



A practical guide to turbulence and flow measurement by thermal anemometry (CTA), laser-Doppler anemometry (LDA) and particle-image velocimetry (PIV)

Part 3: laser-Doppler anemometry

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A PRACTICAL GUIDE TO TURBULENCE AND FLOW MEASUREMENT BY THERMAL ANEMOMETRY (CTA), LASER-DOPPLER ANEMOMETRY (LDA) AND PARTICLE-IMAGE VELOCIMETRY (PIV)

Part 3: laser-Doppler anemometry

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Part 3: laser-Doppler anemometry

1. INTRODUCTION

The determination of flow conditions in terms of velocity and turbulence plays an important role in many experimental investigations. Various techniques can be used to measure these parameters and Reference 1 should be consulted before the decision is made to perform flow measurements using laser-Doppler anemometry (LDA). Laser anemometers² are non-contact optical instruments used for the investigation of fluid flow at a point in gases and liquids. These instruments owe their existence to the invention of the gas laser in the early sixties. Some earlier attempts to measure fluid velocities by optical methods had been made, but it was not until the advent of laser light with its unique properties of spatial and temporal coherence that it became possible to design an efficient optical anemometer.

Laser anemometers offer unique advantages in comparison with other fluid-flow instrumentation:

- Non-contact optical measurement

Laser anemometers probe the flow with focused laser beams and can sense the velocity without disturbing the flow in the measuring volume. The only necessary conditions are a transparent medium with a suitable concentration of tracer particles (or seeding) and optical access to the flow, usually through windows, or *via* a submerged optical probe*. However, a flat window in a curved wall can produce unwanted effects and difficulties also arise if measurements close to the surface are required.

- Little or no calibration - no drift

The laser anemometer response to fluid velocity is absolutely linear because the measurement is based on the stability and linearity of optical electromagnetic waves, which, for most practical purposes, can be considered unaffected by other physical parameters such as temperature and pressure. Optical distortion (*e.g.* due to windows) may require correction.

- Well-defined directional response

The quantity measured by the laser Doppler method is the projection of the velocity vector on the measuring direction defined by the optical system (a true cosine response). The angular response is thus unambiguously defined.

- High spatial and temporal resolution

The optics of the laser anemometer can define a very small measuring volume, thus providing good spatial resolution and allowing precise measurement of local velocity. The small measuring volume, in combination with fast signal processing electronics, also permits high bandwidth, time-resolved measurements of fluctuating velocities, providing excellent temporal resolution. Usually the temporal resolution is limited by the concentration of seeding rather than the measuring equipment itself.

* In the case of a submerged probe there will be some disturbance to the flow but, since the measurement takes place some distance away from the probe itself, this disturbance can normally be ignored.

- Multi-component bi-directional measurements.

Laser anemometer systems, with component separation based on colour, polarization or frequency shift, allow one-, two- or three-component LDA systems to be assembled using common optical modules. Acousto-optical frequency-shift Bragg cells allow measurement of reversing flow velocities.

The combination of these advantages makes the LDA an attractive tool for many flow measurement applications, which, until the advent of this technique, were not easily addressed using invasive hot-wire anemometry systems or pitot tubes.

2. NOTATION

C	calibration constant
c	speed of light
$\vec{c}$	velocity vector of laser light
D_L	diameter of laser beam before colimation
D_w	waist diameter of focussed laser beam
d_p	seeding particle diameter
E	beam expansion factor
e	exponential constant (= 2.71828)
F	focal length of collimating lens
f	laser light frequency
f_b	beat frequency from intersecting laser beams (Doppler shift model)
f_i	frequency of illumination of particle passing through measurement volume (fringe model). Note: $f_i = f_b$
f_0	frequency shift in laser light produced by Bragg cell
f_1	Doppler shifted frequency of particle-scattered light from first laser beam
f_2	Doppler shifted frequency of particle-scattered light from second laser beam
I	Gaussian distributed intensity in laser beam
I_0	maximum intensity in laser beam
$\vec{n}_1$	unit vector normal to first laser beam

