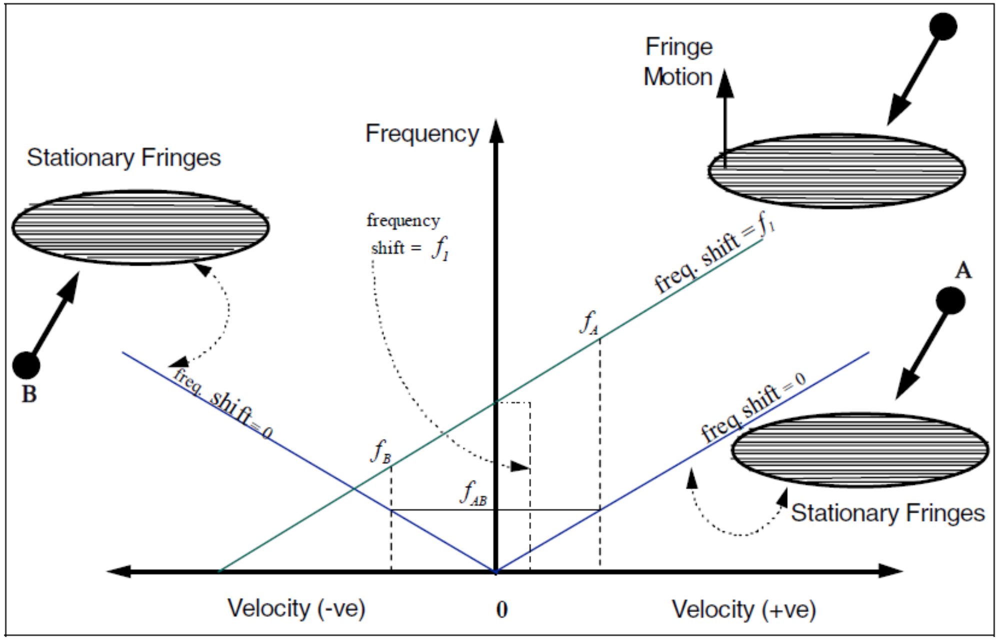
Ability of seeding to follow the flow at 1 and 10 kHz turbulent frequency
Ref: Optical Measurements- Techniques and Applications [Franz Mayinger, Oliver Feldmann]

- Type of particle – flow specific.
- Ability of particle to follow the flow accurately depends on:
  - Density of particle - should not vary much from that of fluid.
  - Particle diameter - in the range of wavelength of visible light.
- Typical seeding particles for gaseous flows:
  - Solids (SiO_2, MgO, Al_2O_3. TiO_2), liquid droplets (water, Silicone Oil), or smoke
- Typical seeding particles for liquid flows:
  - Solids such as Al-powder, latex particles, etc.

Frequency shifting

Purpose of frequency shifting:

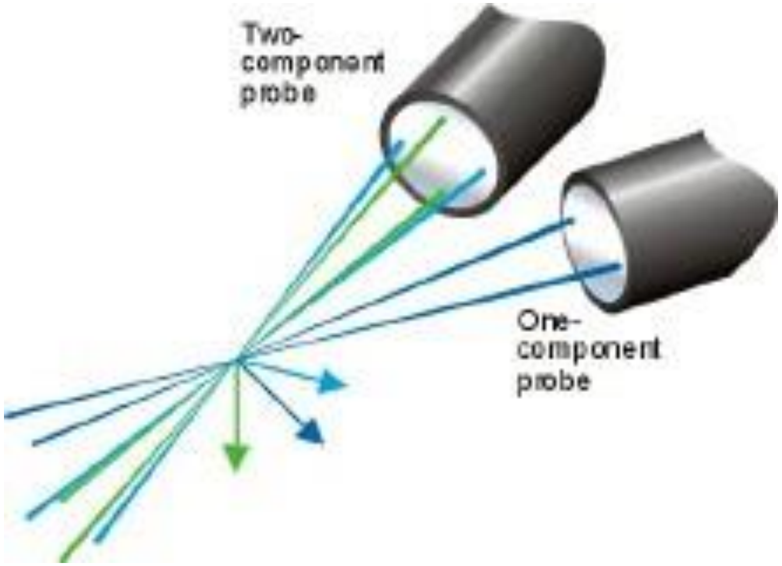
- Measure flow reversal
- Measure small fluctuations in presence of high average velocity
- Extend range of low and high velocities that can be measured by a processor



Frequency shifting
Ref: TSI User manual

- In case of no frequency shift (stationary fringes in fringe model), frequency goes to zero as velocity goes to zero, as well as remains same for both positive and negative velocities of same magnitude (f_{AB}).
- Frequency shift offsets the frequency-velocity curve along y-axis by the shift value (f_1).
- For frequency shifted system (moving fringes in fring model), zero velocity – signal frequency f_1; positive and negative velocities generate different frequencies ((f_a , f_b).

