EPJ Web of Conferences **264**, 01019 (2022) https://doi.org/10.1051/epjconf/202226401019
EFM 2021

Software-based processing system for phase Doppler systems

Jan Jedelsky[1], *Milan* Maly[1*], *Ondrej* Cejpek[1], *Graham* Wigley[2], and *James F.* Meyers[3]

[1]Mechanical Engineering, Brno University of Technology, Brno, Czech Republic
[2]Aero and Auto Engineering, Loughborough University, UK
[3]James F. Meyers, (retired), NASA - Langley Research Center, Hampton, VA, USA

Abstract. A Monte Carlo simulation of Phase Doppler systems has been developed. It consists of three sections, the droplet flow description, generation of the photomultiplier signals and then their processing to determine droplet velocities and the time shift between the signals from the three scattered light detection apertures. With highly realistic Doppler bursts being simulated and processed, the question arises as to whether the signal processing software could be used to process 'real-world' experimental signals. In a preliminary assessment of its capabilities in such a situation, actual spray Doppler signals (from a Dantec fibre-based PDA system with a BSA signal processor) were recorded and used as input to the software signal processor. The signals from the three photomultipliers were input first into a Picoscope and then into the BSA processor. In this way droplet velocities and size estimates would be available from the BSA as control data. The signal outputs were taken as csv files, and input directly into the software signal processor. Initially the software determined the time location of the centre of each signal burst envelop. This approach was shown to measure signal delays from single cycle to multiple cycles. For this experiment, the software was modified by adding a zero-crossing approach to measure the single cycle delays. The introduction of this method should establish the accuracy of the complete software package in the real world as the results from the preliminary experiment show good agreement between the two techniques.

1 Introduction

The Phase Doppler technique, PDA, is accepted as a robust optical method for point-wise simultaneous measurement of size and velocity of particles dispersed in a fluid. It is frequently used for the characterisation of sprays, aerosols and bubbles. This optical diagnostic technique is utilised widely for fluid mechanic experiments and is routinely used in many high-tech laboratories today.

The physical realisation is rather expensive. The instrumentation cost depends on the system specification, robustness, measurement capabilities, extensibility, and variability of the configuration [1]. It ranges from 40,000 €/channel for a basic system to more than 80,000 €/channel for a state-of-the-art system. A significant portion of that price is paid for the signal processor. It is also the hardware and software components that are superseded most often and, after a couple of years updated solutions are offered on the market.

The estimation of droplet or particle size by these commercial PDA systems is only dependent on the specification of the physical configuration of the laser transmitter and receiver systems and the assumption that the light scattering can be determined by geometric optics for either refraction or reflection. The size estimates are derived from determining the phase differences in the Doppler shifted signals, generated by the scattered light from each droplet, arriving at each of the two or three photodetectors in turn.

The size estimates can be extremely accurate if single droplets are probed under simple experimental conditions. As the measurement volume cross section has a Gaussian intensity distribution and that, there is a nominal square law relationship between droplet size and scattered intensity, then the scattered signal intensity becomes a significant factor in estimating droplet size distributions. Furthermore, the light scattering functions for a wide range of sizes are best considered by applying electromagnetic scattering, Mie theory, rather than the simplistic geometric scattering modes of refraction or reflection to determine the probability of measurements over a distribution of droplet sizes.

To understand this issue, a Monte Carlo type simulation program was developed to model phase Doppler systems [2]. The Monte Carlo technique consists of breaking systems down into small units and, using random number generators, develop a realistic approach to the real-world physics. The work is divided into three main sections, the development of a launch strategy of known droplet sizes, the generation of the photomultiplier signals, and then their processing to generate drop size estimates followed by the comparison of these data with the launched data. This provides a linear relationship between dropsize, and the signal time shifts.

The signal processing portion of the simulation measures the Doppler frequency in each signal to estimate

* Corresponding author: milan.maly@vutbr.cz

the droplet velocity. Rather than using measurements of the phase differences between the multiple Doppler-shifted signals the time shift between the arrival times of each signal is used to estimate the dropsize. The transmitter and receiver optical systems are defined as diffraction limited and the laser beams true Gaussian. Optical, and electronic noise sources can also be simulated while the signals generated, being dependant on droplet size, can have intensity levels ranging from photon resolved to photomultiplier saturation levels.

With highly realistic Doppler bursts being simulated and then processed the question arises as to whether the signal processing software could, on its own, be used to process 'real-world' experimental signals. The paper documents an application of the signal processing part to Doppler signals from an actual spray characterization by a Dantec fibre-based PDA system.

2 Material and Methods

In an assessment of the capabilities of the signal processing technique in such a situation, Doppler signals from an actual spray characterization were recorded and used as input to the software signal processor. A Dantec fibre-based PDA system, configured with a transmitter-receiver geometry for refractive scattering, was used with a BSA signal processor. The spray was provided by an artist's air brush.

