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New Developments in Phase Doppler Anemometry

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***Abstract*:** This article reviews a number of recent PDA developments designed to either improve accuracy or extend the technique in measurement range or measurand. Many of these developments have depended on improvements in the computation of light scattering from small particles and initially several of these improvements will be discussed. The sensitivity of the dual-mode PDA to particle sphericity will be discussed, followed by possibilities for the sizing of oscillating particles/droplets. Finally, some remarks will be directed to the dual-burst technique and its use in novel optical systems.

***Keywords*:** phase Doppler anemometry, light scattering, particle sizing.

1. Introduction

All optical particle measuring techniques are based on a fundamental understanding of the light scattering, however optimization of a given technique or innovations employing new configurations rely also on being able to conveniently compute and display scattered light fields. One of the first developments to be discussed in this article is therefore a substantial acceleration of light scattering computations achieved through the use of look-up tables and spline interpolations. Also several new forms of graphical representations of the results will be presented.

The second topic to be discussed is the issue of particle non-sphericity and its influence on typical PDA optical systems. It will be shown that the dual-mode arrangement of detectors may provide some interesting opportunities to size certain non-spherical particles or even oscillating droplets. Finally, the dual-burst technique will be revisited, with some emphasis placed on the information contained in the measurement volume shift.

2. Light Scattering Compuations

Light scattering computations using the Lorenz-Mie Theory (LMT) (van de Hulst, 1981) or the Generalized Lorenz-Mie Theory (GLMT) (Gouesbet et al., 1988) have typically been rather time consuming and more or less impractical to perform for more complex systems, especially if entire particle trajectories must be reconstructed, as is the case for instance when studying the performance of the dual-burst technique. Therefore efforts to accelerate these computations are welcome or even mandatory for the layout of novel systems.

The Fourier Lorenz-Mie Theory (FLMT) (Albrecht et al., 1995) certainly has the potential for massive parallelization with a speed-up factor exactly equal to the number of processors, although to date this has not been fully implemented. A second avenue for speed-up lies in the pre-computation of all S_1, S_2 scattering functions and their storage in a look-up table. More specifically, the scattered field is given as

$$\boldsymbol{E}_{Sc} = \frac{1}{kr} \bullet \begin{bmatrix} S_1(\upsilon) & 0 \\ 0 & S_2(\upsilon) \end{bmatrix} \bullet \begin{bmatrix} -\sin\varphi & \cos\varphi \\ \cos\varphi & \sin\varphi \end{bmatrix} \bullet \boldsymbol{E}_I$$

with

$$S_1 = \sum_{n=1}^{\infty} a_n \pi_n(\upsilon) + b_n \tau_n(\upsilon) \qquad S_2 = \sum_{n=1}^{\infty} a_n \tau_n(\upsilon) + b_n \pi_n(\upsilon)$$

where υ is the scattering angle, ϕ is the second polar angle and π_n and π_n are the corresponding Legendre polynomials. The values of the functions S_1 and S_2 can be stored for a selection of particle sizes and refractive indexes, in each case over a range of scattering angles. The main issue to address is the required angular resolution to be chosen in order to insure a given accuracy in the result. By using spline interpolations the number of angular points at which S_1 and S_2 are computed and stored can be reduced, however still the required density of points turns out to be dependent on the scattered field itself. For example, a 1 μm particle requires a resolution of approximately υ=1°, whereas a 100 μm water droplet requires angular steps of between 0.01° and 0.1°. Therefore, when generating the look-up table, systematic checks are necessary to decide on whether more points are necessary in the spline interpolation or not. The storage space required for the look-up table varies linearily with partcile size. One example of such stored date, together with the fitted spline is shown in Fig. 1. This corresponds to the scattered light field from a 100 μm water droplet in the vicinity of the rainbow. The Mie parameter is $\alpha=\pi d/\lambda$=643.77.