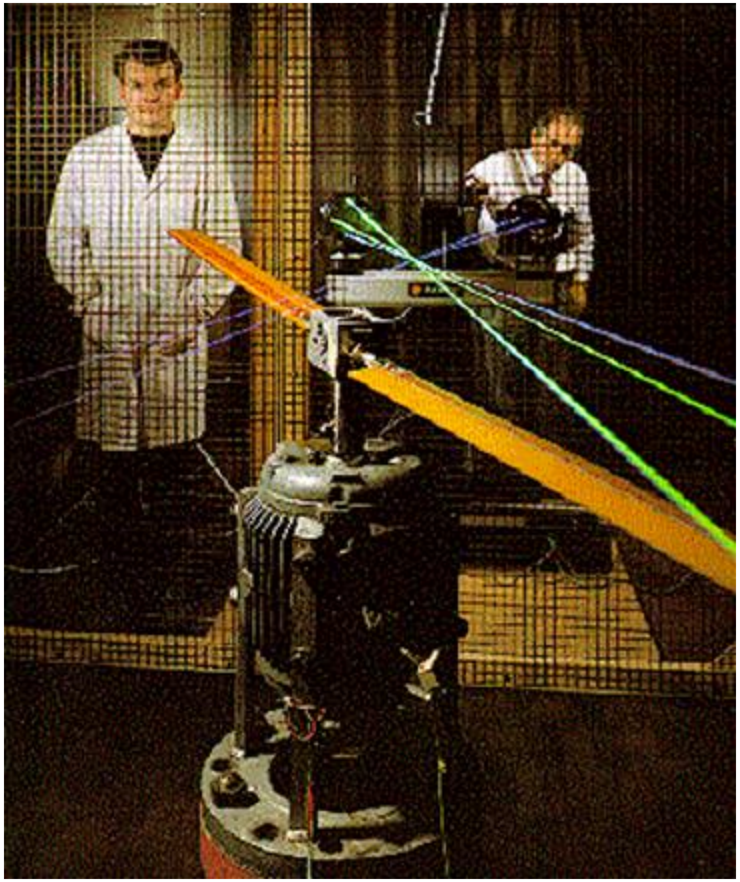
Multicomponent (2,3) velocity measurements



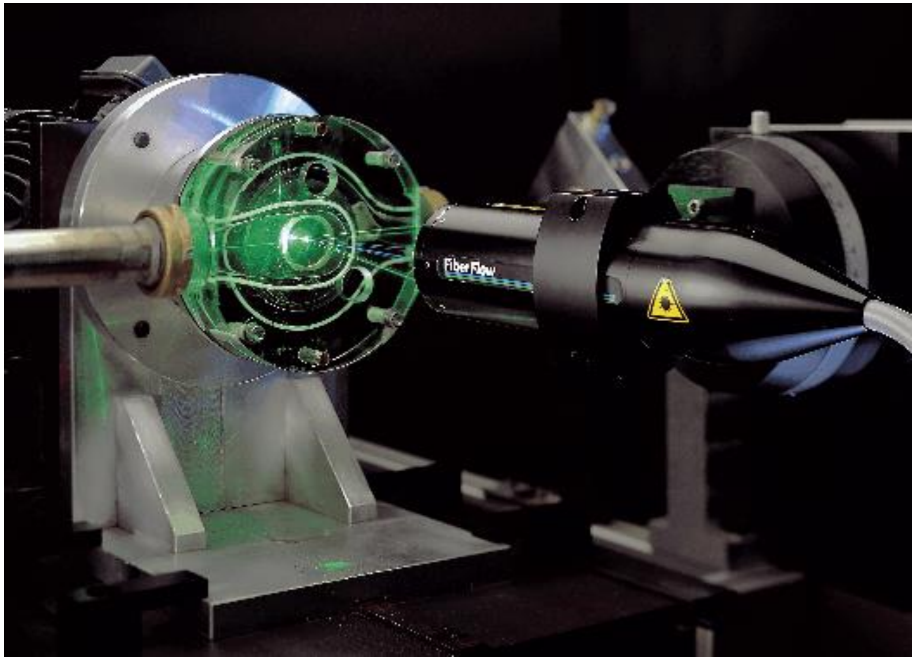
LDV optics for 3-component velocity measurement
Ref: Dantec Dynamics website

- To measure two velocity components, two extra beams can be added to the optics in a plane perpendicular to the first beams.
- All three velocity components can be measured by two separate probes measuring two and one components, with all the beams intersecting in the MV.
- Different wavelengths are used to separate the measured components.