$\vec{n}_2$	unit vector normal to second laser beam
$\vec{u}$	velocity vector in measurement volume
u_x	modulus of $\vec{u}_x$
$\vec{u}_x$	component of $\vec{u}$ in x direction
$\vec{u}_y$	component of $\vec{u}$ in y direction
$\vec{u}_z$	component of $\vec{u}$ in z direction
x	coordinate axis
y	coordinate axis
z	coordinate axis
δ_x	length of probe volume in the direction of the x axis
δ_y	length of probe volume in the direction of the y axis
δ_z	length of probe volume in the direction of the z axis
θ	semi angle between laser beam pair
λ	wavelength of laser light

3. BASIC PRINCIPLES OF OPERATION

3.1 The Doppler effect

When particles suspended in a fluid are illuminated with a laser beam, the frequency of light scattered from the particles differs from that of the incident beam. This difference in frequency, called the Doppler shift, is linearly proportional to the particle velocity. This is the basis on which the LDA operates.

Although the change in frequency of a light beam is of concern, relativistic effects are negligible when the particle velocity is small compared with the velocity of light³ and classical Doppler analysis can be used, giving the shifted frequency of the light scattered by the particle (Fig 3.1) as:

$$f_1 = f \left(1 - \frac{\vec{u} \cdot \vec{n}_1}{|\vec{c}|} \right), \quad (3.1)$$

where f is the basic frequency of the laser light.

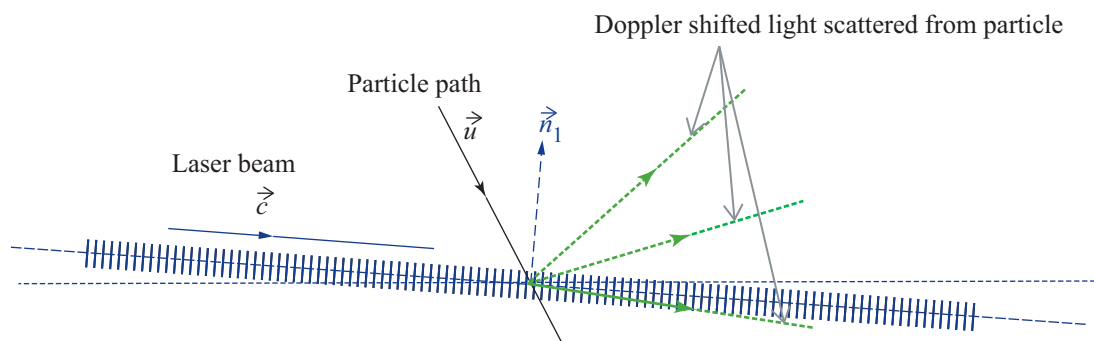


FIGURE 3.1 Doppler shift

This change in frequency cannot be used directly because it occurs irrespective of the position at which the particle crosses the beam, so that spatial resolution is extremely poor in the direction of the beam and will be determined by the characteristics of the receiving optics.

In an LDA this is overcome by using two laser beams focused to a point (Figure 3.2). The incident light from both beams is scattered in all directions but is Doppler shifted by equal and opposite amounts. This arrangement is sometimes referred to as Differential Doppler mode. Light that is scattered simultaneously from both sources (i.e. scattered from a particle passing through the intersection region of the two beams) has a heterodyned (mixed) waveform containing a beat frequency that is directly proportional to the velocity component of the seeding particles perpendicular to the bisector defined by the intersecting laser beams.

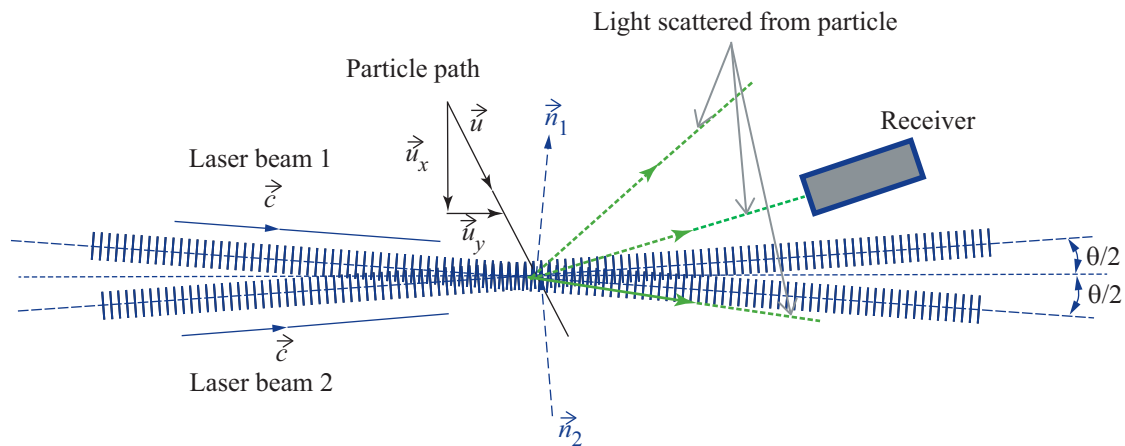


FIGURE 3.2 Differential Doppler mode

Thus, light from beam 2 (Figure 3.2) that is scattered by the particle has a frequency:

