Laser Doppler Based Particle Characterization with Backscattered Light

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The possibility of using elastic light scattering in backscatter for determining size, velocity and refractive index of spherical particles is investigated. The phase Doppler technique is unsuitable for such backscatter configurations, except for very special measurement conditions. Therefore the use of the time-shift technique combined with a laser Doppler velocity measurement is investigated. The time-shifted scattering orders can be generated either by the laser Doppler illumination itself or by a separate, single beam/sheet illumination. Both arrangements are simulated using the Fourier Lorenz-Mie theory (FLMT) and experimentally demonstrated. The arrangement using an additional light sheet for the generation of time-shifted scattering orders exhibits several important advantages compared to a solution based solely on the laser Doppler system.

1. Introduction

An optical instrument for particle characterization in backscatter would be very convenient, permitting the incident and scattered light to pass through a single optical access. Unfortunately the conventional phase Doppler technique provides correct particle sizing only when a single scattering mode dominates, e.g. reflection or first-order refraction, which is not the case in backscatter for particles with commonly encountered refractive indexes. Therefore the resulting phase-diameter curve of the phase Doppler system exhibits very large oscillations and jumps, making sizing impractical [1].

Still within the framework of a laser Doppler technique, an alternative method has been studied in the present work. It is based on the measurement of the time shift of each scattering order, which arises only when shaped beams are used for illumination. This corresponds to the so-called pulse displacement technique [2, 3, and 4] and is also the basis of the time-shift [1, 5] and dual-burst phase Doppler technique [6]. When a particle moves through a shaped beam, each scattering order/mode contributes to the signal from its own virtual measurement volume, which is displaced in space, but has the same size as the illuminated volume [1]. The magnitude of the volume displacement depends on the scattering order, relative refractive index, receiver orientation and the particle size. Accordingly, as the particle moves through the beam, various fractional signals arrive sequentially at the detector. If the different scattering orders/modes are identifiable in the received signal and the particle velocity is known, the diameter can be estimated from the time shift between fractional signals, hence the name time-shift technique.

The situation for the backscatter range is illustrated in Fig. 1, in which a Gaussian intensity distribution is shown for a single incident beam [7]. When the particle moves through the beam, the main signal components in order of occurrence for $m > 1$ will be: surface wave long path (SWLP), reflection ($p = 1$), second-order refraction (inner path), second-order refraction (outer path), surface wave short path (SWSP). Note that there exist two modes for second-order refraction ($p = 3$). These have been designated $p = 3.1$ (inner path) and $p = 3.2$ (outer path).

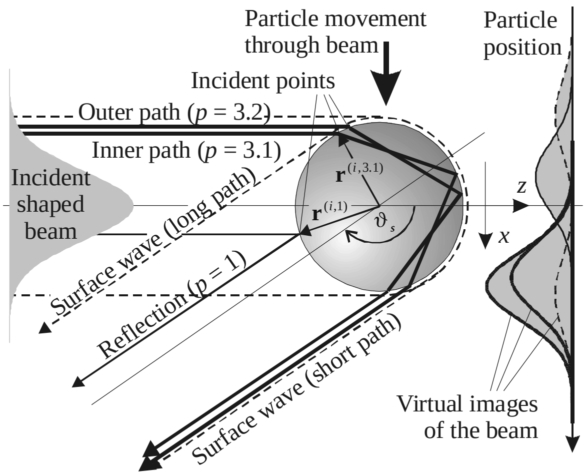

Fig.1: Scattering orders/modes contributing to the signal in the near backscatter

Overlapping of the fractional signals from different scattering orders/modes is reduced by keeping the ratio of the particle diameter to the incident beam width large. For practical applications this means a highly focused beam should be used, insuring good separation of the fractional signals even for small particles.

2. Signal characteristics

2.1 Generation of the fractional signals

The remarks of the previous section pertaining to scattering from a single laser beam indicate that the displacement of the virtual measurement volume corresponding to each scattering order/mode lies in the plane formed by the axis of the incident beam and the detector direction. All fractional signals will therefore only be seen if the particle velocity vector lies in or near this plane. Furthermore, particle sizing using the time-shift technique necessarily requires a measurement of the particle speed. The time shift between scattering orders/modes is measured and this must be related to the volume displacement, hence to the particle size, through speed. Several authors [3, 4] achieved this using two laser beams in a time-of-flight fashion. However the velocity based on time-of-flight yields only one velocity component, which is not sufficient in many applications. Therefore in the present study a two-velocity component velocity measurement using a backscatter laser Doppler system is proposed.