Application examples:

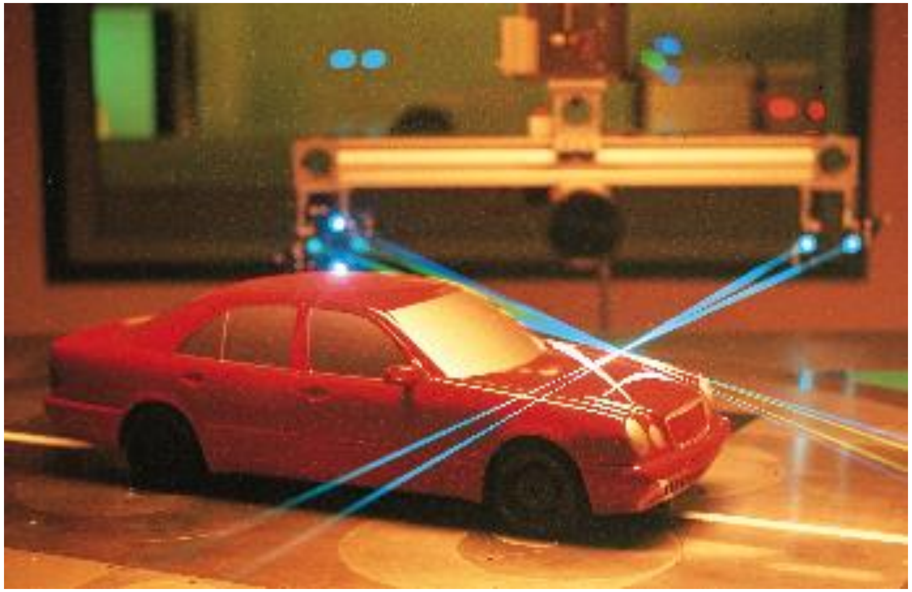


Measurement of air flow around a helicopter rotor model in a wind tunnel
Photo courtesy of University of Bristol, UK
Image from Dantec Dynamics website

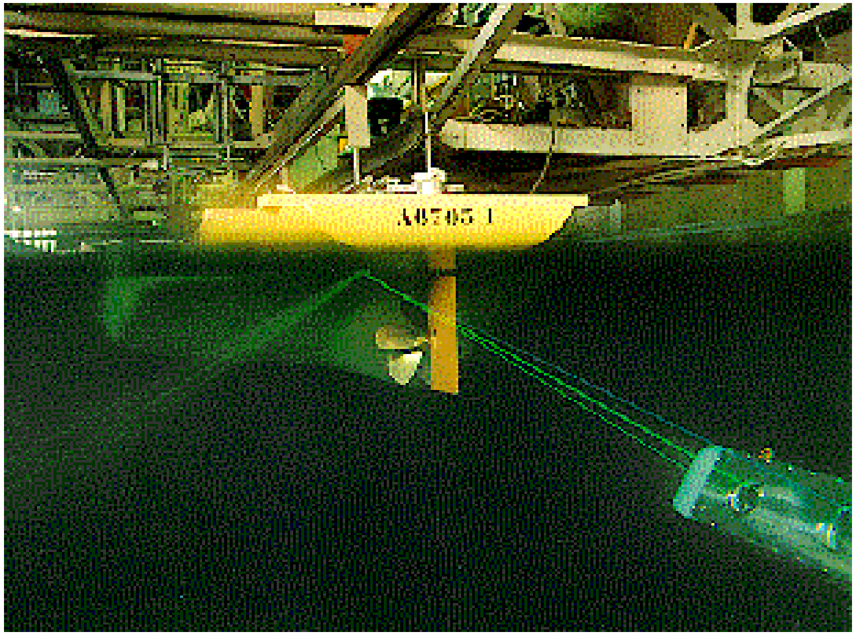


Measurement of water flow inside a pump model
Photo courtesy of Grundfos A/S, DK
Image from Dantec Dynamics website

Application examples:

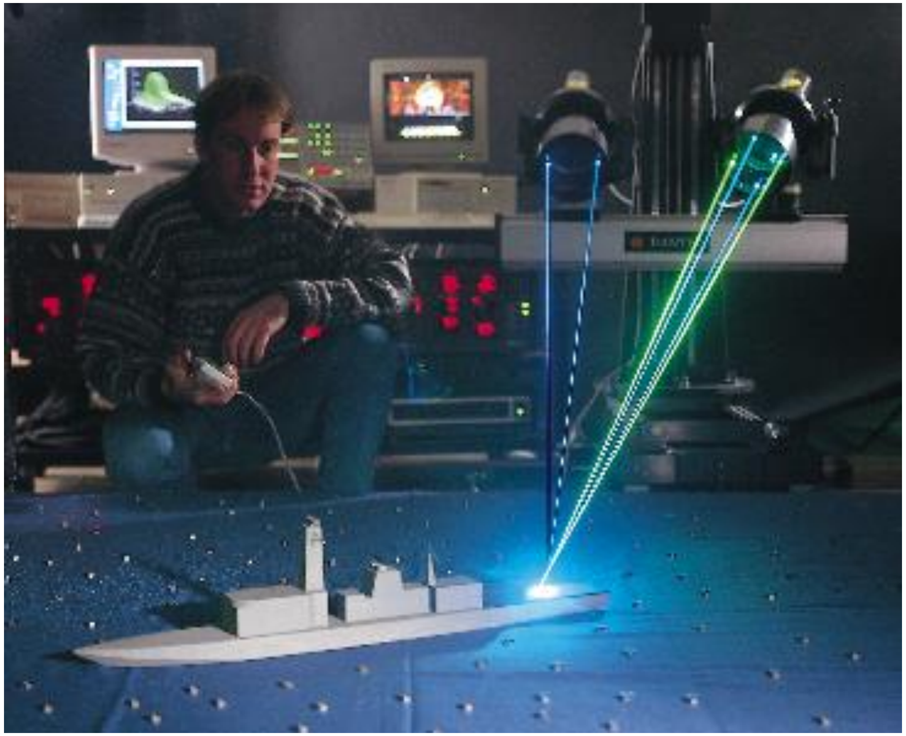


Measurement of flow field around a 1:5 scale car model in a wind tunnel
Photo courtesy of Mercedes-Benz, Germany
Image from Dantec Dynamics website

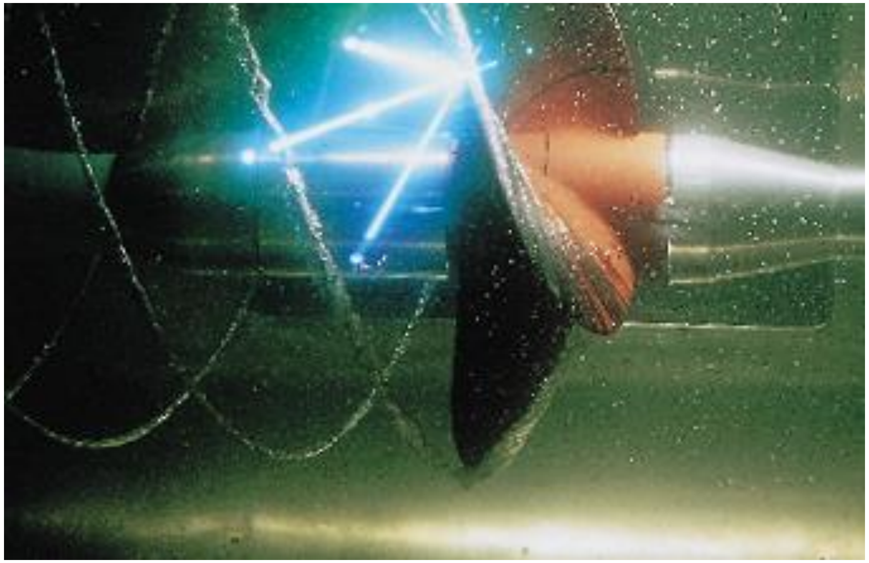


Measurement of wake flow around a ship model in a towing tank
Photo courtesy of Marin, the Netherlands
Image from Dantec Dynamics website

Application examples:



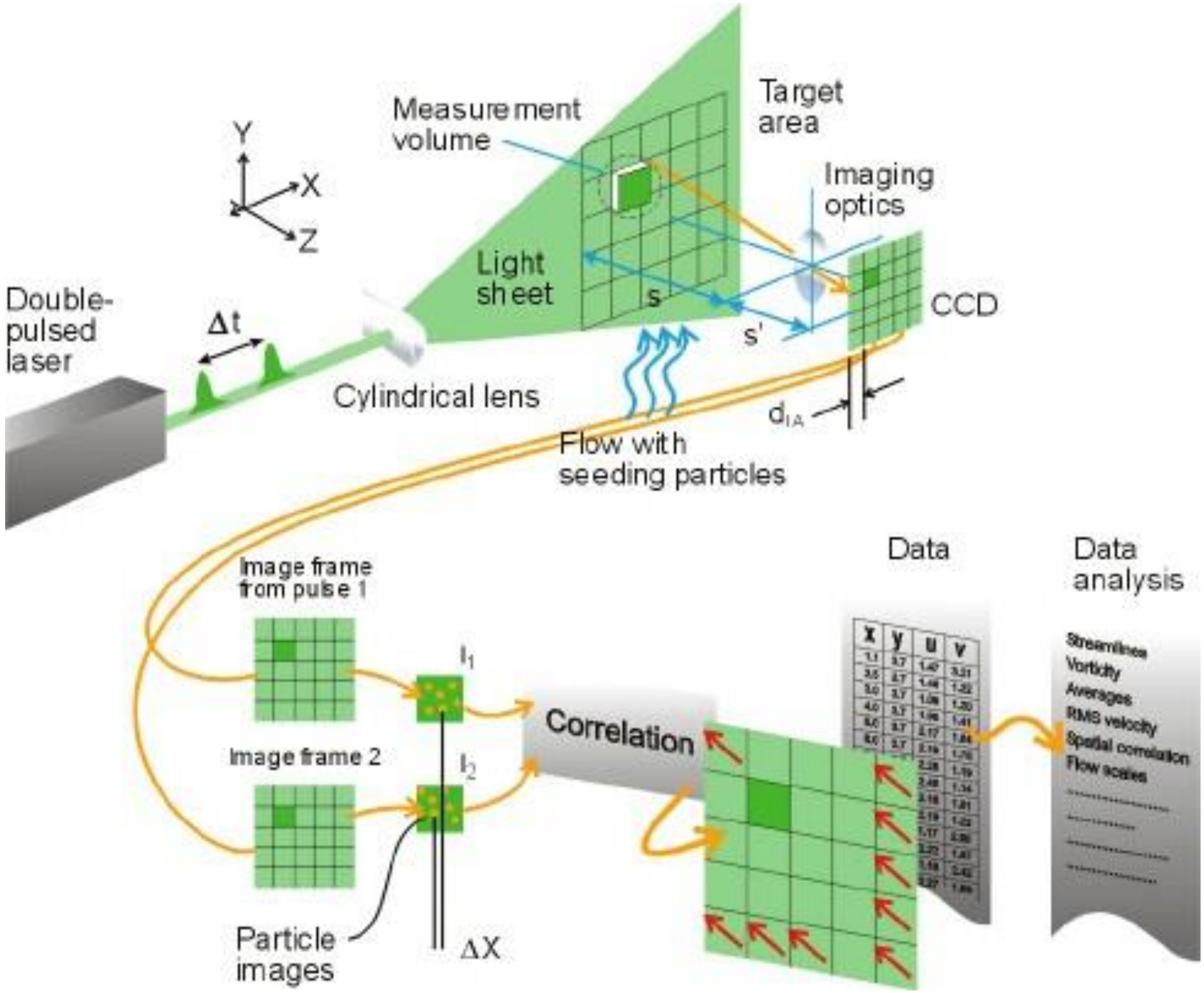
Measurement of air flow field around a ship model in a wind tunnel
Photo courtesy of University of Bristol, UK
Image from Dantec Dynamics website



Measurement of flow around a ship propeller in a cavitation tank
Photo courtesy of Marin, the Netherlands
Image from Dantec Dynamics website

Particle Image Velocimetry (PIV)

Particle Image Velocimetry (PIV)



Instruments required (for Planar PIV):

- Double pulsed laser
- Optical lenses (for making sheet)
- PIV camera
- Neutrally buoyant tracer particles
- Image processing software

Features:

- Non intrusive, planar (or volumetric) technique
- Velocity range: zero to supersonic
- Two (or three) velocity components obtained simultaneously
- Snapshots of flow-fields

