A REVIEW ON THE ACCURATE MEASUREMENT OF PARTICLE SIZE AND REFRACTIVE INDEX WITH INNOVATIVE PHASE-DOPPLER ANEMOMETERS

by

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Considerable research work published in the first half of the 1990s on the Gaussian beam defect and its influence on results of phase-Doppler measurements provided deep understanding of its influence on phase-Doppler anemometry that time [1, 2]. This research has even led to the development of new kinds of PDA systems that are able to eliminate the influence of the defect on the measurement results. The resultant so-called Dual Mode PDA enables such error-free measurements, and, further to that achievement, the feasibility of refractive-index measurements with this system has been taken into consideration. The present paper summarises the basics of the Gaussian beam defect in phase-Doppler anemometry and achievements in measuring the particle refractive index using phase-Doppler techniques. The role of making the Gaussian beam defect a usable effect is particularly accounted for.

INTRODUCTION

The effect of non-uniform light intensity distribution in the measurement volume of a phase-Doppler system has been studied by a considerable number of authors in the first half of the 1990s [1, 2]. Later it has been noticed that sizing errors can also be caused when the refracted ray from a particle is blocked by the slit in the receiving optics, but the reflected ray or a higher-order refracted ray can still be detected [3, 4]. The resulting effect is very similar to the Gaussian beam defect, but the error can be more significant and can also occur with small particles. Different techniques were suggested to minimise the Gaussian beam defect, as reviewed in [2]. Possible approaches to avoid the slit effect have also been proposed in [4]. Among these various suggestions published in the literature there are three approaches that seem to be effective and technically feasible:

1. Use of modified optical arrangements.
2. Rejection of bursts influenced by the Gaussian beam defect or slit effect according to the inconsistency of signal phases in different detector pairs.
3. Rejection of bursts influenced by the Gaussian beam defect or slit effect according to signal amplitude, burst length or SNR. The level for the rejection can be set as a function of measured size.

In the present paper, developments according to the first two items carried out in the active time of development of phase-Doppler anemometry in the 1990s are reviewed.

As another important point, the use of the Dual Mode PDA introduced in 1994 [5] for refractive index measurements is considered theoretically and experimentally. Measurement data obtained using this PDA in streams of monodisperse water droplets are evaluated using a data evaluation procedure that enables the computation of the refractive index [6]. This discussion is put into the context of refractive index measurements using extended phase-Doppler anemometers.

PDA ARRANGEMENTS WITH PARTICLE FLOW PARALLEL TO THE SCATTERING PLANE

The origin of the Gaussian beam defect is illustrated in Fig. 1, where a droplet is in the probe volume half opposite the detector, which is placed in the y-z plane. The incident ray *a*, which is reflected to the detector, exhibits a much stronger intensity than the refracted ray *b*, thus resulting in an unexpected phase in the Doppler signal. In a conventional PDA set-up, the particle flow direction is along the x axis, *i. e.* perpendicular to the scattering plane. It is seen in this case, that the contribution of the reflected light will be always high, independent of the x location of the particle. Only when the particle is in the probe volume half $y > 0$ will refraction dominate the scattering process, as desired. Alternatively, when the particle moves parallel to the scattering plane, *e. g.* along the y axis, both the reflected ray and the refracted ray will pass through the x-z plane but one after the other (note that ray *a* and ray *b* are separated by a distance δ). The refractive scattering will be much larger in amplitude than the reflective scattering. Also, the two contributions from refraction and reflection are separated in time if the particle is large.

Using this concept, the Gaussian beam defect can be completely eliminated for measurements in simple flows by *processing half of the burst*. For a one-component PDA, the main particle flow must be in the x direction in order to perform velocity measurements, since the laser beams are in the x-z plane. The way to realise particles moving in the scattering plane is therefore to place the detectors in the x-z plane. Such a PDA set-up, called the planar PDA, was proposed in reference [2] to permit large particles to be measured without Gaussian beam errors (see also the review of planar PDA in [7]). A numerical investigation of the planar optical set-up with two detectors placed in the side $x < 0$ is presented in Fig. 2a as a map of the phase difference. It is seen that the iso-phase difference lines are rotated by 90° as compared with that of a conventional PDA [2]. In planar PDA, the signal phase is no longer a function of location y but becomes a function of the location x.

