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DESIGN CONSIDERATIONS FOR A 3D FIBRE OPTIC LASER DOPPLER VELOCIMETER FOR TURBOMACHINERY APPLICATIONS

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ABSTRACT

Single headed 3D Laser Doppler Velocimetry (LDV) geometries generally rely upon the use of 3 Doppler difference channels, inclined at differing angles with respect to the mechanical axes of the probe. The transformation between the non-orthogonal measurement co-ordinate system and the Cartesian system can result in large errors in the calculated velocities. A theoretical analysis of the geometrically induced uncertainties in measurements produced by four single headed 3D LDV configurations is presented. These considerations have lead to the development of a single headed fibre optic 3D LDV probe based around the use of two Doppler difference channels to directly measure the transverse velocity channels, and a reference beam channel to measure the on axis velocity component. The f/4 probe head has a working distance of 200 mm, designed to operate within the constraints of the limited optical access available in turbomachinery applications.

I. INTRODUCTION

Full characterisation of the complex, time varying 3 dimensional (3D) flows encountered in engineering systems such as turbomachinery has long been the goal of research in flow measurement instrumentation. Laser Doppler velocimetry (LDV) is capable of producing high quality, high spatial resolution data from a wide range of flow systems. The demands for improved fuel efficiency, reduced emissions, and the requirement for high quality data to allow validation of increasingly complex computational fluid dynamic codes is driving the development of new, simultaneous 3D laser velocimetry configurations.

3D flow characterisation requires the presence of 3 LDV channels in the flow, distinguished using wavelength, time or frequency bias. Ideally the channels directly measure the three orthogonal velocity components. In general, however, the optical access to the flow is limited, such that the measurements have to be made with the 3 channels being inclined at an angle with respect to the Cartesian co-ordinate system. The transformation between the non-orthogonal measurement system and the Cartesian system is sensitive to uncertainties in the angular configuration of the channels, resulting in large errors in the calculated velocity components.

A number of 3D LDV configurations using Doppler difference channels have been demonstrated, all of which show significant limitations when considered in the context of the limited optical access available in turbomachinery applications. In this paper the development of a single headed, fibre optic based, 3D laser Doppler velocimeter is discussed. The probe uses two Doppler difference channels to measure the transverse velocity components, and a reference beam channel to measure the on axis velocity component. It is shown that the use of optical fibres is essential to the operation of the probe.

II. 3D LASER DOPPLER VELOCIMETRY

A number of LDV configurations have been reported, and commercial instrumentation developed, all based upon the measurement of the Doppler frequency shift imposed on light scattered from particles entrained within the flow. The Doppler shift is uniquely determined by the wavelength of the illuminating light, the orientation of the viewing direction with respect to the incident beam, and upon the velocity component perpendicular to the bisector of the illuminating and viewing directions. Measurement of the frequency shift may be achieved in a number of ways; heterodyning the scattered light with a local oscillator derived from the illuminating beam, as in the reference beam anemometer[1] , mixing the light scattered from two illuminating beams, as in the Doppler difference, technique[2,3], using an atomic or molecular line filter to transduce the frequency shift into a change in intensity[4], or measured directly on a Fabry-Pérot interferometer[5].

The reference beam LDV configuration, shown in figure 1(a), was the first to be developed. Scattered light collected from the flow is mixed with a reference beam on a detector, yielding a beat signal at the Doppler frequency. The measured frequency shift is given by the expression

$$\nu_D = \frac{2}{\lambda}\cos\left(\frac{\theta}{2}\right)V\cos(\beta\ ) \qquad \textbf{(1)}$$

where υ_D is the measured Doppler frequency, λ the wavelength, V the velocity and θ angle between the illumination and collection directions. The velocity component measured is parallel to the bisector of the illumination and collection directions. When working in backscatter this allows measurement of the on-axis velocity component. While this configuration has been used to measure flow velocities in real engineering applications, and formed the basis of the first 3D LDV configuration[6], it suffers from a number of practical limitations, including the dependence of the measured frequency shift upon the viewing direction, poor signal to noise characteristics due to mismatch in the ratio of signal to reference beam powers, the stringent alignment conditions required to achieve efficient heterodyning which demand alignment of signal and reference beams to better than a few minutes of arc, and a limited collection aperture due to coherence considerations and broadening of the Doppler frequency spectrum. The reference beam system has a very long measurement volume, limiting the spatial resolution, complicating near wall measurements. When working in direct backscatter the Doppler shift measured in the reference beam method is twice the velocity divided by the wavelength, placing a limit of around 40m/s on the maximum velocity which may be measured using illumination at 800 nm and a 100 MHz signal processing unit.

The development of the Doppler difference method, shown in figure 1(b), in which the frequency shift is independent of viewing direction and is dependent only upon the geometry of the illuminating beams, lead to reference beam systems being largely abandoned. In the Doppler difference technique two mutually coherent beams are crossed in the flow to create an interference pattern. The scattered light is amplitude modulated at a frequency given by the ratio of the velocity to the fringe spacing.

$$\nu_D = \frac{2}{\lambda}\sin\left(\frac{\theta}{2}\right)V\cos(\beta) \qquad (2)$$

The velocity component measured is perpendicular to the bisector of the illuminating beams, i.e. the transverse velocity component. The Doppler difference method allowed large apertures to be used to collect the scattered light, and alignment and beam ratio requirements to be relaxed, being transferred to the illumination section of the system, where they could be more easily satisfied.

A number of 3D LDA configurations have been reported[7,8], and commercial instrumentation developed. The limited optical access available in many real flow system complicates the development of 3D instrumentation. As a result, 3D LDA instrumentation generally relies upon the use of three inclined Doppler difference channels, which requires careful calibration and alignment to achieve meaningful results. A number of schemes using Doppler difference channels to directly measure the transverse velocity components and a reference beam channel to measure the on-axis velocity component have been proposed[9,10,11,12] with a number of 2D LDV configurations using a single Doppler difference channel and a reference beam channel reported, constructed using conventional optical components, and the extension to simultaneous 3D measurement discussed. To date, however, there has been no report of the operation of such a simultaneous 3D LDV instrument, which may be related to the practical difficulties encountered when implementing reference beam anemometers using conventional (bulk) optical components . The following section analyses and compares the accuracy of a number of single headed 3D LDA configurations.