A further compression of the data is achieved by using fixed step widths in refining the angular resolution. A data bank has been generated consisting of particle sizes ranging from 1 μm to 838 μm in 1 μm steps and 18 different refractive indexes, which fits onto one 650 MB CD. A second program is then used to define a particular measurement system and to access the stored scattering functions according to the defined apertures, etc. The overall speed-up is presently a factor of 30, with an expected improvement of up to 100. With such speed-up

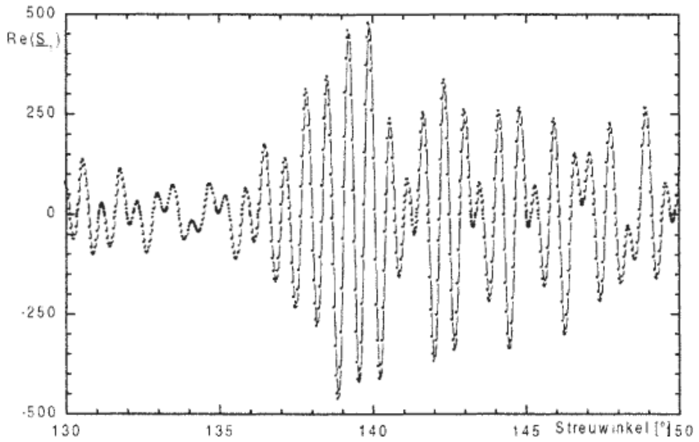


Fig. 1. Portion of the scattering function reconstruction from stored data using splines: α=643.77, m=1.334, number of stored points (0°-180°) 6105, accuracy 10^{-4}.

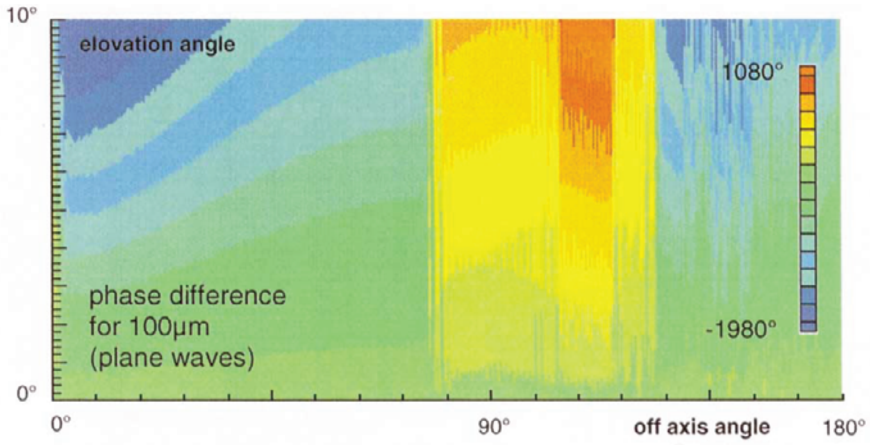


Fig. 2. Example computation of phase shift in a PDA system shown as a function of scattering angle and elevation angle (α=643.77, m=1.334).

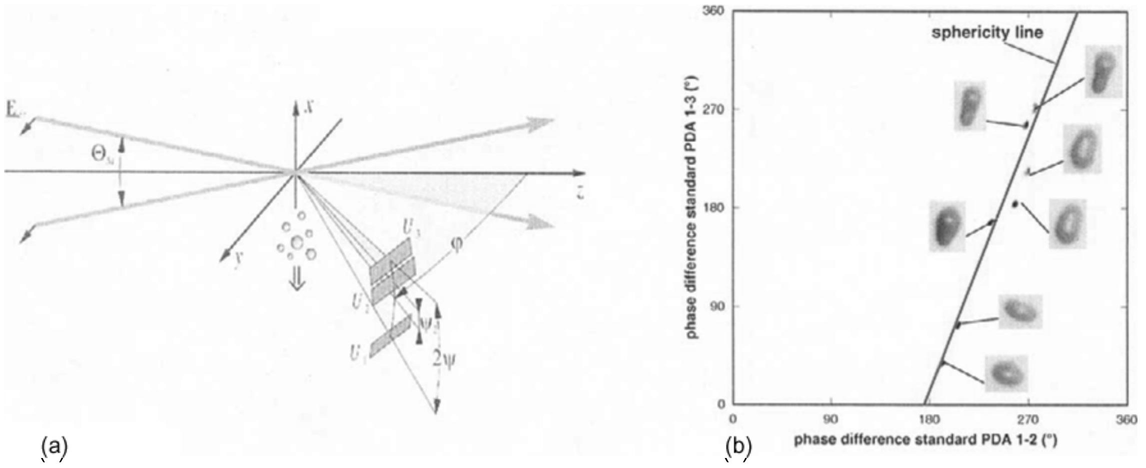
factors, more detailed studies of light scattering become feasible. In Fig. 2, the phase difference in a PDA system (m =1.334, λ=488.0 nm) is shown as a function of scattering angle and elevation angle. Such data representations are helpful in choosing detector apertures.