Physically, this means: although the Gaussian beam defect cannot be removed, its influencing zone is moved from the probe volume half $y < 0$ to the half $x > 0$. When a particle crosses the LDA fringes along a trajectory parallel to the x axis from a negative x location to

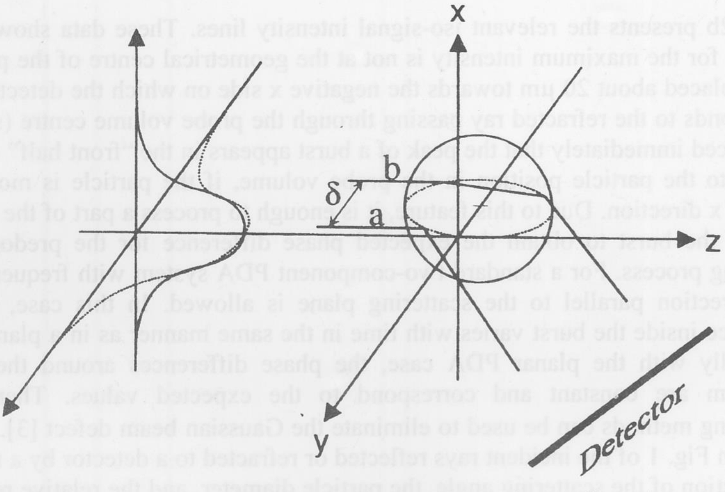
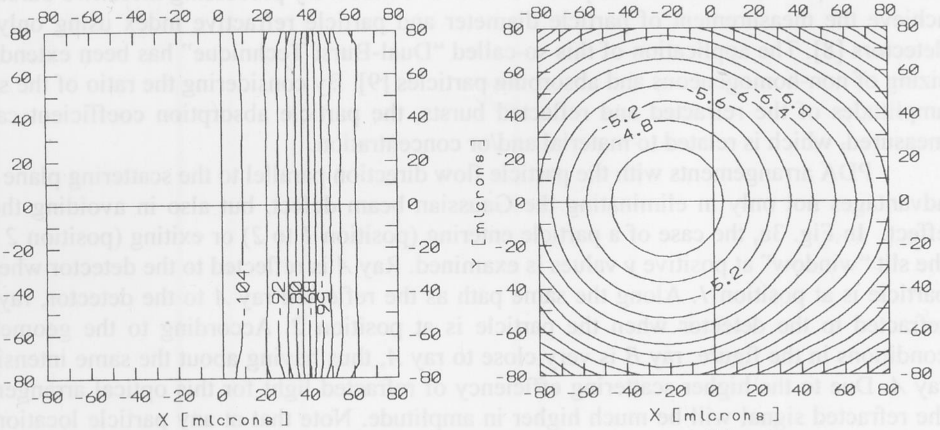


Figure 1. The effect of the Gaussian intensity profile in the probe volume on the dominant light scattering mechanism



(a) (b)

Figure 2. Map of (a) phase difference in degrees and (b) signal intensity in log(W). Drop size $d_p = 52\mu m$, beam waist diameter $w_0 = 40\mu m$, $\alpha = 2.04°$, $\psi_1 = 26.31°$, $\psi_2 = 33.69°$

a positive one, the front part of the burst is coming from the probe volume half $x < 0$, where the intensity gradient of the incident Gaussian beams has no influence on the signal phase. By processing this part of the signal only, the system can be free of the Gaussian beam defect.