III. ACCURACY CONSIDERATIONS.

A. Introduction

Extracting the 3D information from data produced by a single headed 3D LDV probe requires a matrix transformation from the non-orthogonal measurement co-ordinate system to the Cartesian system. The conventional way to analyse the performance of such an operation is to consider the conditioning of the transformation matrix[13]. The system **Ax** = **b** is said to be well conditioned if small errors in the coefficients have a small effect on the solution, and is ill-conditioned if the effect is large. The solution may be thought of in terms of the intersection of three planes. If the planes are orthogonal, then the intersection point is well defined, and small errors in the inclination of the planes have little effect upon the location of the intersection. This corresponds to being well conditioned, and the transformation matrix has a condition number of unity. However, as the relative inclination of the planes is reduced, any uncertainties in the geometry may result in large inaccuracies in the calculated intersection point, and the condition number increases. In this section the matrix conditioning of 4 single headed 3D LDA configurations are compared. The configurations are illustrated in figure 2.

The 3D micro LDV reported by Ahmed[14,15] employs three angularly separated Doppler difference channels in the geometry illustrated in figure 2(a). Its practical implementation utilised a single Doppler difference channel in the flow, rotated to three positions, separated by 120°, to perform the measurements. The 5 beam 3D LDA system (figure 2(b)) uses colour separation to multiplex the three Doppler difference measurement channels[15]. Two blue beams, derived from the output from an Ar^+ ion laser, lie in the vertical plane, forming a single Doppler difference channel, measuring the transverse, y, velocity component. In the horizontal plane the output from the centre of the lens is comprised of co-propagating violet and green beams, which form two Doppler difference channels with the violet and green beams exiting from the either side. The measurements provided by these channels contain information on the transverse, x , velocity component and the on-axis, z, velocity component. The first 3D LDA configuration reported relied upon the use of three spatially multiplexed reference beam channels using a single illuminating beam[1], as shown in figure 2(c) The original configuration operated in forward scatter, with three angularly separated receiving heads arranged symmetrically about the optical axis. The geometry could also be configured to operate in backscatter using a single probe head. The configuration illustrated in figure 2(d), which will be considered in more detail later in this paper, is being proposed by the authors to overcome some of the limitations of previously reported 3D LDA geometries. It relies upon the use of two Doppler difference channels to directly measure the transverse velocity components, and a reference beam channel to measure the on axis velocity component. The illumination beam for the reference beam channel is off-axis, with the aim of reducing the effects of flare and improving the performance of near-wall measurements.

B. Matrix Conditioning

The condition number of each of the transformation matrices was calculated as a function of the *f* number of the probe, and are compared in figure 3. In general, it is considered that condition numbers < 20 should provide adequate performance[12], which implies that all of the configurations should operate with small uncertainties in the calculated velocity components for *f* numbers <5. Typically, to allow measurements to be made along the entire length of a turbine blade, f numbers > 4 have to be employed. The 3D micro LDV and 3D reference beam configurations show very similar performance even though they predominantly measure different velocity components: the on-axis component in the case of the 3D reference beam geometry, and the transverse components in the 3D micro LDV. The condition number of the hybrid probe is consistently less that that of the other configurations. The conditioning number provides a convenient figure of merit for comparing the relative tolerances placed on the calibration and alignment of the configurations. However, this does not take into account the relative magnitudes of the velocity components being calculated, which has a significant impact upon the uncertainties in the results, as noted by Chervin[16] and Neti[17].

C. Error Analysis

Following a similar approach to that reported by Morrison[18], the errors in the measured velocities were calculated for the single headed probes as a function of the probe *f* number. The approach is outlined below.

The transformation between the non-orthogonal measurement co-ordinate system and the Cartesian system may be described by

$$\begin{pmatrix} U_1 \\ U_2 \\ U_3 \end{pmatrix} = \begin{pmatrix} a_{11}(\alpha,\gamma) & a_{12}(\alpha,\gamma) & a_{13}(\alpha,\gamma) \\ a_{21}(\alpha,\gamma) & a_{22}(\alpha,\gamma) & a_{23}(\alpha,\gamma) \\ a_{31}(\alpha,\gamma) & a_{32}(\alpha,\gamma) & a_{33}(\alpha,\gamma) \end{pmatrix} \begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} \qquad (3)$$

where the matrix coefficients $a_{ij}(\alpha,\gamma)$, where α and γ are defined in figure 2, are dependent upon the angular configuration of the probe head, U_i are the measured velocity components, and $V_{x,y,z}$ are the orthogonal velocity components. To extract the orthogonal velocity components, the inverse transform has to be calculated

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \begin{pmatrix} c_{11}(\alpha,\gamma) & c_{12}(\alpha,\gamma) & c_{13}(\alpha,\gamma) \\ c_{21}(\alpha,\gamma) & c_{22}(\alpha,\gamma) & c_{23}(\alpha,\gamma) \\ c_{31}(\alpha,\gamma) & c_{32}(\alpha,\gamma) & c_{33}(\alpha,\gamma) \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \\ U_3 \end{pmatrix} \quad (4)$$

This analysis is mainly concerned with the errors in the calculated on-axis velocity component, since 3D LDA geomtries tend to directly measure the transverse velocity components. The on-axis velocity component error may be calculated from the following expression

$$dV_z = \sqrt{\sum_{i=1}^{3}\left(\left(\frac{\partial c_{3i}(\alpha,\gamma)}{\partial\gamma} d\gamma\, U_i\right)^2 + \left(c_{3i}(\alpha,\gamma)dU_i\right)^2 + \left(\frac{\partial c_{3i}(\alpha,\gamma)}{d\alpha} d\alpha\, U_i\right)^2\right)} \quad (5)$$

Typically, for turbomachinery applications, the on axis velocity component is very much less than the transverse components. In the following discussion, the angular uncertainties in the probe head geometry, dα and dγ are assumed to be 1°, and the velocity measurement accuracy to be 1%. The graph shown in figure 4 shows a comparison between the performances of the four 3D LDA configurations outlined in the previous section, assuming that the velocity components in the Cartesian system are V_x=V_y=10 m/s, V_z=1 m/s. These values were chosen since, in general, the on-axis velocity components which will be experienced in our application will be no more than 10% of the transverse components. The errors shown in figure 4 will scale approximately linearly with the total velocity, provided that the components are in the ratio 10:10:1. The configurations based around the use of three Doppler difference channels exhibit large errors for probes with *f* numbers > 2. Typically, for turbomachinery applications, optical access and working distances dictate the use of probes with f numbers > 4. These considerations have lead to the development of a single headed probe relying upon the use of two Doppler difference channels to directly measure the transverse velocity components, and a reference beam channel to measure the on axis velocity component

IV. PROBE DESIGN

The use of optical fibres is central to the operation of the hybrid probe, easing the limitations associated with bulk optic reference beam configurations, allowing the direct measurement of the on-axis velocity component, and allowing the sensitive semiconductor laser diodes and detectors to be isolated from the flow region. Constraining the signal and reference beams to propagate through the same fibre automatically satisfies the stringent alignment conditions required to achieve optimum heterodyning. The fibres spatially filter the collected scattered radiation, producing high quality wavefronts. We have recently demonstrated a polarisation based optical configuration which allows optimisation of the signal to reference beam ratios while making optimum use of the received light, a significant consideration when using infra-red radiation[19]. The use of a direct backscatter configuration for the reference beam channel, however, produces a long measurement volume, limiting the ability to perform measurements near solid surfaces. To overcome these limitations, the off-axis configuration shown in figure 3 (d) has been developed.