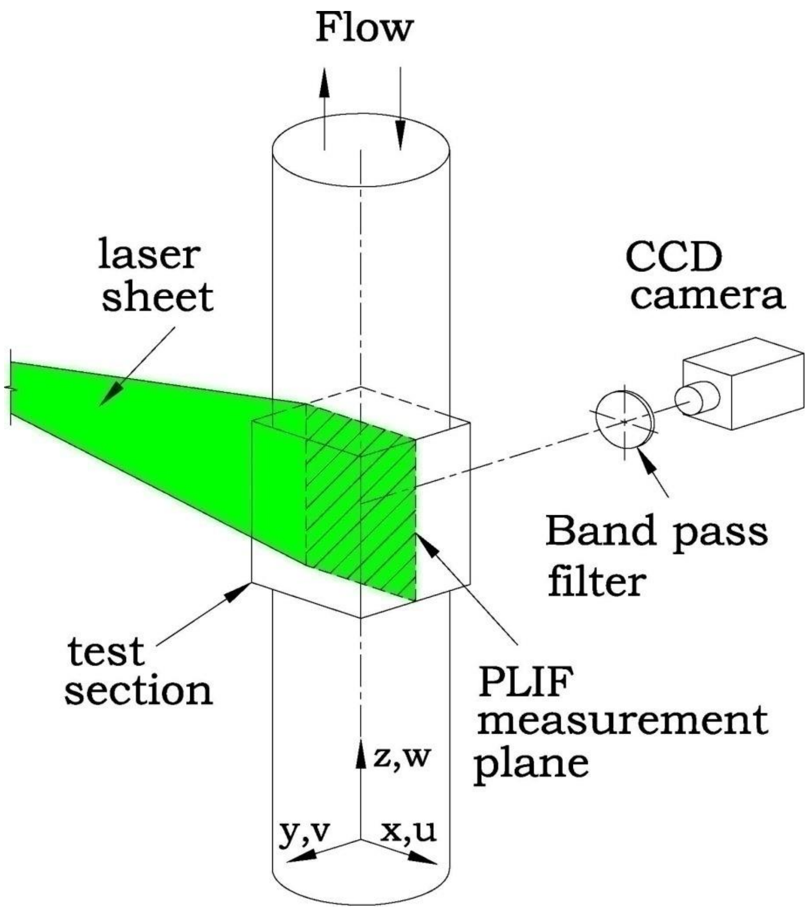
-Usually 10 Hz data rate. Time resolved PIV – use high speed lasers. Low speed flow, can use continuous wave laser.

Limitations:

- Optically accessible test section
- Both large and small scales of the flow can not be resolved simultaneously

Planar Laser Induced Fluorescence (PLIF)

- One of the mixing fluids is seeded with the fluorescent dye (passive tracer)
- Dye is excited by planar laser sheet
- Part of the absorbed energy is emitted spontaneously in the form of fluorescence by the dye
- emitted signal is captured by a CCD camera



Experimental setup

Instruments required for PLIF:
- Continuous wave/pulsed laser
- Optical lenses (for making sheet)
- CCD camera and a band pass filter
- Fluorescent dye

Features:
- Non-intrusive, planar visualization technique
- Quantitative measurements of concentration fields
- Spatial resolution down to single pixel

Limitations:
- Optically accessible test section
- Refractive indices of the mixing fluids must be matched to avoid loss of spatial homogeneity of light sheet (Commonly used solute pairs: Epsom salt-sugar, glycerol-potassium phosphate, isopropyl alcohol-NaCl, ethyl alcohol-NaCl)

Estimation of concentration field

Instantaneous fluorescence field collected by a CCD

$$I_f = A a_d C_d + D$$

Where, A accounts for the spatial distribution of laser intensity, quantum yield, fraction of the fluorescence collected, reference laser intensity etc. , a_d accounts for the intensity attenuation due to presence of dye,

$$a_d = \exp(-\varepsilon \int C_d ds)$$

and D is dark response of camera.

Instantaneous concentration field

To eliminate the unknown A, $C_d = C_f + C_b$

where C_f is concentration associated with the flow and C_b is background concentration. Typical values used in our experiments, C_f =0.5 ppm and C_b =0.02 ppm.

Thus, $I_f = A(a_f a_b)(C_f + C_b) + D$

where a_f and a_b correspond to attenuation due to dye in the flow and in the background respectively ($a_d = a_f a_b$).