Figure 2b presents the relevant iso-signal intensity lines. These data show that the particle position for the maximum intensity is not at the geometrical centre of the probe volume, but it is displaced about 20 μm towards the negative x side on which the detector is placed. This corresponds to the refracted ray passing through the probe volume centre (see Fig. 1). It can be deduced immediately that the peak of a burst appears in the "front half" of the signal with respect to the particle position in the probe volume, if the particle is moving towards the positive x direction. Due to this feature, it is enough to process a part of the signal around the peak of the burst to obtain the expected phase difference for the predominant refractive scattering process. For a standard two-component PDA system with frequency shift, particle flow direction parallel to the scattering plane is allowed. In this case, the signal phase difference inside the burst varies with time in the same manner as in a planar optical layout. Identically with the planar PDA case, the phase differences around the signal intensity maximum are constant and correspond to the expected values. Therefore, the same processing methods can be used to eliminate the Gaussian beam defect [3]. The separation δ shown in Fig. 1 of the incident rays reflected or refracted to a detector by a refracting particle is a function of the scattering angle, the particle diameter, and the relative refractive index. If the particle diameter is large enough, typically larger than half of the probe volume diameter, two consecutive bursts are produced when a particle passes through the probe volume in a trajectory parallel to the scattering plane. One of the bursts is due to reflection, and the other is due to refraction. Given the PDA set-up, the phase difference in the reflected burst is only a function of the particle diameter, while the phase difference in the refracted burst is a function of particle diameter and particle refractive index. By processing these two bursts, we achieve the measurement of particle diameter and particle refractive index using only two detectors [8]. The application of this so-called "Dual-Burst Technique" has been extended to sizing of non-homogeneous and absorbing particles [9]. By considering the ratio of the signal amplitudes of the refracted and reflected bursts, the particle absorption coefficient can be measured, which is related to material and/or concentration.

PDA arrangements with the particle flow direction parallel to the scattering plane have advantages not only in eliminating the Gaussian beam defect, but also in avoiding the slit effect. In Fig. 3a, the case of a particle entering (position *1* to *2*) or exiting (position *2* to *1*) the slit "window" at positive *y* values is examined. Ray *A* is reflected to the detector when the particle is at position *1*. Along the same path as the reflected ray *A* to the detector, ray *B* is refracted to the detector when the particle is at position *2*. According to the geometrical conditions in the figure, ray *B* is very close to ray *A*, thus having about the same intensity as ray *A*. Due to the higher scattering efficiency of refracted light for this optical arrangement, the refracted signal will be much higher in amplitude. Note that at any particle location, the reflected ray, like ray *A*, has a refracted ray like ray *B* as its counterpart. It can be concluded that the signal maximum corresponds to the refracted light, although at some locations, as in position *1*, the refracted ray is blocked by the slit. If the signal processor performs the phase measurement on the highest amplitude part of the burst, the refractive scattering will dominate the phase difference measurement. Figure 3b depicts the case of a particle entering or exiting the slit window at negative y values. Similar arguments can be used here to show that, again, the highest amplitude will be due to refractive scattering and thus will yield an accurate size measurement. It should be noticed here, although the signal phase at positions like position *2* is not correct because of the Gaussian beam defect, the particle size is measured accurately when the particle is at locations like position *1*, where the reflected light

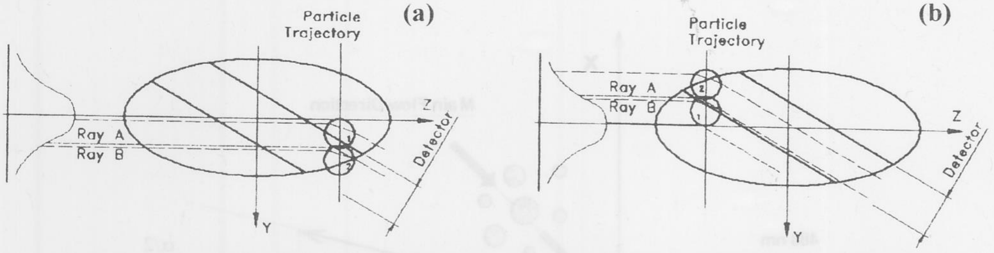


Figure 3. Schematic representation of particle detection with slit aperture when particles move parallel to the scattering plane