Five beams illuminate the flow, forming two Doppler difference channels and a reference beam channel. the Doppler difference channels directly measure the transverse velocity components, while the off-axis illumination direction of the reference beam channel (7°) results in the measurement predominantly containing the axial component with a small contribution from the transverse components. The use of off axis illumination is aimed at reducing the effects of flare from solid surfaces, improving the performance of near wall measurements, and reducing the length of the measurement volume.

Figure 5 shows a cross section of the probe head. Light is delivered to the head by polarisation maintaining (pm) optical fibre, to ensure matched linear polarisation states for the interfering beams, and thus optimum fringe visibility. The fibre ends are terminated with GRIN lens collimators, and the beams focused into the flow by the front lens. The outer portion of the lens (f = 200 mm) collimates backscattered light, and the second lens launches this into the multi-mode fibre. The central portion of the bi-focal lens (f = 40 mm) launches scattered light into the pm fibre mode fibre to act as the signal for the reference beam channel. The specifications of the probe have been chosen to allow the probe to perform measurements on turbomachinery test are rigs, and are detailed in table 1.

V. Experimental Configuration and Results

The three measurement channels are distinguished using wavelength-division-multiplexing, implemented using three 150 mW SDL 5420 series semiconductor laser diodes operating at slightly differing wavelengths around 800 nm.

Figure 6 shows a schematic of the lay-out of the of the launch/receive unit. The output from the laser diodes are coupled into polarisation maintaining fibre. The two Doppler difference channels incorporate fibre pigtailed 40 MHz Bragg cell frequency shifters which act as 50/50 beamsplitters and allow direction discrimination. The pigtailed Bragg Cells have an insertion loss of < 2dB. The 40 MHz rf drive signal for the Bragg cells is derived from the Dantec BSA signal processor. The diffraction efficiency of the Bragg cells is controlled via a voltage applied to an rf amplifier, allowing optimisation of the intensity ratio of the beams. The reference beam channel incorporates a variable split ratio polarisation preserving directional coupler, set such that 95 % of the power is guided to the probe head, and the remaining 5% used as the reference beam. This ratio can be adjusted to optimise the signal to noise ratio.

Scattered light is delivered to the detectors via a multi-mode fibre and a polarisation preserving fibre. The output from the multimode fibre is incident upon a diffraction grating to demultiplex the Doppler difference channels' wavelengths. The two Doppler difference signals are then monitored on avalanche photodiodes. The signal for the on axis measurement is derived from the polarisation maintaining return fibre, and mixed with a frequency shifted reference beam. A band pass filter is used to remove the unwanted signals from the Doppler difference channels. The diffraction efficiency of the Bragg Cell is again voltage controlled, providing a convenient method for controlling the signal to noise ratio. The signals are analysed on three Enhanced Dantec Burst Spectrum Analysers.

Figure 7 shows 3D data obtained from a rotating disk for the three measurement channels. The measurements were performed using the relative orientation of the disc and probe head as illustrated in figure 8. The data points show the orthogonal velocity components calculated from the transformed Doppler frequency measurements. The solid lines indicate the orthogonal velocity components predicted from measurements of the angular frequency of the disc, showing good agreement with the measured data.

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Figure Captions

Figure 1(a). Reference beam laser Doppler velocimetry geometry

Figure 1(b). Doppler difference laser velocimeter configuration.

Figure 2. Single headed 3D LDV configurations. (a) 3D Micro LDV[14,15], (b) 5 Beam 3D LDV[20], (c) 3D Reference Beam LDV[6], (d) Hybrid reference beam/Doppler difference (this work).

Figure 3. Comparison of the Matrix Conditioning for the single headed 3D LDV configurations illustrated in figure 2, as a function of the probe f number.

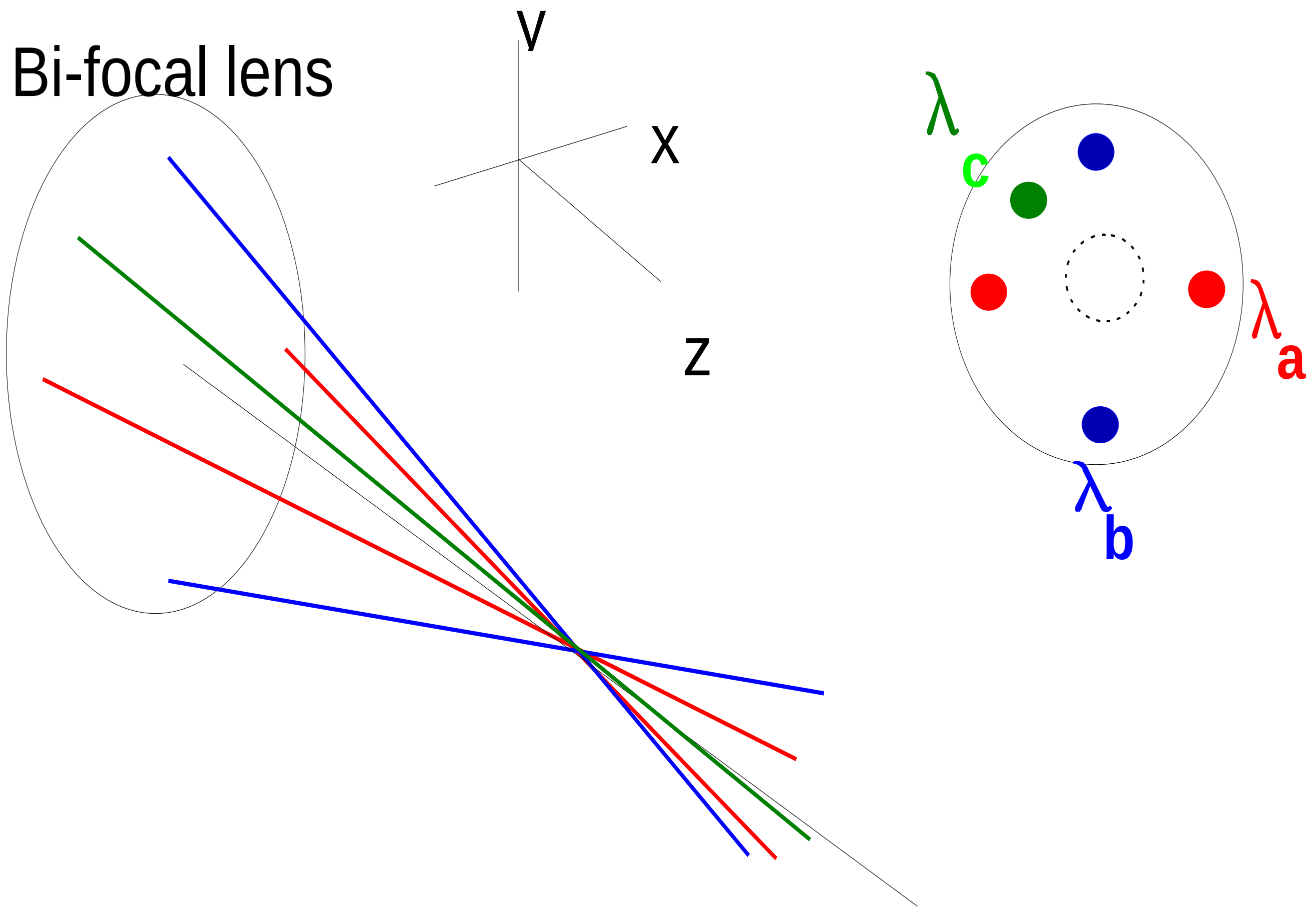
Figure 4. (a) Comparison of the errors in the measured on axis velocity component for the probe illustrated in figure 2 as a function of the probe f number. The insert shows the errors for the hybrid and 3D reference beam system on an expanded scale (b) Transverse velocity component errors. The insert shows the errors for the 3D μLDV and 5 beam configurations on an expanded scale. The errors are calculated assuming that the angular geometry of the probe is known to 1º, and that the orthogonal velocity components are V_x=V_y= 10 m/s, and V_z=1 m/s.