Fluorescence due only to the background is, $B = A a_b C_b + D$

and the concentration field,

$$C_f = C_b\left[\frac{1}{a_f}\left(\frac{I_f - D}{B - D}\right) - 1\right]$$

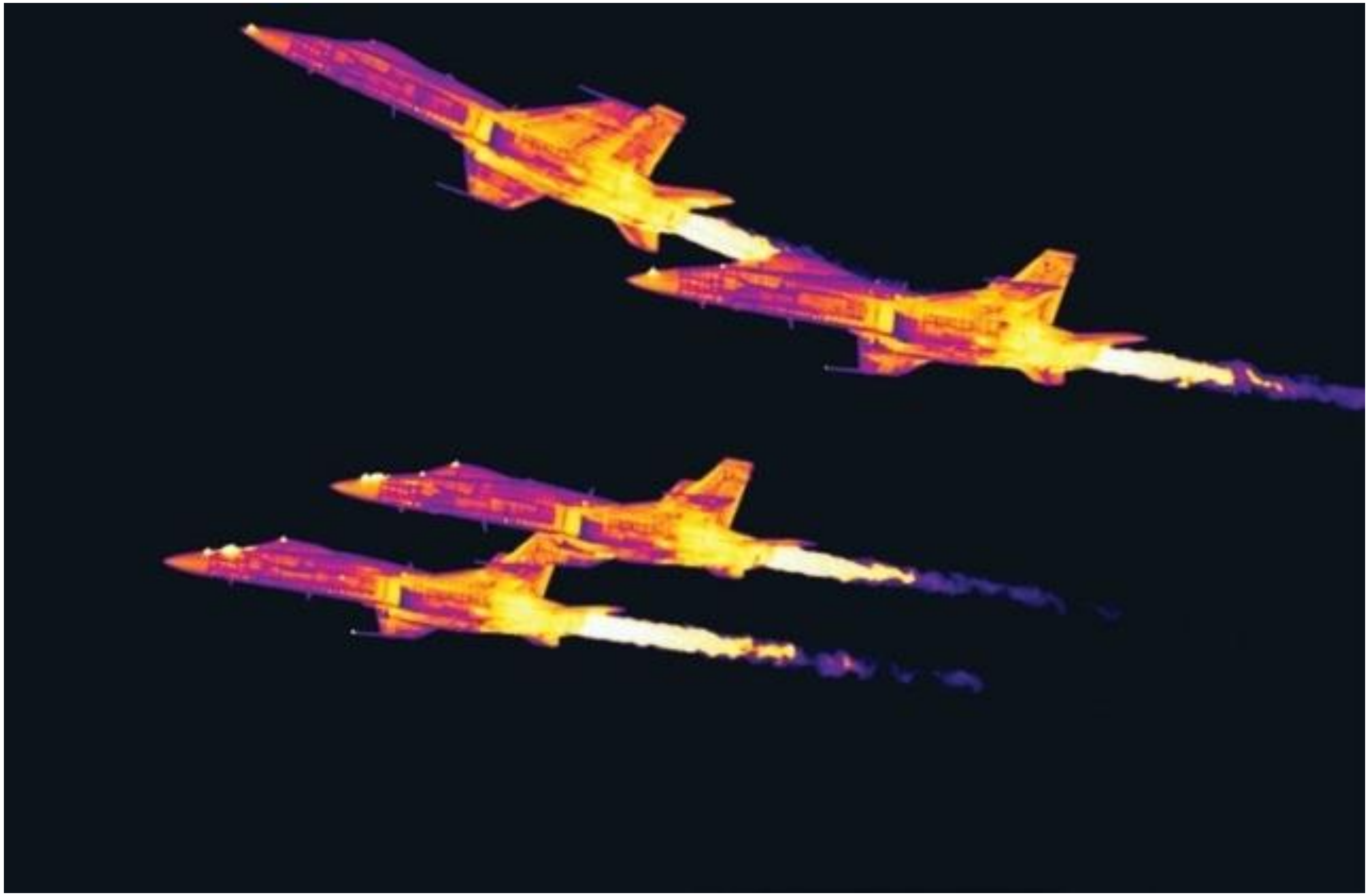
Scale of the smallest concentrations fluctuation η_B (Batchelor scale) is,

$\eta_B = \eta_K \, Sc^{-1/2}$

where $Sc = \nu/D$ and η_K is the Kolmogorov scale.

The molecular diffusivity D for fluorescent dyes ~10^{-6} cm^2/s ($Sc \sim 10^4$). The smallest concentration scales are approximately 100 times smaller than the smallest scales of motion.

THERMAL IMAGING



Stop motion image of FA-18 Hornets

* Taken from FLIR with permission

FUNCTIONING

- Detects & measures the IR radiation emitted by any object.
- **Detector** receives IR radiation – **Sensor** produces electronic signal – **Processor** converts signal into temperature – **Colour** assigned to a particular temperature – sent for **display**.
- A type of **non-contact** temperature measurement.
- Spans **area** – unlike point measurement devices like thermocouples.
- Temperature range – **(-50)^{0}C to (1400)^{0}C** – depends on the detector.
- Response time – in general a few '***ms***' – can reach a few '$\boldsymbol{\mu s}$'.
- **Corrections** – required for Background temperature & Object Emissivity

TYPES

Cooled *Quantum* type

SENSORS:
Indium Antimonide (InSb)
Indium Gallium Arsenide (InGaAs)
and more
Accuracy: $\pm$2% / 2^{0}C

Uncooled *microbolometer* type

SENSORS:
Amorphous Silicon (a-Si)
Vanadium oxide (VOx)
and more
Accuracy: $\pm$2% / 2^{0}C