is blocked by the slit and the refracted light attains the highest intensity. It should be emphasised that the PDA arrangements introduced in this section are effective in eliminating the Gaussian beam defect and the slit effect only when particle flow directions are parallel to the scattering plane. For measurements in complicated flows, the Dual Mode PDA has been developed [5, 10].

DUAL MODE PDA

The Dual Mode PDA optics consist of a standard two-colour, four-beam transmitting unit and a special four-detector receiving unit, as shown in the sketch in Fig. 4 and the photograph in Fig. 5. The two laser beams and the detector pair aligned in the y-z plane constitute a planar PDA, and the two other beams in the x-z plane with the two other detectors make up a standard PDA. Compared with a conventional four-detector two-component PDA, the detector pair U1-U3 used in the conventional PDA to overcome the 2π ambiguity and to perform the sphericity / inconsistency check is replaced with the planar PDA detectors. The idea in this design is to use the characteristics of the planar PDA to recognise and reject bursts influenced by the Gaussian beam defect / slit effect. The similarities and differences between a standard four-detector PDA and the Dual Mode PDA are as follows:

- In Dual Mode PDA, the accurate phase is measured with the standard PDA (SPDA) detector pair while the 2π-jump information is provided by the planar PDA (PPDA) detector pair, as in a conventional PDA. However, the ratio of phase factors SPDA/PPDA can be higher than the phase factor ratio used in the conventional PDA, thus having higher measurement accuracy.
- When particles flow in one direction, a conventional PDA works as well as the Dual Mode PDA if the flow is arranged parallel to the y axis. When the particle flow velocities exhibit components in two directions, for measuring mass flux and concentration accurately, the flow has to be arranged in the x-y plane, both for the conventional PDA and Dual Mode PDA.

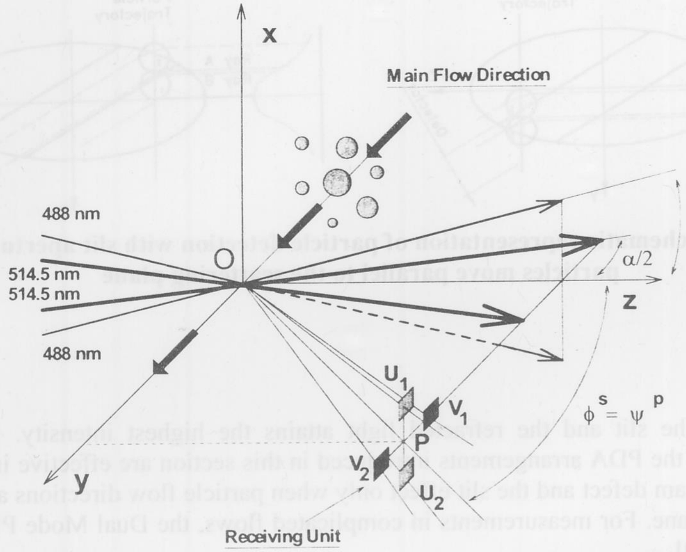


Figure 4. Sketch of the optical arrangement of a Dual Mode PDA [10]