Initially the software determined the location, in time, of the exact centre of each signal burst envelop. This approach was shown to measure signal delays from single cycle to multiple cycles. For this experiment, the signal processing software was modified by adding a zero-crossing approach to measure the single cycle delays. The introduction of this method should establish the accuracy of the complete software package in the real world as the results from the preliminary experiment show good agreement between the two techniques.

2.1 Principles of phase Doppler systems

The PDA technique (Phase Doppler Anemometry, or less frequently called phase Doppler interferometry) is a point-wise optical measuring method to provide Eulerian description of the flow field with embedded fluid markers. It gives statistical moments of the particle velocity and size. The principle of the technique is illustrated in Figure 1a, and it is detailed by [3]. A continuous-wave monochromatic laser beam is directed into a transmitting optics where it is split into two coherent beams of equal intensity that are intersected symmetrically at a small angle θ by a transmitting lens. The two in-phase beams interfere in the volume of their intersection (the measurement volume[a]) in a way to generate a series of parallel planes[b] of light and darkness (the so called fringes) as shown in Figure 1b. Light scattering from boundaries between two different phases (such as small inhomogeneities, particles or bubbles, present in the particle laden gas or liquid flows or artificially added tracer particles) generate a scattered light signal while passing through the small fringe zone. To eliminate the ambiguity of the direction which the particle passes through the measurement volume, the frequency of one of the beams is shifted by a fixed frequency amount f_0 using a Bragg cell so that the fringe pattern "scrolls" through the measuring volume with a known velocity. A receiver lens[c], placed in a separate receiving optical system, projects a portion of the light and dark interference bands (the fringe patterns) scattered by the particle on to a photodetector (receiver) which produces a "Doppler burst" signal (Fig. 1c) with a Doppler frequency[d], f_D, proportional to the velocity component u_n of particle motion normal to the fringe orientation divided by the fringe separation s:

$$f_D = f_0 + \frac{u_n}{s} = f_0 + u_n \frac{2\sin\theta/2}{\lambda} \tag{1}$$

where λ is the wavelength of the laser light. The light signal is converted into a digital record and processed to provide information on velocity and arrival time of each individual particle.

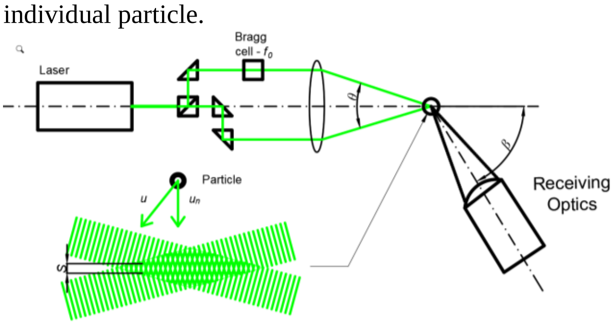

Fig. 1 The principle of the PDA: optical configuration of the system, fringe pattern formed by two coherent laser beams crossing with the fringe.

The Doppler signals are sensed by at least two detectors. The detector pair observes the light scattered by at the same scattering (the so called off-axis) angle, β. The detectors are located symmetrically about the observation plane at angles $\pm\,\psi$ with respect to the plane. A mask with two rectangular and horizontally elongated slits is used to define the elevation angles. A vertical slit can be used to reduce the effective length of the probe volume from where the scattered light is collected.

The Doppler signals collected at the different elevation angles ψ show a phase difference, $\Delta\varphi$, or a time shift with respect to each other. This shift depends on the particle radius R in the scattering direction and increases with increasing the elevation angles of the detectors. It may also depend on the particle/fluid refractive index n_p and may, to some, extent show fluctuations in the size diagram caused by partial wave resonances.

According to [3], the particle size can be determined based on:

[a] The measuring volume has a shape of 3D ellipsoid.
[b] The fringe planes are parallel to the bisector of the laser beams and perpendicular to the plane formed by the two beams

[c] which can be positioned in the forward, side, or backscatter direction
[d] often referred to as the Doppler frequency

• *either the instantaneous phase shift between modulated signal parts of the two detectors (phase Doppler technique)*

• *or the time shift between the signal maxima on the two detectors (time-shift technique)*

For the phase Doppler technique, a simple relationship between particle size and phase shift can be found using geometric optical ray traces based on refraction or reflection:

$$\Delta\varphi = \frac{4\pi R n_p}{\lambda}\,\Phi \qquad (2)$$

The parameter Φ depends on the scattering mode and geometrical configuration of the PDA system [3]. The phase shift $\Delta\varphi$ is determined from the time lag of the two signals, Δt, with respect to the period of the Doppler burst $T = 1/f$ as indicated in Fig. 1b: $\Delta\varphi = 2\pi\Delta t/T$. The phase shift becomes ambiguous when it exceeds the 2π period. In this case a third detector is placed at a smaller elevation angle[e].