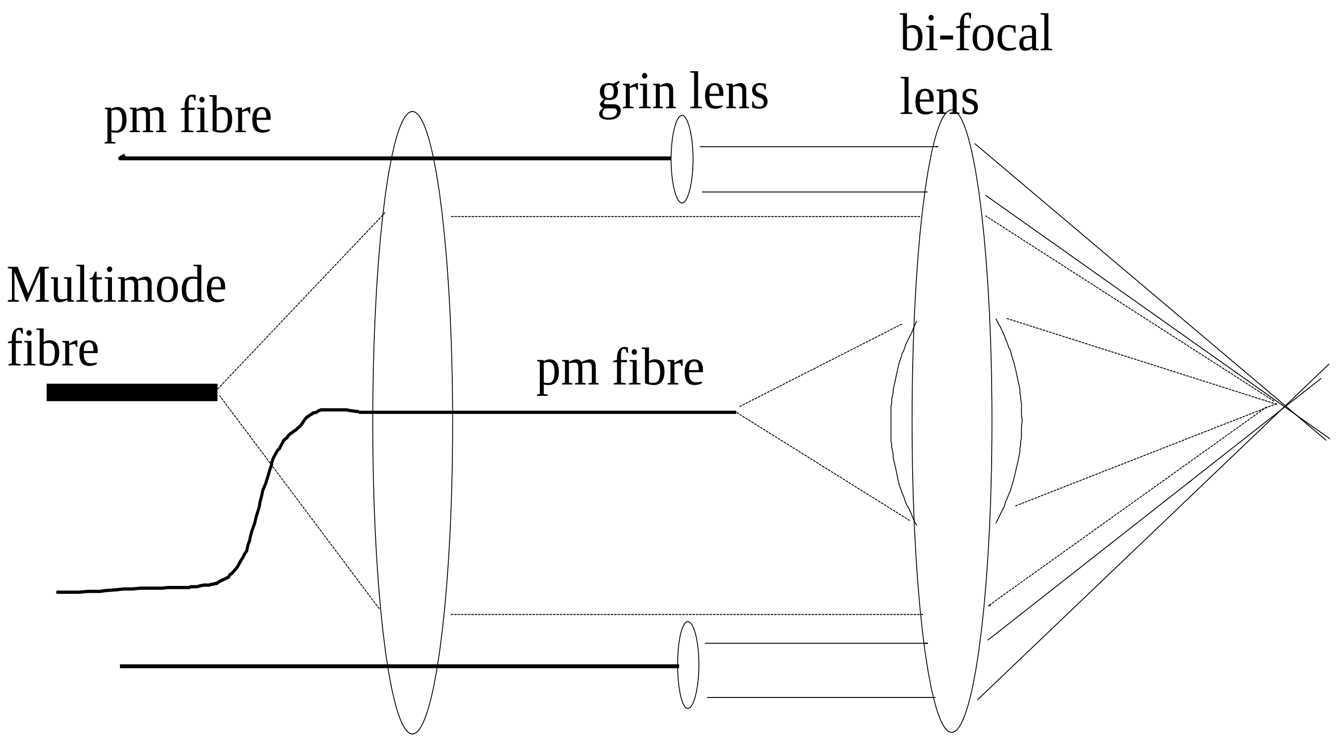
Figure 5. Cross-section through the hybrid probe. pm, polarisation maintaining fibre, mm, multi-mode fibre. The focal lengths of the bifocal lens are 200 mm and 40 mm.