Evidently, to obtain the time-shifted scattering order/modes, a highly focused beam must be used. There are two approaches to achieve this. In the first approach an additional beam of different colour can be added to the laser Doppler system, used solely to implement the pulse displacement technique. Obviously separate receivers are required for the sizing and velocity channels respectively. Alternatively, the two intersecting beams of the laser Doppler themselves could be highly focused, from which the time-shifted signals would also be generated. For such a system no additional receivers are needed, but the laser Doppler optics must be modified to produce a very small illuminated volume. The first approach will be referred to as the single beam technique, the second as the laser Doppler technique.

In the second approach a separate set of virtual measurement volumes will exist for each incident beam and each detector. As discussed in [7] the optical arrangement shown in Fig. 2 is very convenient for this case. In this system the beam-intersection angle is kept small and the detectors are placed symmetrically in the same plane as the incident beams. This optical configuration corresponds exactly to a planar backscatter phase Doppler arrangement. In keeping with the notation used for phase Doppler systems, the angle ψ is then known as the elevation angle and the off-axis angle is $\phi = 180$ deg .

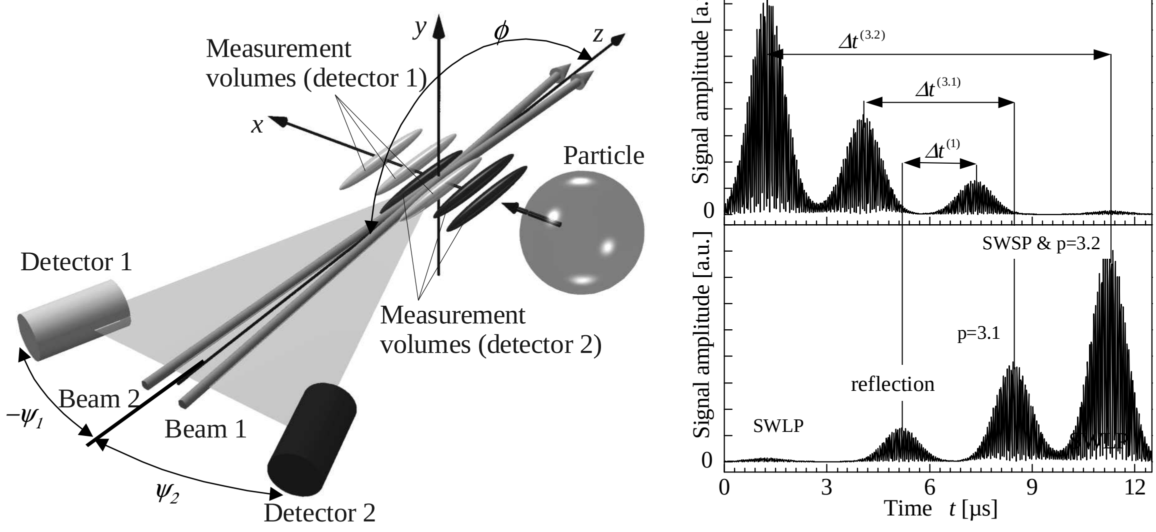

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Fig. 2: Planar laser Doppler system in backscatter. **a** Optical arrangement and virtual measurement volumes; **b** Signals from two receivers and the time shifts to be measured

The signal recorded on each of the detectors in Fig. 2a consists of four distinct fractional Doppler bursts (Fig. 2b) corresponding to the scattering orders/modes shown in Fig. 1 for the single beam. The order of the fractional signals is reversed for each detector. The size information is available by measuring the time shift, either between different orders on the same detector or between the same orders on different detectors, the latter shown in Fig. 2b.

If the pulse displacement method is used, i.e. only one beam is used, then no Doppler modulation will be observed in the fractional signals. Typical signals received at a single detector for both methods are shown in Fig. 3. Both signals have identical envelope structure and equally shifted scattering orders. In Fig. 3 simulations using FLMT and measured signals are shown, demonstrating that the simulations are highly reliable for further design of the system.