Figure 5. Photograph of a Dantec Dual Mode PDA

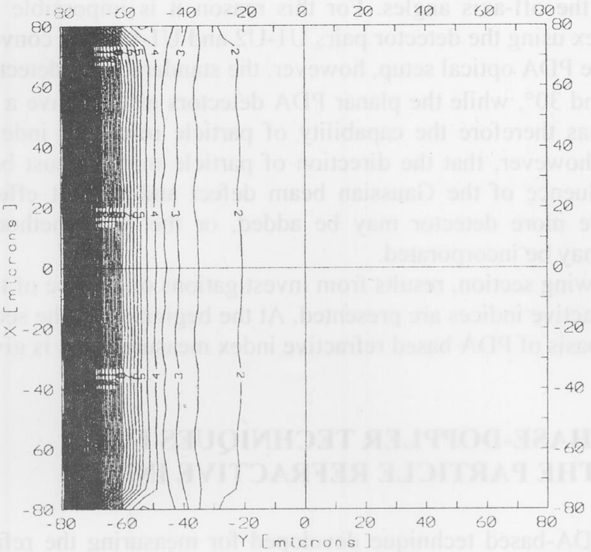


Figure 6. Map of the SPDA/PPDA iso-phase difference ratio in the probe volume [5]

- When particles move in the x direction, signals from all four detectors of the Dual Mode PDA may have unexpected phases, which is due to the Gaussian beam defect. Figure 6 presents the phase difference ratio of the standard PDA detectors to the planar PDA detectors, computed using GLMT [5]. As shown in the figure, the phase difference ratio varies drastically in the region $y < -20$ µm. The bursts influenced by the Gaussian beam defect can therefore be recognised and rejected due to inconsistency in measured sizes. In the case of a conventional PDA, although the size measured with detectors U1-U3 can also be compared with that measured by detectors U1-U2, the method is not very effective. The reason for this is that the planar PDA has different characteristics from the standard PDA, especially in that the standard PDA has a negative phase factor for refraction and a positive phase factor for reflection with about the same absolute value, while the planar PDA has negative phase factors both for refraction and reflection, and the absolute value for reflection is extremely low. For example, in a typical Dual Mode PDA set-up, the phase factors of the standard PDA detectors are -3.37 / 4.23°/ µm for refraction / reflection, while the corresponding values for the planar PDA detectors are -1.16 / -0.193°/ µm. Within the measurable size range, the standard PDA has six nodal points while the planar PDA has none.
- Due to the feature described above, the Dual Mode PDA is much more effective in recognising and rejecting bursts influenced by the slit effect when particles flow in the x direction. Measurement results and comparisons are given in reference [10].
- As pointed out in [6] and [11], the particle refractive index measurement using the extended phase-Doppler method requires that the two detector pairs have a large

difference in the off-axis angles. For this reason it is impossible to measure particle refractive index using the detector pairs U1-U2 and U1-U3 in a conventional PDA. With the Dual Mode PDA optical setup, however, the standard PDA detectors have an off-axis angle of around 30°, while the planar PDA detectors always have a zero off-axis angle. The system has therefore the capability of particle refractive index measurements. A limitation is, however, that the direction of particle motion must be the y direction to avoid the influence of the Gaussian beam defect and the slit effect. To remove this limitation, one more detector may be added, or the third method mentioned in the introduction may be incorporated.

In the following section, results from investigations on the use of the Dual Mode PDA for measuring refractive indices are presented. At the beginning of the section, a short review of the theoretical basis of PDA based refractive index measurements is given.

REVIEW OF PHASE-DOPPLER TECHNIQUES FOR MEASURING THE PARTICLE REFRACTIVE INDEX

The first PDA-based technique developed for measuring the refractive index of the scattering particles was the Extended Phase-Doppler Anemometry (EPDA) technique [12-14]. The EPDA technique is based on two pairs of scattered light signals detected from each sample particle that penetrates the measuring volume. The detection takes place at two different scattering angles, and with the employed standard optical configuration, two separate PDA receiving optics units were used, each equipped with two photodetectors. Therefore, two phase-shift measurements for each particle result. The relationship between the droplet diameter d_p and the phase shift Φ between the received Doppler signals may be described by the well-known equation

$$\Phi_i = F_i(\alpha, \lambda, m, \psi_{i1,2}, \phi_i) \cdot d_p \tag{1}$$

for the detector units i=1,2. If refraction dominates the scattered light received by each of the detector pairs, the two phase shifts may be used to compute a phase shift ratio as given below [14]:

$$\frac{\Phi_1}{\Phi_2} = \frac{\sin\psi_1}{\sin\psi_2}\left(\frac{(1+\cos\alpha\cos\psi_2\cos\phi_2)\left\{1+m^2-m[2(1+\cos\alpha\cos\psi_2\cos\phi_2)]^{1/2}\right\}}{(1+\cos\alpha\cos\psi_1\cos\phi_1)\left\{1+m^2-m[2(1+\cos\alpha\cos\psi_1\cos\phi_1)]^{1/2}\right\}}\right)^{1/2} \tag{2}$$

Solving this equation with respect to the refractive index, one obtains an equation for the refractive index as a function of the measured phase shift ratio and the geometry of the EPDA set-up. This equation may be written as

$$m = -\frac{1}{2}\frac{\sqrt{f_2} - A\sqrt{f_1}}{A-1} + \sqrt{\left(\frac{1}{2}\frac{\sqrt{f_2} - A\sqrt{f_1}}{A-1}\right)^2 - 1} \tag{3}$$

where

$$f_1 = 2(1+\cos\alpha\cos\psi_1\cos\phi_1)$$
$$f_2 = 2(1+\cos\alpha\cos\psi_2\cos\phi_2)$$
$$A = \left(\frac{\Phi_1}{\Phi_2}\frac{\sin\psi_2}{\sin\psi_1}\right)^2\frac{f_1}{f_2}$$

This equation provides real solutions only for non-vanishing denominators and positive square root arguments, thus involving the validation criterion

$$\sqrt{\frac{f_2}{f_1}}\sqrt{\frac{\sqrt{f_2}-2}{\sqrt{f_1}-2}} \le \frac{\Phi_1}{\Phi_2} \le \sqrt{\frac{f_2}{f_1}}\,. \qquad (4)$$

For an optical arrangement with scattering angles $\phi_1 = 60°$, $\phi_2 = 30°$, elevation angles $\psi_{1,2} = \pm 3.69°$, and a beam crossing half angle of $\alpha = 1.69°$ [10], these limiting values are

$$0.5663 \le \frac{\Phi_1}{\Phi_2} \le 1.1152$$

Taking eq. (3) and the validation condition (4) into account, the value of the refractive index can be determined for every pair of phase shifts detected by the two receiving optics units.

This direct method can only be used for computing refractive indices from the phase shifts detected by the standard EPDA arrangement. For the case of the Dual Mode system, eq. (2) must be modified, since the planar system works with a non-symmetrical arrangement of the photodetectors with respect to the symmetry plane between the laser beams. Denoting the standard system with subscript *St*, and the planar system with subscript *Pl*, the new equation for the phase shift ratio reads

$$\begin{aligned}\frac{\Phi_{Pl}}{\Phi_{St}} = &-\frac{\sin\psi_{Pl1}}{\sin\psi_{St}}\sqrt{\frac{(1+\cos\alpha\cos\psi_{St}\cos\phi_{St})}{(1+\cos\alpha\cos\psi_{Pl1})}}\cdot \\ &\cdot\sqrt{\frac{1+m^2-m[2(1+\cos\alpha\cos\psi_{St}\cos\phi_{St})]^{1/2}}{1+m^2-m[2(1+\cos\alpha\cos\psi_{Pl1})]^{1/2}}}+ \\ &+\frac{\sin\psi_{Pl2}}{\sin\psi_{St}}\sqrt{\frac{(1+\cos\alpha\cos\psi_{St}\cos\phi_{St})}{(1+\cos\alpha\cos\psi_{Pl2})}}\cdot \\ &\cdot\sqrt{\frac{1+m^2-m[2(1+\cos\alpha\cos\psi_{St}\cos\phi_{St})]^{1/2}}{1+m^2-m[2(1+\cos\alpha\cos\psi_{Pl2})]^{1/2}}} \end{aligned} \qquad (5)$$