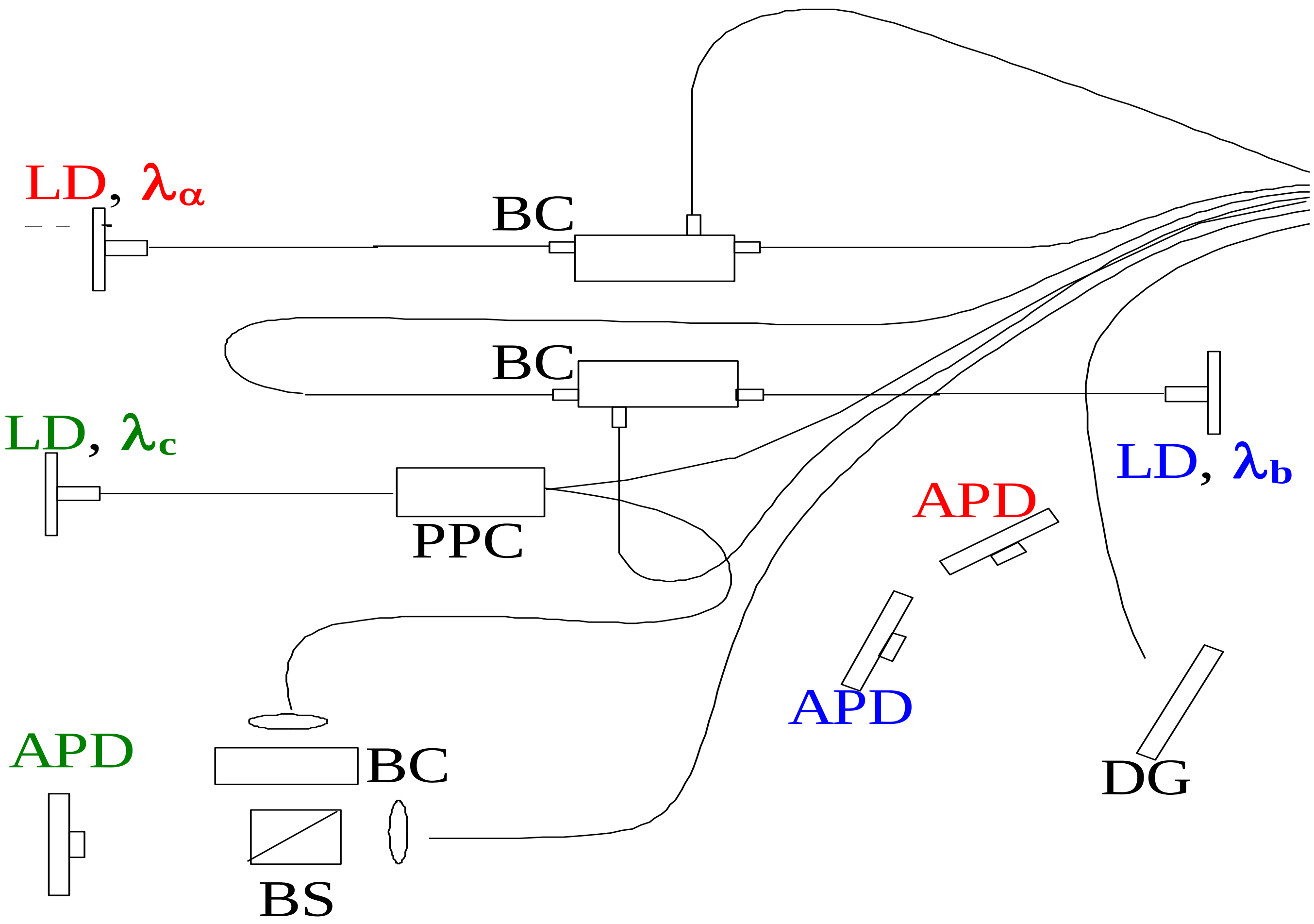
Figure 6. Schematic of the launch/receive section of the anemometer. LD, Laser Diode; FPBC, fibre pigtailed Bragg cell; BC, Bragg cell; APD, avalanche photodiode; mm, multimode fibre; BS, beamsplitter; DG, diffraction grating; VPPC, variable polarisation preserving coupler; IF, interference filter; MMF, multi-mode filter. All unmarked fibres are polarisation maintaining.

Figure 7. 3D measurement of the velocity of a spinning disc.

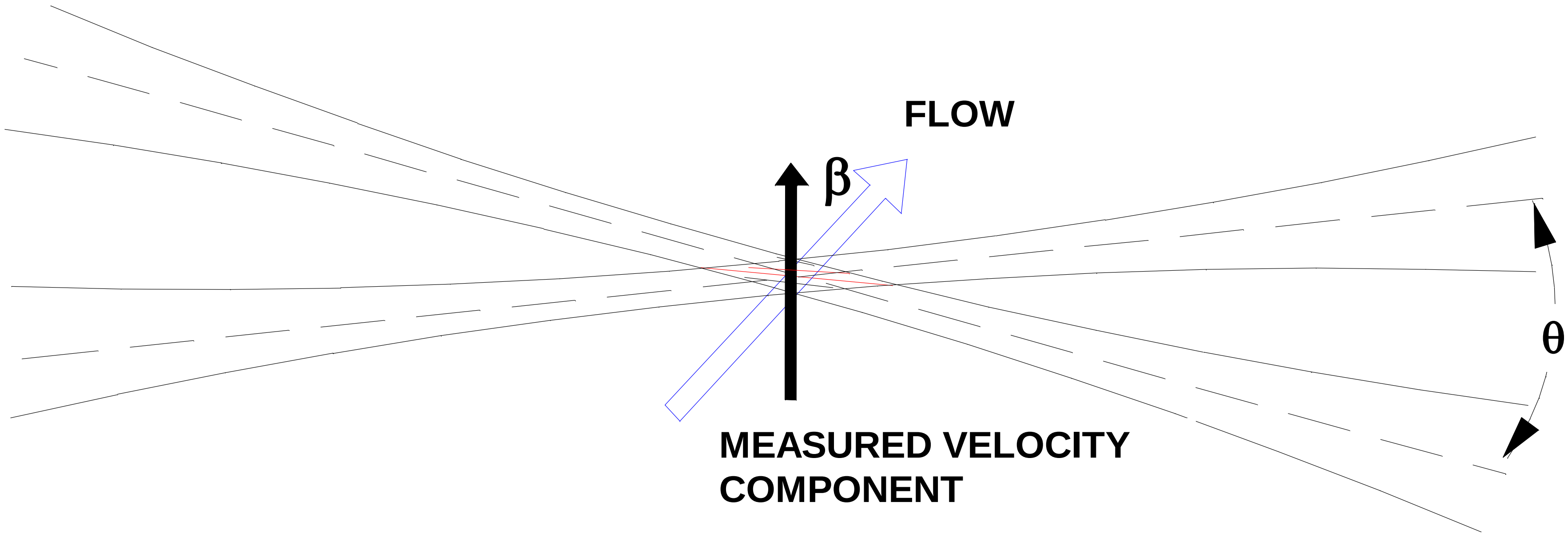
Figure 8. Measurement geometry.