$$f_2 = f \left(1 + \frac{\vec{u} \cdot \vec{n}_1}{|\vec{c}|} \right). \quad (3.2)$$

Note that, because $\vec{n}_2$ is drawn in reverse direction to $\vec{n}_1$ (Figure 3.1), the sign here is positive.

Scattered light from a particle passing through the small volume at the intersection of the beams has a waveform that is a combination of f_1 and f_2 . Because these frequencies are close, this results in a frequency,

f , that corresponds to the colour of the laser beam pair, modulated by a beat frequency, $f_b = \frac{f_2 - f_1}{2}$, i.e.:

$$f_b = f \frac{\vec{u} \cdot (\vec{n}_2 - \vec{n}_1)}{|\vec{c}|} = f \frac{u_x}{|\vec{c}|} 2 \sin(\theta/2) = 2 \frac{u_x}{\lambda} \sin(\theta/2). \quad (3.3)$$

It is common practice to refer to f_b as the Doppler frequency of the LDA signal and this terminology is used in this document.

3.2 The Fringe Model

The Doppler-effect model is relatively complex to explain and is commonly replaced by the fringe model to explain the process at the intersection of the laser beams in an LDA. Because the fringe model is easier to visualize it will be largely used in this document.

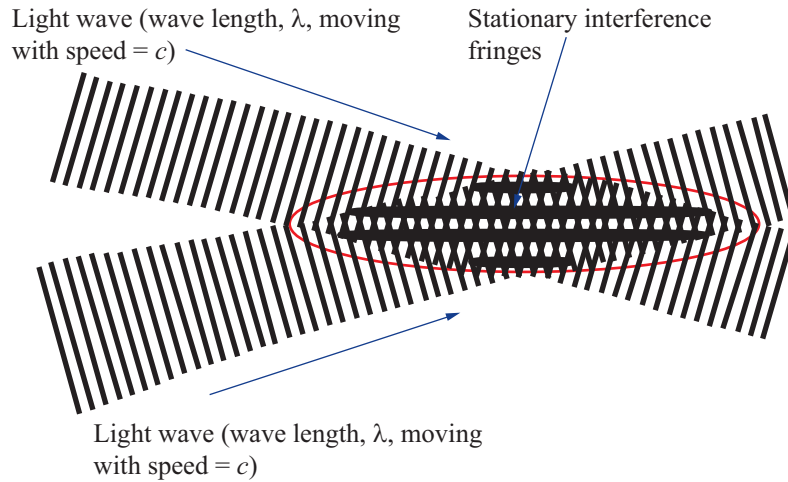


FIGURE 3.3 Interference between laser beams (Fringe model)

Interference between the beams produces a set of stationary dark fringes (Figure 3.3) and a particle passing through the beam-intersection region is illuminated only in the regions between these fringes. The intensity of illumination will therefore vary with a frequency that is proportional to the component of the particle velocity, u_x .

The distance between the interference bands is given, by simple geometric calculation, as:

$$\delta_1 = \frac{\lambda}{2 \sin(\theta/2) v} \quad (3.4)$$

The illumination intensity therefore has a frequency,

$$f_i = \frac{u_x}{\delta_1}, \quad (3.5)$$

which is exactly the same as the beat frequency, f_b , given by the Doppler analysis (Section 3.1). Thus

$$u_x = \delta_1 f_i = \frac{\lambda}{2 \sin(\theta/2) v} f_i = C f_i = C f_b, \quad (3.6)$$

where $C \left(= \frac{\lambda}{2 \sin(\theta/2) v} \right)$ is called the “Calibration factor”.