An important characteristic of the PDA systems for measuring the refractive index of scattering particles discussed here is the sensitivity of the measured quantity to changes in the refractive index. In the present cases of standard EPDA and Dual Mode PDA, this sensitivity is represented by the behaviour of the functions Φ_1/Φ_2 and Φ_{Pl}/Φ_{St} respectively. In order to compare these characteristics, the functions were computed for relative particle refractive indices between 1.2 and 1.4 against air. The results are shown in Fig. 7, where the characteristic parameters of the system geometries are also given. It can clearly be seen that the sensitivity of the Dual Mode system to refractive index changes is higher than that of the standard EPDA system. It is therefore to be expected that the Dual Mode system is at least as powerful for measuring the refractive index of the scattering particles as the standard EPDA [6].

In the following section, a comparison of results of refractive index measurements carried out with the two systems will be given.

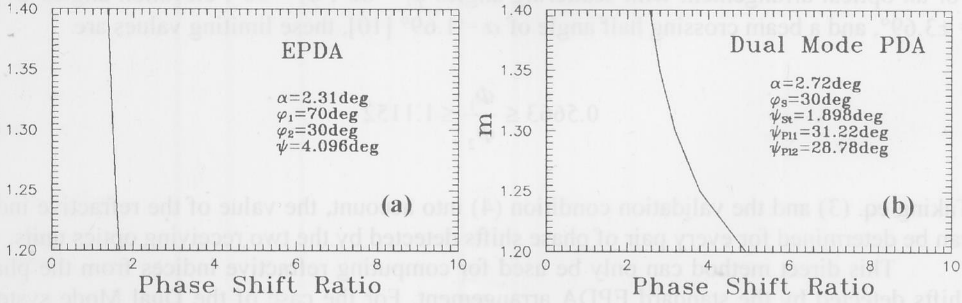


Figure 7. Sensitivity of the phase shift ratios with respect to the refractive index measured by (a) a standard EPDA and (b) a Dual Mode PDA

EXPERIMENTAL RESULTS

The above derivations were verified experimentally by using an EPDA and a Dual Mode PDA system for measuring the refractive index of monodisperse water droplets. The off-axis angles of the EPDA system were $\phi_1 = 60°$, $\phi_2 = 30°$, the elevation angles were $\psi_{1,2} = \pm 3.69°$, the beam-crossing half angle was $\alpha = 1.69°$. The Dual Mode system used for the present investigations is characterized by the following data: $\phi_{St} = 30°$, $\psi_{St} = \pm 1.898°$, $\psi_{Pl1} = 31.22°$, $\psi_{Pl2} = 28.78°$, $\alpha = 2.72°$. The ratio of the phase shifts measured by the two different sets of photodetectors in each system, the refractive index, and all other quantities of interest were computed with a postprocessing software. Since eq. (5) cannot be solved directly with respect to the refractive index, for treating the Dual Mode data a numerical procedure had to be applied for finding the refractive indices that corresponded to the measured phase shift ratios.