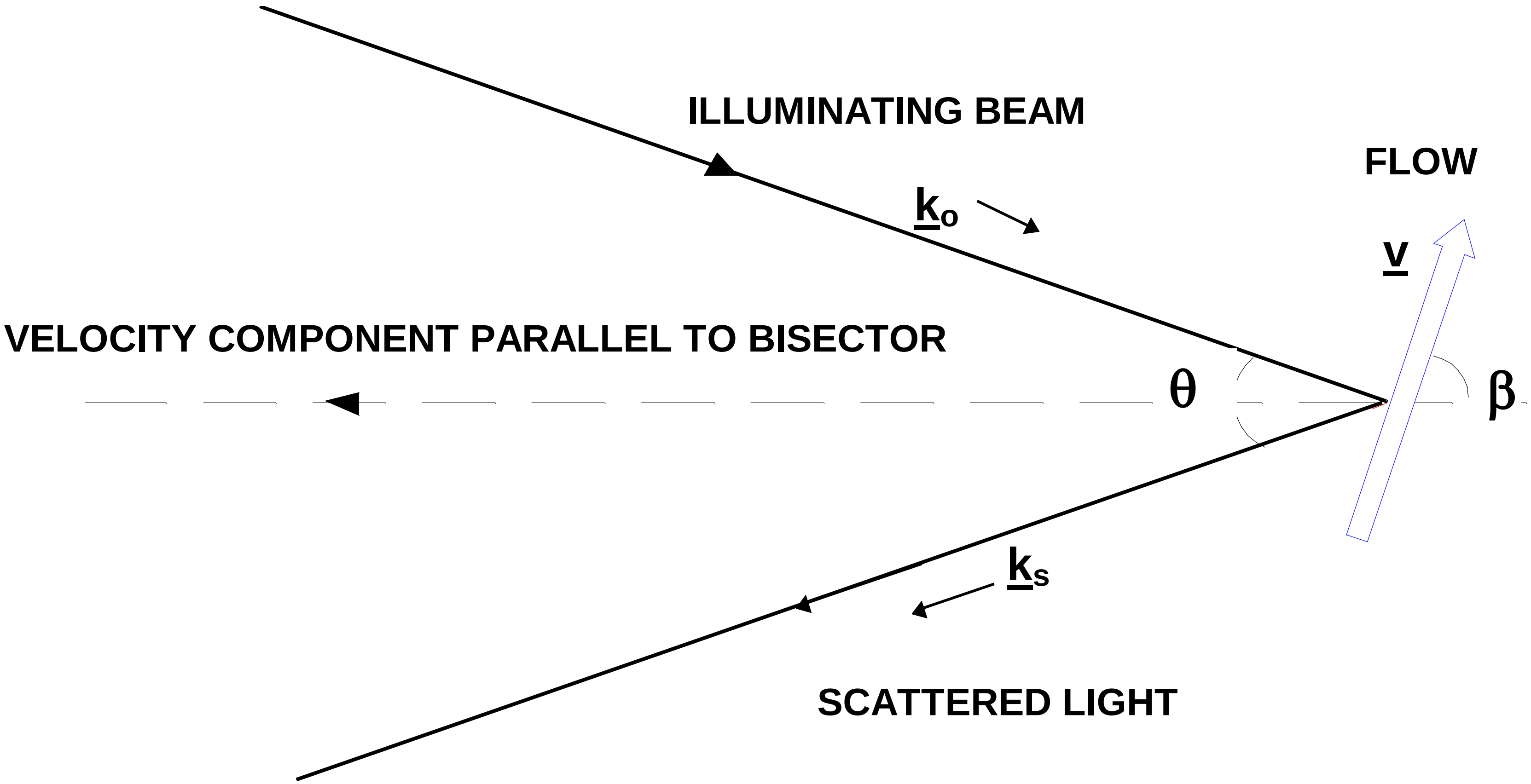

Bi-focal lens
y
x
z
λ_c
λ_a
λ_b

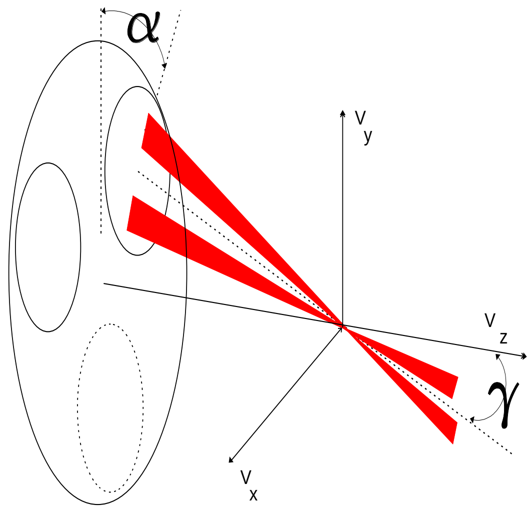

bi-focal
lens
grin lens
pm fibre
Multimode
fibre
pm fibre

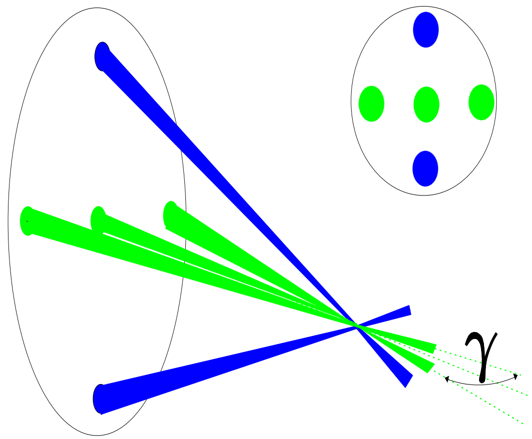


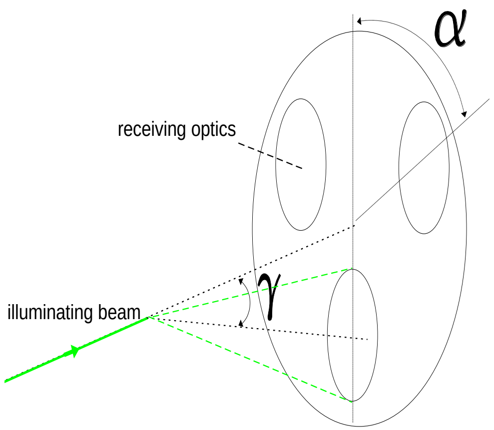
LD, λ_a
BC
BC
LD, λ_c
LD, λ_b
APD
PPC
APD
APD
BC
DG
BS