The same data bank can be used to compute light scattering from Gaussian beams if the Fourier Lorenz Mie Theory is used. In this case, the incident wave is treated as the summation of 400-600 plane partial waves, each being computed using the look-up table and a weight factor. This approach is necessary when Doppler signals are simulated, since the particle is then moved step by step along its trajectory through the measurement volume. For each step an FLMT computation is necessary. Some examples of such signals are given in Section 4.

3. Dual-mode PDA

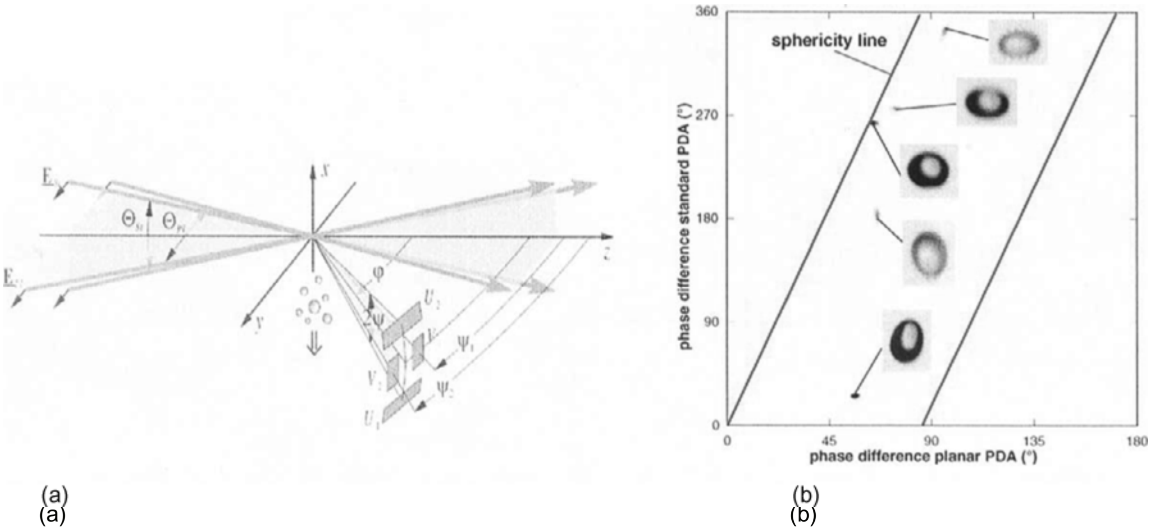
The processing of PDA signals and the derived phase differences is generally based on the assumption that the scattering particle is spherical. If this is not the case, the computed size would be erroneous. For this reason, a sphericity "check" is desirable, essentially filtering out any non-spherical particles from subsequent data processing. Physically this sphericity check is implemented by operating two PDA systems simultaneously, i.e. two pairs of detectors, observing different parts of the particle. If the two derived diameters are equal, then the chances of sphericity are deemed high and the measurement is accepted.

For standard three detector PDA systems this scheme has been shown to be inadequate (Damaschke et al., 1998a). The reason lies in the fact that the two pairs of detectors, U_1-U_2, U_1-U_3 in Fig. 3(a), observe glare points very close to each other on the particle and thus, their derived diameters will agree even for strongly deformed particles. This is illustrated in Fig. 3(b) in which oscillating droplets from a monodispersed droplet generator are



(a) (b)

Fig. 3. Measured phase difference response of a standard three detector PDA to deformed droplets.



(a) (b)

(a) (b)

Fig. 4. Measured phase difference response of a dual-mode PDA to deformed droplets.

measured at various downstream distances, corresponding to various degrees of oblateness or prolateness. Despite the deformation, the phase differences U_1-U_2 correspond closely with the diameter equivalent phase difference U_1-U_3, represented in Fig. 3(b) by the solid line marked sphericity.

The dual-mode receiver arrangement (Tropea et al., 1996) displays a significantly different response, as shown in Fig. 4. In this case, the detector pair U_1-U_2 measures a diameter based on the meridianal curvature whereas the detector pair V_1-V_2 detects an equatorial diameter. These differ significantly in a deformed droplet. Consequently, the sphericity check using the dual-mode is a much more sensitive validation than with a three detector receiver configuration. This response of the dual-mode receiver is studied more systematically using ray-tracing applied to elliptic particles. For particles aligned with the PDA X-axis, the corresponding phase differences are given in Fig. 5.