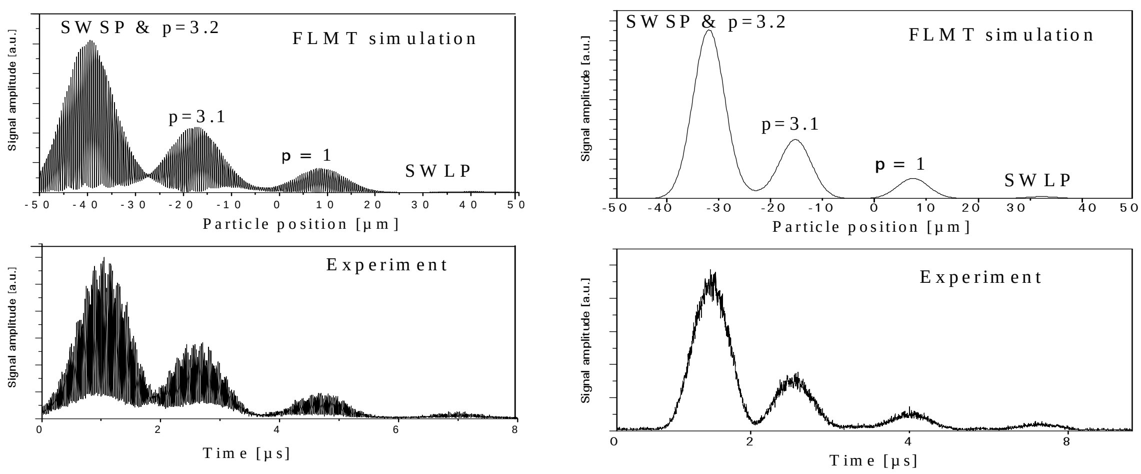

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Fig. 3: Signal at a single detector ($\psi = 25$ deg, $\lambda = 514.5$ nm, $d_p = 80$ μm, $d_b = 20$ μm). **a** Laser Doppler time-shift system ($\Theta = 7.4$ deg); **b** single beam system

2.2 Influence of the particle size, trajectory, refractive index and shape.

The signal characteristics of a laser Doppler time-shift arrangement were studied in [7] and some of the more important points for its practical implementation are briefly summarized here.

For very small particles, the fractional signals from a single detector begin to overlap increasingly. Therefore, the time shift is better measured between like orders from different detectors, since then no overlap exists, as indicated in Fig. 2b. Furthermore, the measurement is then less sensitive to the particle trajectory along the *z* axis.

The signal generated from the surface waves exhibits the highest sensitivity to particle size and the least sensitivity to other influencing parameters.

The reflected signal exhibits the weakest sensitivity to size, but is also completely insensitive to relative refractive index. The refractive index influences on the position of the $p = 3.1$ fractional signal, which exhibits a monotonic but non-linear increase of time shift with relative refractive index. Unfortunately, the $p = 3.1$ fractional signal is also sensitive to the shape of the particle. Therefore, either refractive index can be measured or the variations of the particle shape can be discriminated, but not both at the same time.

The time shift is determined from the position of the envelope maxima. For trajectories parallel to the *x* axis the time shift is a direct measure for the volume displacement. In the case of oblique trajectories, this time shift leads to a systematic error of the volume displacement, as illustrated in Fig 4. For this reason the velocity component in the *y* direction must be measured for further corrections, which necessarily requires a two-velocity component laser Doppler system.