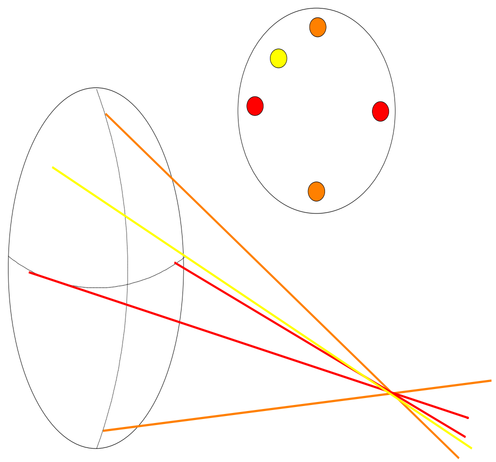

FLOW
β
θ
MEASURED VELOCITY
COMPONENT

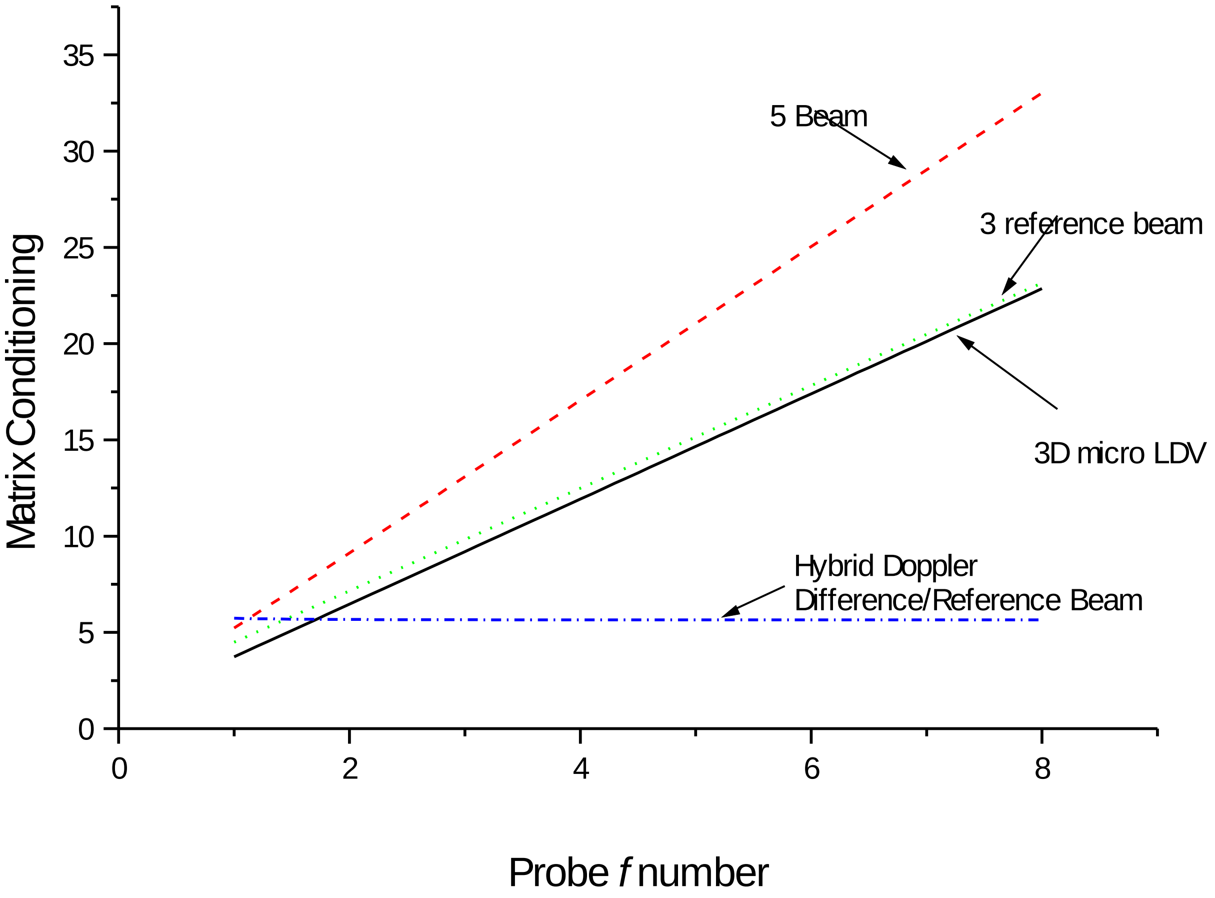

ILLUMINATING BEAM
FLOW
k o
v
VELOCITY COMPONENT PARALLEL TO BISECTOR
θ
β
k s
SCATTERED LIGHT


α
V
y
V
z
γ
V
x

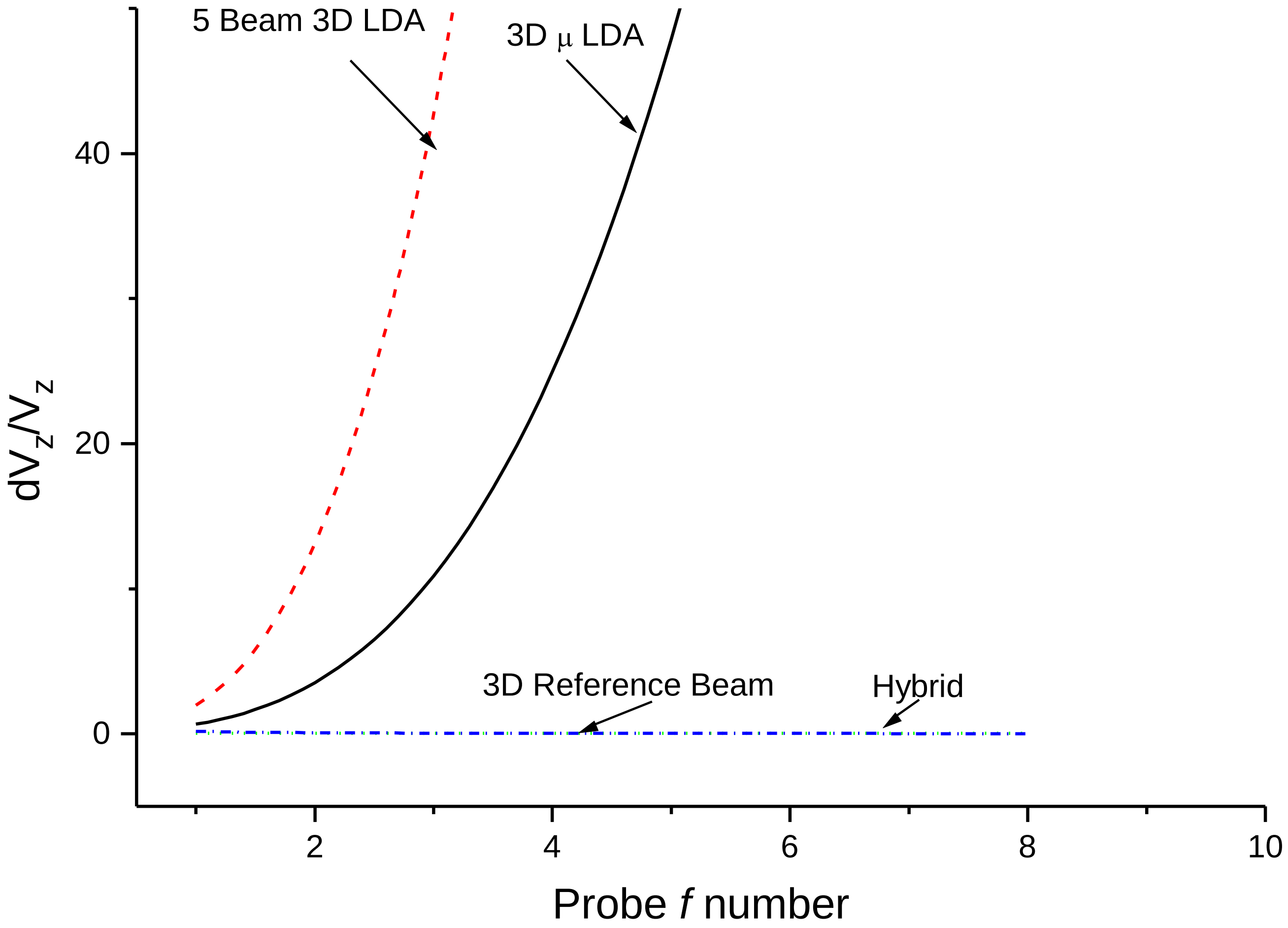

γ


α
receiving optics
illuminating beam
γ

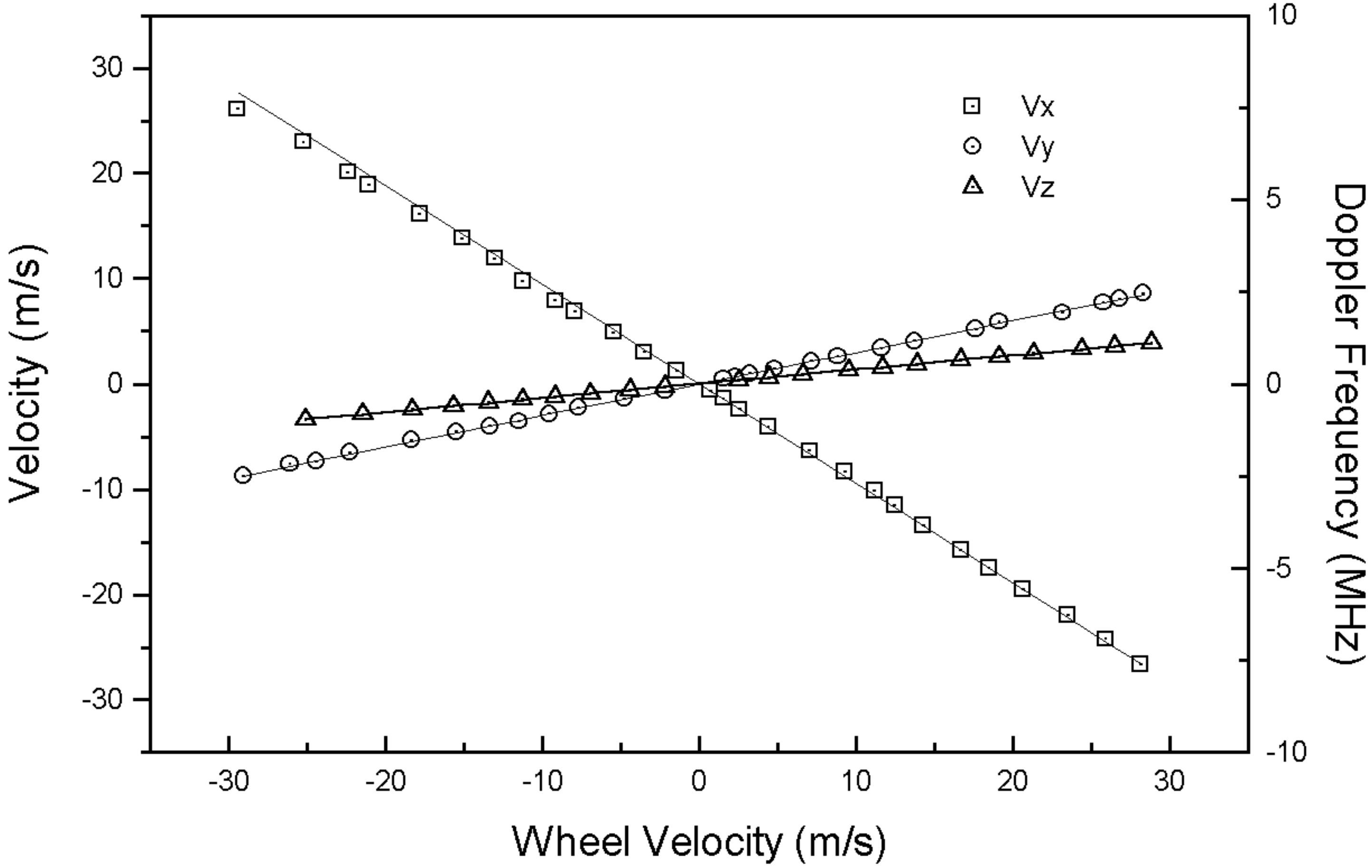




Matrix Conditioning
35
30
25
20
15
10
5
0
0
2
4
6
8
Probe f number
5 Beam
3 reference beam
3D micro LDV
Hybrid Doppler
Difference/Reference Beam



5 Beam 3D LDA
3D μ LDA
3D Reference Beam
Hybrid
40
20
0
dVz/Vz
2
4
6
8
10
Probe f number



Velocity (m/s)
30
20
10
0
-10
-20
-30
Vx
Vy
Vz
10
5
0
-5
-10
Doppler Frequency (MHz)
-30
-20
-10
0
10
20
30
Wheel Velocity (m/s)

<u>TABLE 1</u>

working distance	200 mm
lens focal lengths	200 mm, 40 mm
input beam waist	0.5 mm
wavelength	810 nm
beam spacing	40 mm
half angle	5.7°
fringe spacing	4μm
Velocity Range	up to 300 ms^{-1}
measurement volume size (Doppler diff. channels)	50μm x 50 μm x 500 μm
measurement volume size (reference beam channel)	24 μm x 24 μm x 500 μm

Table 1: Specifications of the 3D laser Doppler velocimeter.

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