Although the fringe model, in which the signal is regarded as a variation in illumination intensity, is adequate for most practical purposes, it implies that the only frequency reaching the detector is $f_i (= f_b)$. However, the higher frequency, f , (Section 3.1) corresponding to the colour of the laser-beam pair is also present, thus allowing colour separation by the receiving optics where beam pairs of different colours are used for two and three component measurements (Section 7).

3.3 Directional Ambiguity (Inability to Distinguish Forward and Reverse Movement)

If the blue particle and red particles, shown in Figure 3.4, are moving at the same speed then the frequency of the Doppler signal will be identical.

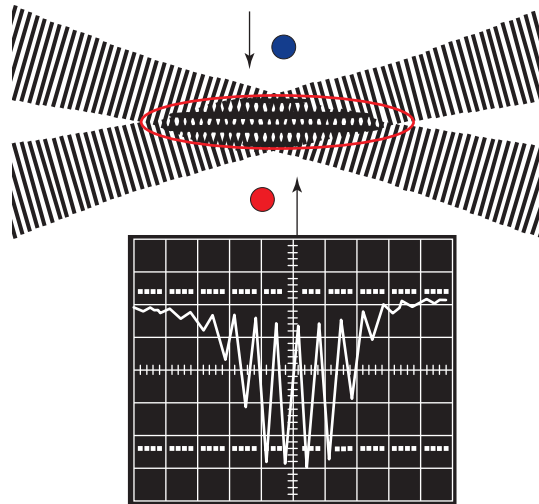


FIGURE 3.4 Directional ambiguity

Because the modulated wave is independent of direction, the receiver cannot distinguish between the motions of the two particles and thus there is a directional ambiguity in the measured velocities. Directional ambiguity is resolved by applying a suitable bias to the signal. This is achieved by changing the frequency of one of the two laser beams by f_0 , which effectively results in a velocity shift of

$$\Delta u_x = C f_0. \quad (3.7)$$

In the fringe model this corresponds to the replacement of the stationary interference fringe system (Figure 3.3) with one moving with velocity Δu_x normal to the bisector of the two laser beams. This frequency shift is produced by a Bragg cell (Sections 4 and 9).

4. SYSTEM COMPONENTS

Figure 4.1 is a schematic diagram of a fibre-optic backscatter system, which is the most common type of Laser-Doppler Anemometer.

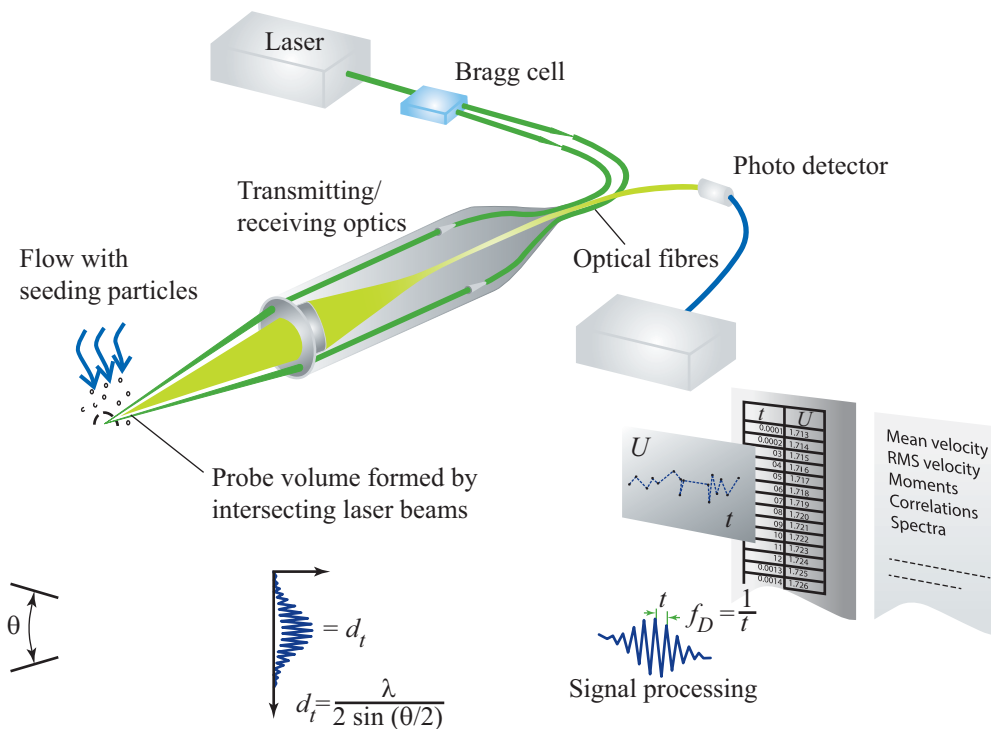


FIGURE 4.1 Components of a typical LDA system (fibre optic backscatter)