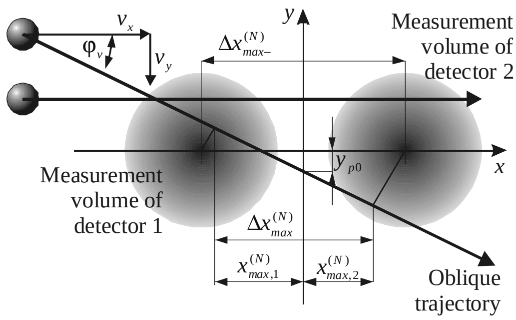

Fig. 4: Influence of oblique particle trajectories on signal maxima

3. Particle sizing using the time-shift or pulse-displacement technique

Size information can be extracted by examining the time shift between signals of like scattering order/mode at different detectors and, using the particle velocity, converting this to a volume displacement. For either the laser Doppler system considered here or for a single beam along the *z* axis, the time shift simplifies to [1]

$$\Delta t_{12}^{(1)} = \frac{d_p}{v_x} \sin \frac{\psi}{2} \qquad (1)$$

A normalized displacement or normalized incident point position, independent of particle size, can be defined by normalizing Eq (1) with the particle radius $r_p = d_p / 2$.

$$\delta^{(p)} = \frac{\Delta^{(p)}}{r_p} \approx \frac{\hat{x}^{(p)}}{r_p} \quad , \qquad \Delta t_{12}^{(p)} \approx \frac{d_p}{v_x} \delta^{(p)} \qquad (2)$$

For reflection $\delta^{(1)} = sin(\Psi/2)$. For refraction and higher scattering orders the normalized displacement is influenced additionally by the relative refractive index m. For $p > 2$ the normalized displacement can be computed using geometrical optics [1]. For every ray path, e.g. either reflection or second-order refraction, the resulting time shift is given by

$$\Delta t_{12}^{(p)} = \frac{d_p}{2v_x}\left(\delta_1^{(p)} - \delta_2^{(p)}\right) \quad (3)$$

where δ_1 and δ_2 are the respective relative displacements for detectors 1 and 2. δ_1 and δ_2 are defined by the optical geometry (and relative refractive index). The particle diameter is found by measuring the velocity v_x and the time shift of the considered scattering order/mode and solving Eq. (3) for d_p and for particles moving parallel to the x axis. For other trajectories with $v_y \neq 0$, corrections of the time shift must been made by measuring the v_y velocity component.

4. Simulations

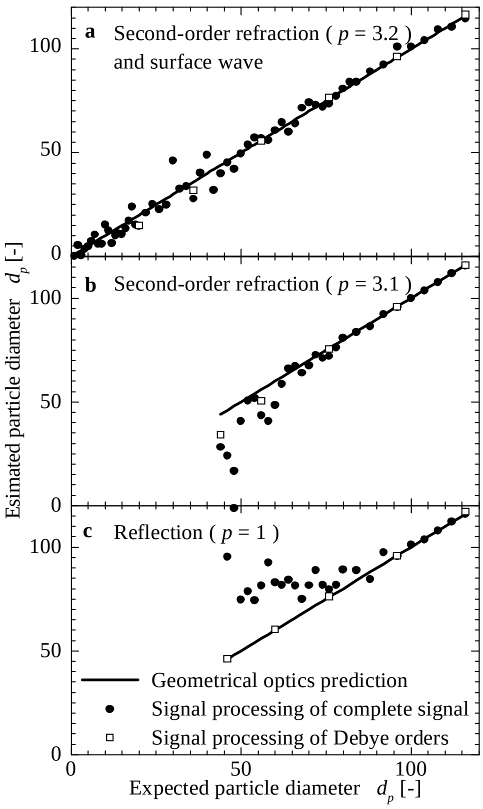

Fig. 5: Particle size estimates using various fractional signals

Particle sizing using the time-shift technique has been simulated with FLMT. The simulations were performed for the detector elevation angles $\psi_1 = 20\,\text{deg}$ and $\psi_2 = -20\,\text{deg}$, and for a measurement volume diameter of $20\,\mu\text{m}$. The results are shown as solid symbols in Fig. 5 for time shifts measured from the different fractional signals. The best results are achieved for the surface wave (short path) + refraction ($p = 3.2$) and the accuracy increases for larger particles. The increased scatter for small particles (for all fractional signals) arises because of the increased overlapping of fractional signals, hence the uncertainty in determining the envelope maximum.

As expected, the smallest measurable particle size using this technique will be determined by the focused size of the measurement volume ($d_{p,min} \approx 20\,\mu\text{m}$). Evidently the lower sizing limit is not sufficient for many applications. The obvious way to improve the sizing range is to decrease the size of the focused beam, thus improving the separation of the scattering orders. Simulations of both the laser Doppler system and the single beam system have been carried out for a focused beam of 5µm. The sizing results are presented in Fig. 6.