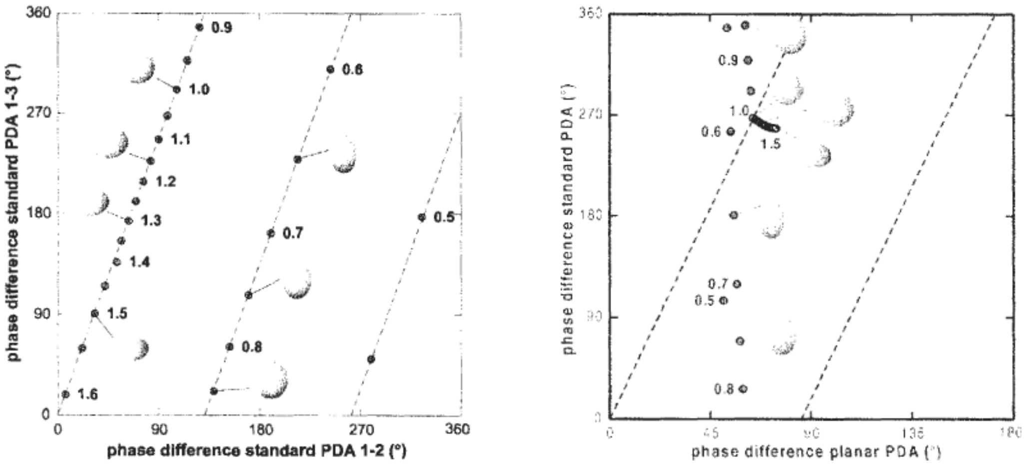


Fig. 5. Computed phase difference response of a 3-detector standard and a dual-mode PDA to deformed droplets.

In a further experiment, the PDA signals arising from an oscillating droplet are digitised using a transient recorder and processed in such a way that the phase difference between detectors U_1 and U_2 is shown as a function of time during the particle passage through the measurement volume. Typical results are shown in Fig. 6. Clearly the PDA system is able to detect the particle shape changes in a systematic manner. If a dual-mode arrangement is used and the phase difference evolution for both U_1-U_2 and V_1-V_2 are tracked, it is feasible to map out the oscillation on a figure similar to Fig. 5. An extrapolation of the measured phase difference trace to the sphericity line would then give an estimate of the volume equivalent diameter. This technique has, however, not yet been verified. Furthermore, the influence of a tilt between the axis of rotational symmetry of the particle and the PDA X-axis has not yet been investigated. In any case, the signal processing must be capable of following the phase difference evolution with time. Several suggestions for this implementation have been put forward (e.g. Lehmann et al., 1995).

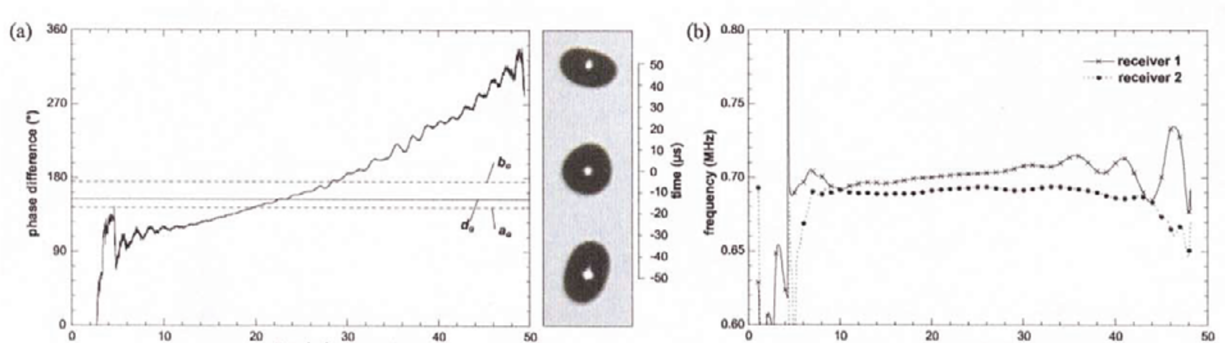


Fig. 6. Variation of measured phase difference and frequencies as an oscillating droplet traverses the measurement volume of a two detector standard PDA.