The laser produces a single beam, which is split into two by the Bragg cell, which also causes the frequency shift, in one beam, that is needed to resolve directional ambiguity (Section 3.3)*. These two beams are then transmitted, *via* optical fibres, to the combined transmitting/receiving optical unit, which focusses them onto a small volume in the flow (the probe volume). Light scattered back from seeding particles, deliberately introduced into the flow, is collected by the receiver optics and directed *via* another optical fibre to the photo detector, which then supplies an electrical signal to the signal processing unit that analyses the signal to produce particle velocity data.

Many variations on this layout are found in practice. Optical components may be aligned for direct transmission of light, rather than using optical fibres. A beam splitter may be used instead of, or in combination with, the Bragg cell (Section 9). Transmitting and receiving optics may be split into separate units and aligned in different ways to facilitate the detection of forward-scattered, back-scattered or off-axis scattered light, depending on experimental requirements.

* When flow reversal (and hence directional ambiguity) is not an issue, the Bragg cell can be replaced by a simple beam splitter.

5. THE PROBE VOLUME

The spatial resolution of the LDA is determined by the characteristics of the intersection region of the two laser beams, since it is only when a seeding particle passes through this volume (referred to as the probe volume) that a valid signal is produced. The measurement volume depends on how much of the probe volume can be seen by the receiving optics and is less than the probe volume if the receiver is not directly normal to the fringes produced by the two laser beams, *i.e.* in forward or backscatter mode (Section 6), The measurement volume is discussed further in Section 6.2.4.

The probe volume depends solely on the transmitting optics and the characteristics of the two laser beams (Figure 3.3).