The laser Doppler based technique shows large sizing error scatter at small sizes and a systematically increasing error with increasing particle size, which is not observed for the single beam arrangement. This error is caused by the erroneous velocity estimation. For the laser Doppler with the beams focused to 5 µm, the fringe spacing in the probe volume is not constant, but diverges strongly from the center. This leads to a systematic velocity error as the particle size increases and the incident points on the particle surface are displaced away from the center of the measurement volumes. If the correct velocity is used in the simulations, then the error disappears and the results agree with those of the single beam arrangement Fig. 6b.

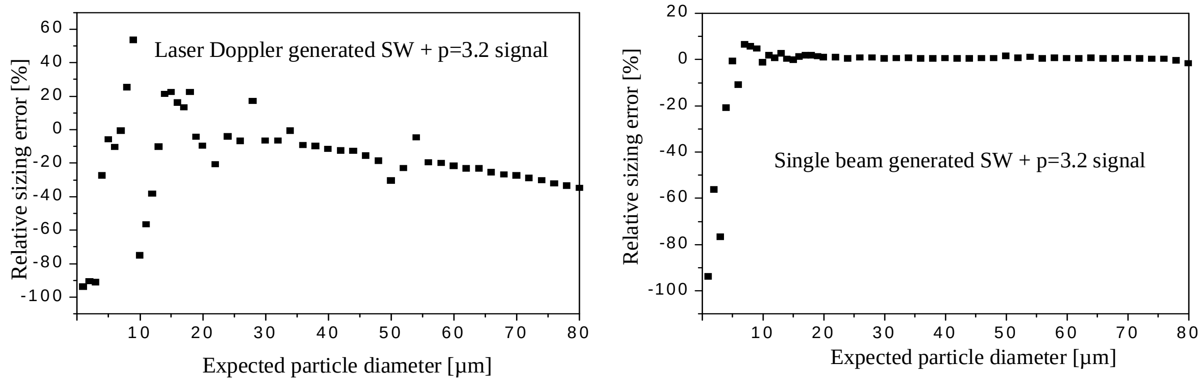

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Fig. 6: The relative error of particle sizing with the SW component and a beam diameter of 5 µm **a** laser Doppler system; **b** Pulse displacement system

5. Practical realization and experimental verification

The results of the previous section suggest that an optical arrangement based only on the focused beams of a laser Doppler system will not allow sizing of small particles. On the other hand, the single-beam arrangement still requires a velocity measurement. Therefore, a combination of a two-velocity component laser Doppler system (not necessarily highly focused) and a highly focused central beam of a different colour, with corresponding separate detectors, appears to be the ideal solution. One obvious drawback of such a system is that the particles must pass through the center of the laser Doppler volume to be also sized. Furthermore, any trajectory deviating from the *x* axis will lead to a loss of fractional signals. A solution to both of these difficulties is afforded by using not a highly focused beam but a highly focused light sheet. In this case, virtual light sheets will exist for each scattering order/mode, as shown in Fig. 7. Oblique particle trajectories will still lead to signals with all fractional components.

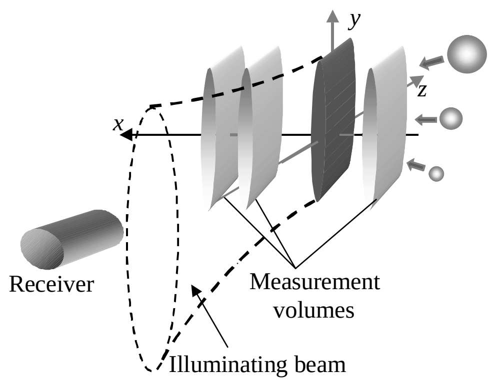


Fig. 7: Virtual measurement volumes for the light-sheet illumination

The final optical arrangement for the sizing instrument is shown in Fig.8. As a basis for the setup a standard Ar-Ion based laser Doppler system configured for backscatter operation is used. An additional light sheet is generated