4. Dual-burst Technique

The dual-burst technique was originally introduced as a possible means to recognize the Gaussian beam effect and to also insure reliable size measurements in spite of this effect (Brenn et al., 1995). However, already at this early stage, and also in further work (Onofri et al., 1996), the potential for measuring refractive index or even absorption coefficient was recognized. To review briefly, the dual-burst technique relies on a large ratio between particle size and beam cross-section, which leads effectively to a spatial separation between the reflective and refractive measurement volumes. This results in a temporal separation of the signals arising from reflectively scattered light and that due to refraction. Thus the origin of the Gaussian beam effect, which in general is a nuisance in the classical PDA arrangement, becomes a fundamental principle in the dual-burst technique.

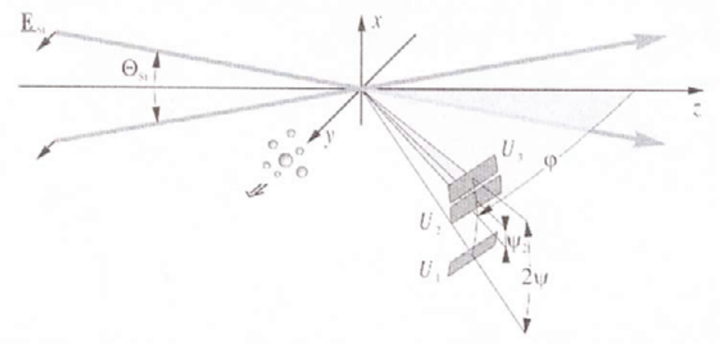


Fig. 7. Optical arrangement for the dual-burst technique.

The dual-burst technique can be realized using standard PDA optical configurations by reducing the diameter of the measurement volume. An adequate size is about 3 times the diameter of the smallest particle to be measured. In general, it is advantageous to align the main flow direction along the Y-axis, as shown in Fig. 7. For this reason, a two component system is desirable, otherwise the main velocity component of the particle would not be registered.

An example signal pair from the dual burst system is shown in Fig. 8, together with those signal parameters which contain important information. As in conventional PDA, there exists a phase shift between the two signals in each of the reflective and refractive portions. This phase shift correponds to the conventional PDA value but does show an evolution as the dominant scattering mode changes from reflection to refraction or vica versa. Then there exists a time shift between the reflective and refractive bursts on each of the detectors, which corresponds to the spatial separation of the effective detection volumes. The magnitude of this time shift (detection volume displacement) can also be computed as a function of particle size and refractive index and one such example is shown in Fig. 9. The effective measurement volume separation can be visualized for a given optical system as shown in Fig. 10 for a 100 μm droplet at various positions along the Z-Axis.

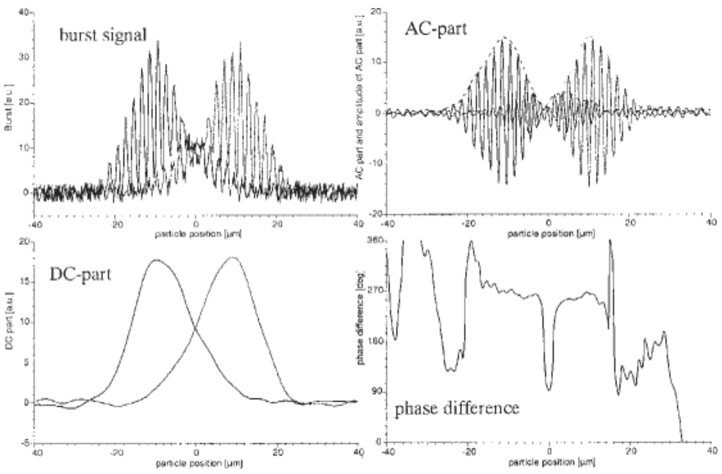


Fig. 8. Example signals from a dual burst optical arrangement (unfiltered, DC part, AC part).

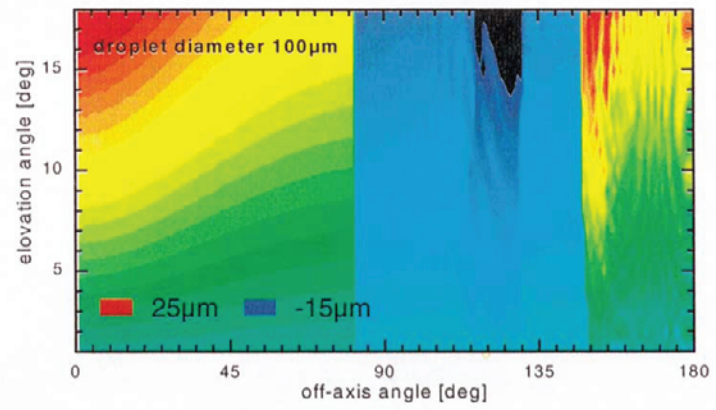


Fig. 9. Computed measurement volume displacement as a function of detector position for a 100 μm water droplet.