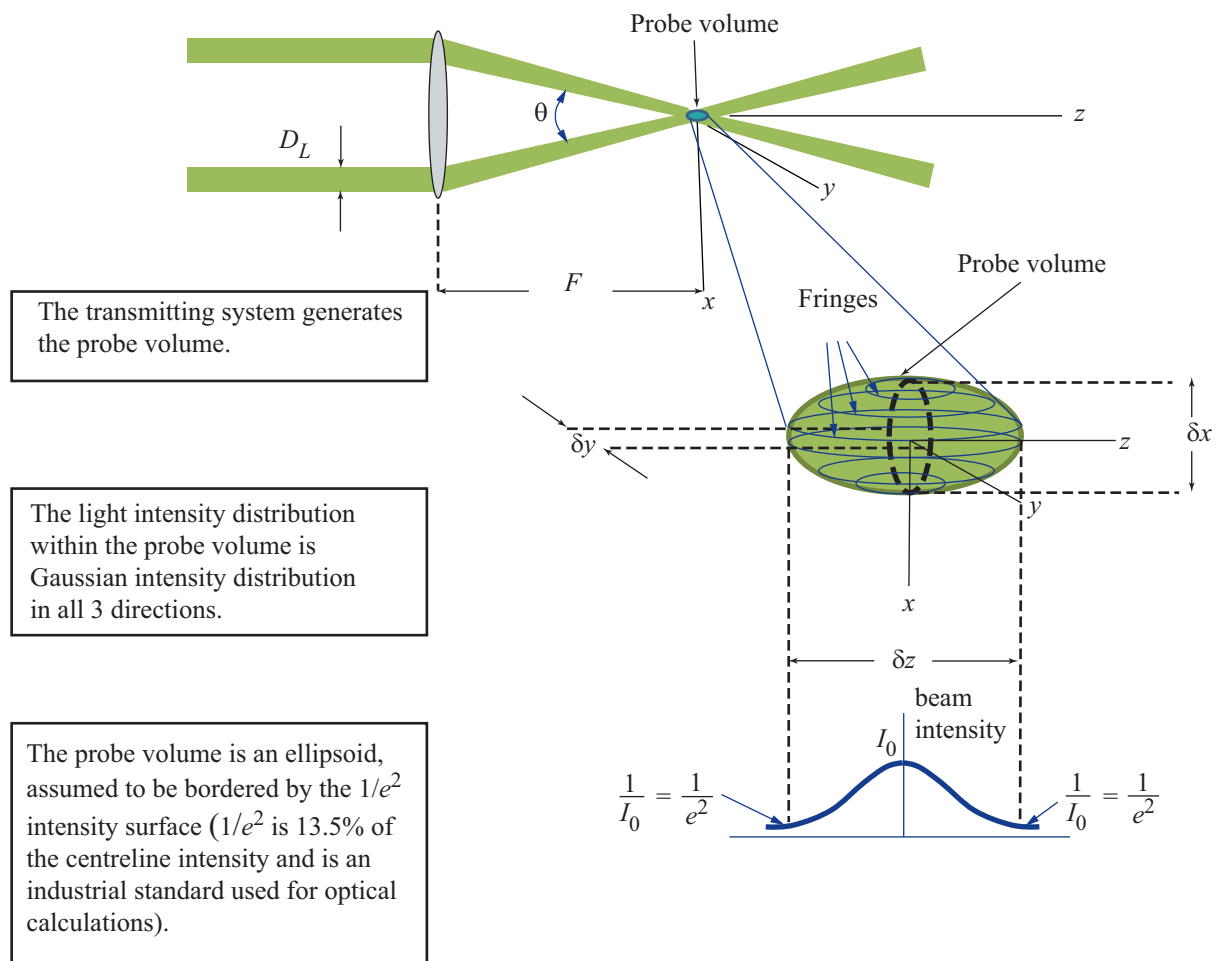


FIGURE 5.1 Generation of the probe volume

The beams are focused at the centre of the probe volume. Each beam is assumed to have Gaussian intensity distribution and its local radius is taken as the radius at which the intensity, I , has fallen to $1/e^2$ (*i.e.* 0.1353) times the centre-line value, I_0 . The minimum diameter, called the waist diameter, D_w , to which each of the crossing beams can be focused, is located at the centre of the probe volume and is limited by diffraction effects. The theoretical value, for beams with a perfect Gaussian intensity distribution, is:

$$D_w = \frac{4F\lambda}{\pi D_L} \quad (5.1)$$

The size of the probe volume is directly related to D_w . Only limited control is afforded by choice of F or λ because F is constrained by the physical requirements of system geometry and λ by the laser used. However, it can be seen from Equation (5.1) that D_w can be reduced by increasing the collimated beam diameter from D_L (Figure 5.1) to ED_L before it enters the focussing lens. This is achieved using an optical device, known as a beam expander. This is a combination of lenses in front of, or replacing, the front lens of a conventional LDA system. It converts the beams exiting the optical system to beams of greater diameter. At the same time the spacing between the two laser beams is increased, since the beam expander also increases the aperture. Provided the focal length, F , remains unchanged, the larger beam spacing will thus increase the angle between the two beams and reduce the size of the measuring volume. Because the beam expander reduces D_w light intensity on the scattering particles is increased. Also the greater receiver aperture is able to pick up more of the scattered light.

The benefits of the beam expander are therefore:

- A reduction in the size of the measuring volume at a given measuring distance.
- Either an improved signal-to-noise ratio at a given measuring distance, or a greater measuring distances at a given signal-to-noise ratio.

The dimensions of the probe volume, bounded by the $\frac{1}{e^2}$ surface defined in Figure 5.1, are given by:

$$\delta x = \frac{4F\lambda}{\pi ED_L \cos(\theta/2)}, \quad (5.2)$$

$$\delta y = \frac{4F\lambda}{\pi ED_L}, \quad (5.3)$$

and

$$\delta z = \frac{4F\lambda}{\pi ED_L \sin(\theta/2)}. \quad (5.4)$$

The fringe separation, δ_f , in the x direction (*i.e.* the direction of the measured velocity component), which is independent of E , is :

$$\delta_f = \frac{\lambda}{2 \sin(\theta/2)} \quad (5.5)$$

and the number of fringes, N_f is given by:

$$N_f = \frac{4F\lambda}{\pi ED_L \sin(\theta/2)}. \quad (5.6)$$

In practice system imperfections will make D_w slightly larger than the theoretical minimum given by Equation (5.1), but this is ignored here.

The dimensions of a typical probe volume are $\delta_z = 1 \text{ mm}$, $\delta x = \delta y = 50 \mu\text{m}$.