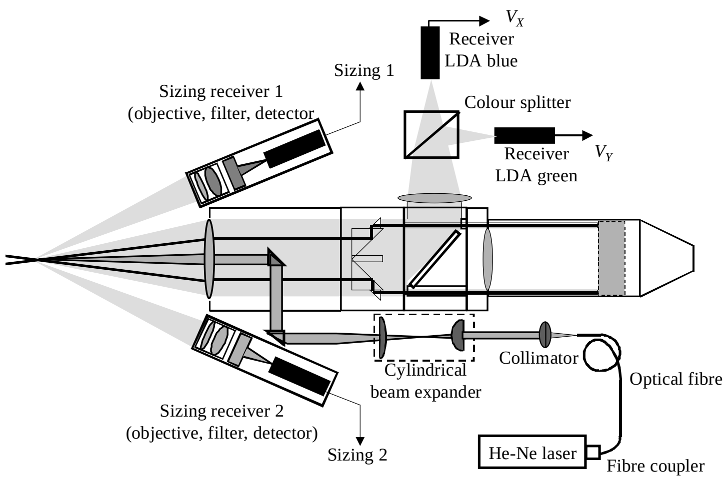
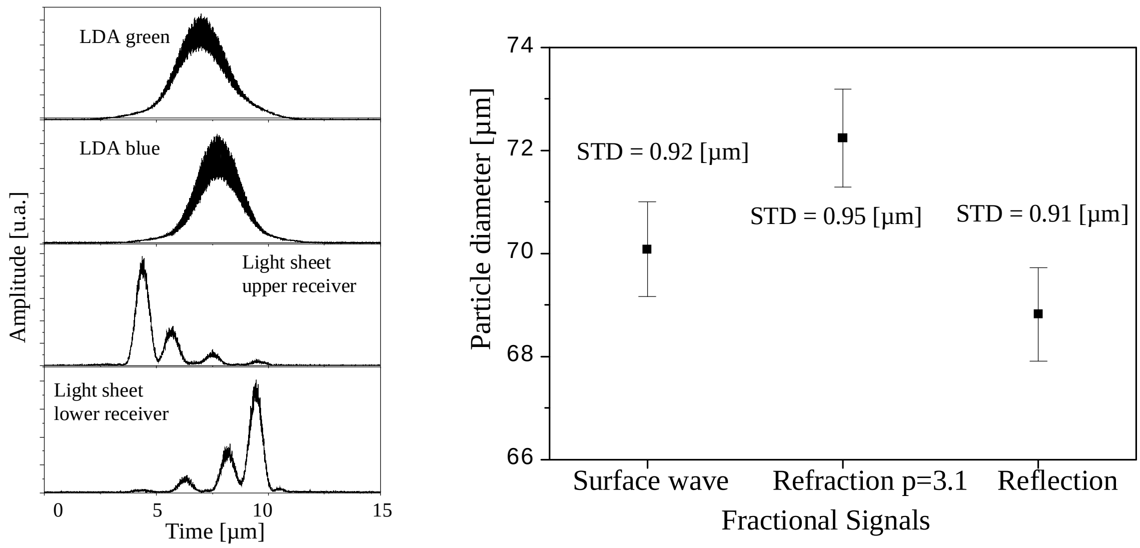


Fig. 8: Optical arrangement for the experimental sizing instrument

using a He-Ne laser, delivered to the probe by an optical fiber, and then focused by a cylindrical beam expander. The light sheet is centered in the laser Doppler measurement volume. Two additional detectors equipped with red interference filters are mounted symmetrically to the optical axis of the probe. The signals from the four detectors (two velocities, two size) are sampled and stored by a transient recorder and then passed on to a PC for signal processing [7].

In Fig. 9 the experimental signals produced by a water drop are depicted. The conditions were as follows: laser Doppler wavelengths of 0.514µm and 0.488µm, beam-intersection angle ±5.3°, beam-waist diameter 50 µm; particle sizing channel with 15µm x 150µm light sheet and receiving angles of ±27°. Water droplets of diameter 70.7µm were generated using a vibrating orifice particle generator. With this particle size all fractional signals are separated and any of them can be used to obtain the particle diameter. This is demonstrated in Fig. 9b, in which the sizing results for different scattering orders are shown. For the variance estimate a set of 20 sequential signals has been used. The reproducibility of the measurements was very good, which resulted in very small scatter of the measured size, probably caused by actual diameter variations of the generated particles.