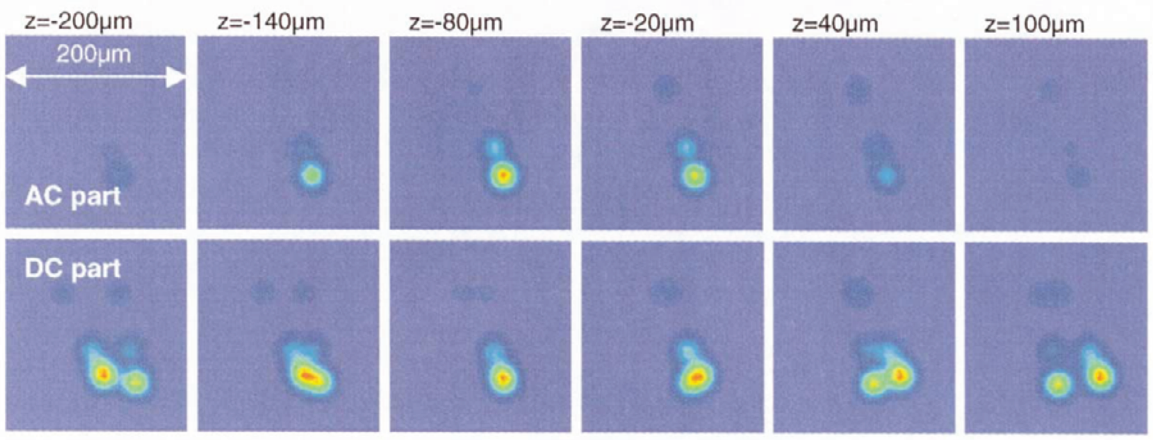


Fig. 10. Computed measurement volume displacement as a function of particle position for a 100 μm water droplet in a small beam waist (d_p=100 μm; m=1.333; x_w=25 μm; z_w=143 μm; Θ=10°).

Physically, it is important to realize that the time shift due to the effective measurement volume displacement only occurs because of the non-uniform intensity distribution of the incident light. This would disappear for a plane wave. The phase shift on the other hand, is always present. Thus these time/phase shifts contain redundant information which can be used either for validation purposes or to estimate the refractive index, if this is unknown.

In Fig. 8, a separation between the reflected and refracted burst in each signal is also recognized. Also this time shift is directly related to the particle size and refractive index.

Finally, the amplitude of the signals contain information. The refracted light will be lower in amplitude when the particle is less transparent. Thus for some solutions and mixtures, the concentration can be estimated from the signal amplitude. By examining the amplitude ratio between the refracted and reflected signal portions, it is even possible to eliminate the need for a calibration. In these applications, a simple Beer-Lambert law can be applied to describe the light absorption in the particle or, for more heterogeneous mixtures, some new models have recently been suggested (Onofri et al., 1998).

Thus, the dual burst technique shows potential for measuring particle size, velocity, refractive index and possibly concentration. One pre-requisite, however, is that the signal processing is able to estimate the various measurement quantities shown in Fig. 8.

5. Closing Remarks

The field of optical particle measurements remains fascinating, with many new developments over the past years to impove instrument accuracy or to measure new quantities. Starting from the classical PDA, several new arrangements have already proven to be useful in studying particulate and droplet laden flows. The major differences lie in the signal processing, leaving the concept of an LDA transmitting optics and a single receiving optics unaltered.

Strictly speaking not all of the new techniques can still be called phase Doppler anemometry, since neither the phase difference nor the Doppler frequency are necessarily used in the processing.

Acknowledgements

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Nils Damaschke: He studied electrical engineering and received his Dipl.-Ing. at the University of Rostock, Germany, 1997. During this period, he worked in the research area of Laser Doppler and Phase Doppler developments, especially in the field of light scattering simulations. He is presently carrying out a Ph.D at the Technical University of Darmstadt with Prof. Tropea. His work is in the area of optical particle measerement of nonspherical and inhomogeneous particles.