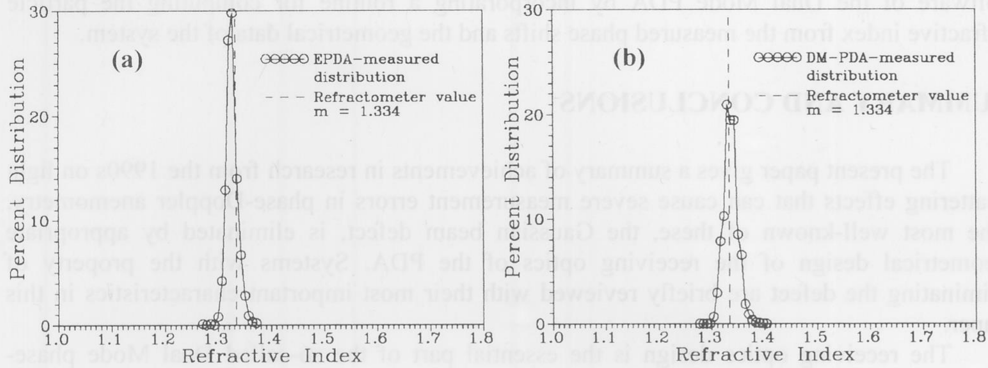


Figure 8. Results of refractive index measurements carried out with (a) a standard EPDA and (b) a Dual Mode PDA system. The deviations of the measured mean refractive indices from the correct value of 1.334 for water are of the same order of magnitude

Results of the verification experiments are shown in Fig. 8. In the case of the EPDA measurements, typical results showed that the measured mean refractive index of 1.3260 deviates by -0.6% from the correct value. A normalised standard deviation of the refractive index distribution of $7.95 \cdot 10^{-3}$, *i. e.* less than 1%, was achieved (Fig. 8a). In this experiment, the diameter of the water droplets was $d_p = 71.8$ µm. The results obtained by processing the data from the Dual Mode measurements are shown in Fig. 8b. The measured water droplets had a diameter of 62.1 µm. The distribution of measured refractive index values is slightly broader than the one achieved with the EPDA (normalised standard deviation $9.76 \cdot 10^{-3}$), but the distribution is more symmetric around the measured mean value of $\overline{m} = 1.3325$, which deviates from the correct value by only --0.11%. The number of samples taken in the EPDA experiments was 1000, while in the Dual Mode experiments 3000 samples were taken. It was expected at the time when these investigations were carried out that the relatively large fluctuations in the measured refractive indices could be reduced by the use of a more accurate signal processor. In between, however, it is widely accepted that the limitations to the accuracy of refractive index measurements with PDA-based techniques is limited due to even slightest non-sphericity of the particles.

To the best knowledge of the authors this was the very first and the only attempt to date to use a Dual Mode PDA data for determining the refractive index of particles. In these investigations no special effort has been spent for the alignment of the receiving optics. The Dual Mode PDA system therefore appeared to be quite suitable for the measurement of the refractive index of the particles. It involves only one receiving optics unit which is therefore easy to adjust. Only recently, however, efforts were started to extend the data processing software of the Dual Mode PDA by incorporating a routine for computing the particle refractive index from the measured phase shifts and the geometrical data of the system.

SUMMARY AND CONCLUSIONS

The present paper gives a summary of achievements in research from the 1990s on light scattering effects that can cause severe measurement errors in phase-Doppler anemometry. The most well-known of these, the Gaussian beam defect, is eliminated by appropriate geometrical design of the receiving optics of the PDA. Systems with the property of eliminating the defect are briefly reviewed with their most important characteristics in this paper.

The receiving optics design is the essential part of the so-called Dual Mode phase-Doppler anemometer. One interesting and promising aspect of this kind of PDA system is the simultaneous presence of two scattering angles, since always a standard and a planar PDA are used simultaneously. Further to the feasibility of error-free measurements, this feature enables the use of the measured phase shifts for determining the refractive index of the scattering particles. This approach is quite similar to the use of two receiving optics units in standard EPDA. Results of verification experiments showed good accuracy of the measured mean values, comparable to the degree of accuracy achievable with standard EPDA. This suggests that a Dual Mode phase-Doppler anemometer is suitable for future applications to measure the refractive index of scattering particles. The statistical fluctuations of the results are of the same order of magnitude as experienced with standard EPDA systems. The hope expressed in the middle of the 1990s that the accuracy of PDA-based refractive index measurements may be increased by phase shift determination with higher accuracy was not confirmed by date. Nonetheless the achievable accuracy is still sufficient for distinguishing between particles of clearly separate refractive index, such as oil and water droplets, in order to provide separate measurement results for two or more phases in the flow field.

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