a **b**

Fig. 9: Experimental particle sizing. **a** Recorded signals; **b** Particle diameter obtained with different fractional signals (STD – standard deviation)

In the above discussion a transparent particle with a smooth surface was assumed. The smooth surface is necessary, but the transparency is not. The instrument can be used for the sizing of absorbing and opaque particles as well, since the reflected fractional signal is available in both cases. For the partially absorbing particles the ratio of the fractional signal amplitudes will also depend on the particle size. This may be used as an additional validation factor and gives the basis for further particle characterization.

The scattering characteristics of inhomogeneous particles can be very difficult to simulate and therefore some experiments were first performed to investigate the instrument performance with such liquids. As a first test, different concentrations of milk were used. Fig. 10 shows the signals from the sizing channel for two drops of different milk concentrations and approximately equal size. As can be inferred from the signals, the reflection related peaks are clearly seen in both cases. For the dissolved milk (25% milk in water) the other fractional signals are also partially identifiable, but in the case of 100% milk all rays propagating inside the particle are nearly completely diffused by the inhomogeneities. The size information can be definitely obtained from the time-shift of the reflected component and additionally from the width of the total pedestal. The possibility of estimating concentration must be further studied.

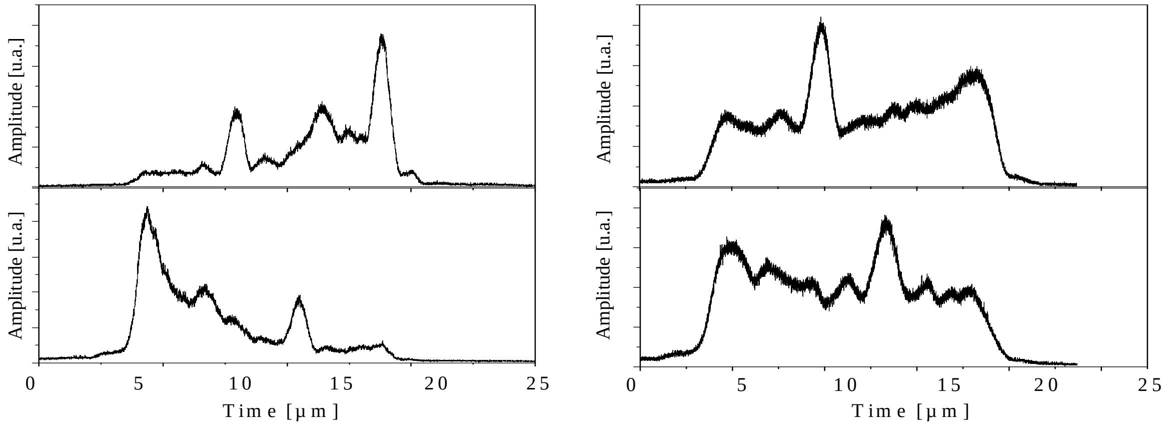


Fig. 10: Signals recorded from the sizing detectors. **a** 25% milk and 75% water; **b** 100% milk

6. Conclusions

Two possible realizations of the time-shift based particle sizing technique in backscatter have been studied – the laser Doppler time-shift technique and a technique combining the pulse displacement particle sizing with a laser Doppler based velocity measurement. The time-shift related signal parameters of both versions are completely identical. The results demonstrate that both techniques work well for particle diameters larger than the beam waist diameter. For the laser Doppler time-shift instrument the reduction of the probe volume size leads to the loss of the precision for the particle velocity and size measurement, therefore the sizing is possible only for the particles larger than 20-30 µm. This is not the case for the combined instrument, since the measurement volume dimensions can be controlled independently.

A novel optical arrangement for the combined instrument is introduced, which uses a light sheet for the generation of the time shifted fractional signals instead of a focused laser beam. To demonstrate this new technique, simulated and experimental signals were obtained and processed. It is found that the newly proposed combined laser Doppler–light sheet method has several important advantages as compared to a standard laser Doppler system and can be used for particle characterization in backscatter. The possibility of sizing inhomogeneous particles has also been tested and found to be feasible.

6. References

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