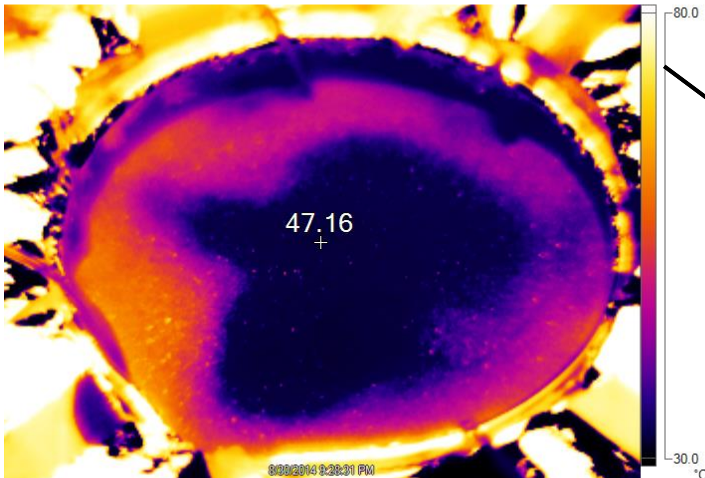
Accuracy – enhanced by using precise value of **emissivity** in the camera

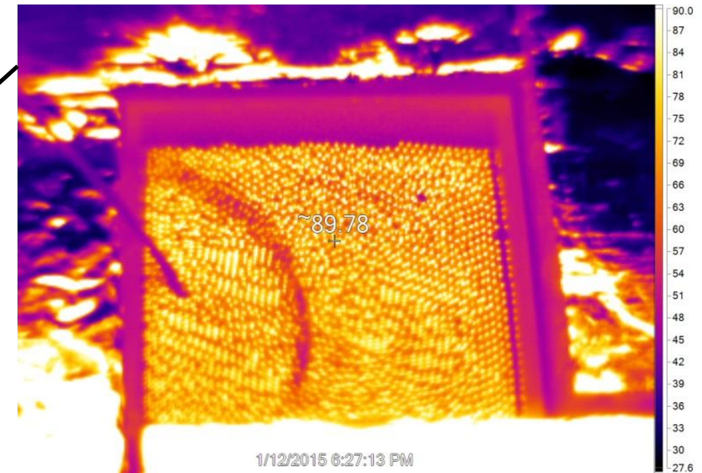
EXAMPLES – Evaporation of water from Porous Media

IR heating from above – 1000 W/m^2

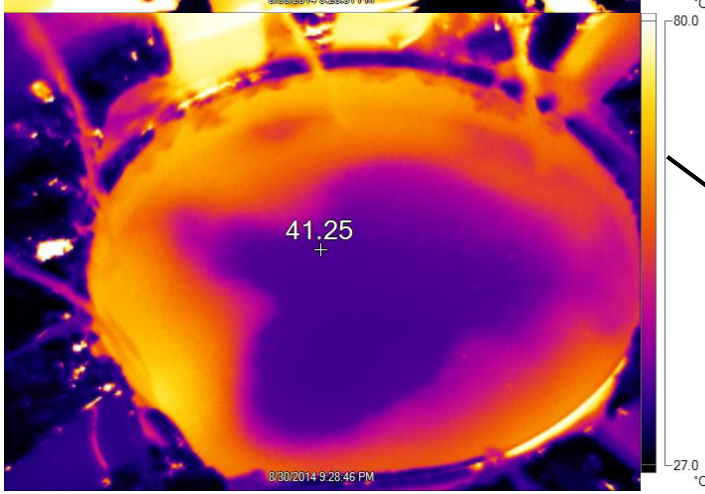
GLASS BEADS – 0.10-0.16 mm

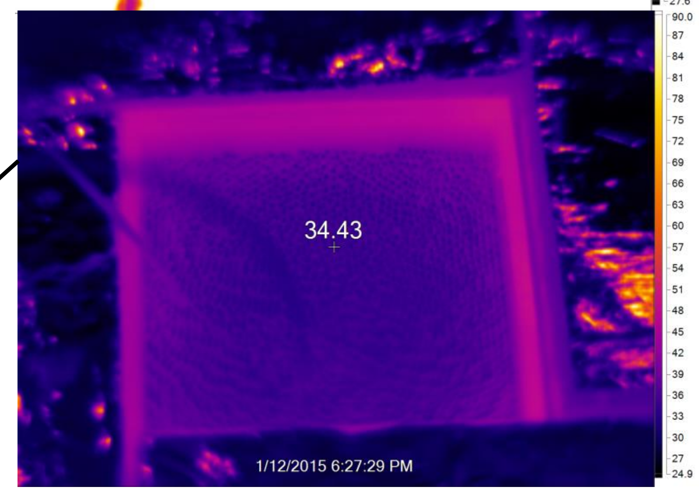
STAINLESS STEEL BALLS – 1.0 mm





NO
Shielding





With
Shielding

Change in temperature – due to Reflected radiation from the object (surface)