This provides two pairs of detectors with different phase relationships to help extend the dropsize range. Even so the maximum phase measurement will still not exceed $5\pi/2$. For the larger drop sizes the depth of the signal cycle modulation decreases making phase difference measurements uncertain. The dropsize measurement range is generally accepted to be no better than 45:1. However, these limitations are based only on the geometric calculations for the phase dropsize relationship and the signal visibility. The laser power, PM voltage and amplification levels determine the minimum detectable signals from small droplets and the PM saturation for large droplets.

Eqs. (1 and 2) show that the probed velocity component and particle size linearly depend on the measured frequency and phase shift respectively multiplied with a physical and geometrical constant.

The time shift approach determines the location in time, i.e. the mark, in each of the three sequential signal bursts that have the same signal characteristics. The first consideration would be to use the peak cycle signal to establish the mark location, but, with no synchronisation between the A/D sampling frequency and the Doppler signal frequency the marks would not have the same representative locations. This would also be the case for when the peak cycle is not at the mid-point of the signal burst.

The method used was to invert the signal burst, then apply a trigger level that was above the base noise. The samples, with amplitudes greater than the trigger level, are then accepted and used as the weight function in a weighted average process applied to the whole signal burst. The time shift delays are determined by the difference between the weighted average time of signal B subtracted by the weighted average time of signal A. Likewise, the same procedure is applied to the times between component C and component A. These two delays are then converted to two estimates of the droplet size based on equations (1) and (2).

The Doppler bursts from photo detectors are sent to a signal processor which extracts the velocity, transit and arrival time and possibly size data in digital form for further analysis. The opto-electronic part of LDA/PDA instruments is supplemented with a computer that controls the collection, manipulation, analysis, and data presentation.

[e] Present PDA systems use typically three detectors integrated into a single fiber-optic receiver.

2.2 Setup of phase Doppler system

The actual Phase Doppler system used a Spectra Physics 164 argon ion laser, operating in all lines mode, coupled with a Dantec fibre flow transmitter box, 60X41 and linked to a 112 mm fibre probe, 60X81 fitted with a 2X beam expander. For this work only the green, 514 nm, wavelength was selected. The output beam polarization from the probe was in the horizontal plane, i.e., parallel to the fringes in the measurement volume. The receiver was the Dantec 57X50. The essential optical parameters are given in Table 1.

Table 1. Optical set up parameters.

Transmitter		Receiver	
Beam diameter	2.70 mm	Aperture dia.	78 mm
Beam separation	75.24 mm	Lens aperture mask	A
Lens focal length	500 mm	Lens focal length	500 mm
Fringe spacing	3.429 µm	Spatial filter – slit	100 µm
Probe volume dia.	122.9 µm	Scattering angle	70 deg.

These settings were inherited from a previous experiment on a confined spray. There was no attempt whatsoever to optimise these settings to suit the measurement of the droplet size distributions contained in a spray generated by an artist's air brush as used in this study. However, this does not detract at all from the scientific integrity of the work here which was to use the Phase Doppler system purely as a tool to generate Doppler signals that could be then digitised and processed in software.

The air brush is a precision air blast atomizer. It was positioned 30 cm vertically above the measurement volume and operated with 2 bar compressed air. The working fluid was water.

The signals from the three photomultipliers were input first into a Picoscope 3405B with a 1 MOhm input impedance and then, via BNC T pieces, into the BSA processor. In this way droplet velocities and size estimates would be available from the BSA. The Picoscope is a very cost effective four channel A to D convertor with fast sampling, digital triggering, and a deep memory. In this preliminary experiment it was set up to record the three channels of photomultiplier signals with 668 sequential

Doppler bursts at a sampling rate of 0.25 GHz. The signal outputs were taken as csv files for ease of viewing and input into the software signal processor.

The photomultiplier, PM, voltage levels were determined using the signals displayed by the picoscope. The peak voltages were judged to be when signal limiting was first observed. The BSA PM output monitor signal should not be used as the output is non-linear making choice of the peak voltage levels for balanced Doppler bursts ambiguous. Furthermore, it adds noise and time/ phase shifts to the signals when compared with the PM signals direct.

3 Results and Discussion

3.1 Doppler Bursts and Processing

Two Doppler bursts from apertures A and C for one droplet are shown in Fig. 2 as acquired by the PDA system.

The time shift approach, as with any measurement technique, has limits and problems. The time shift approach does not have the 5π/2 phase limit of cycle-based methods, but it does have limits regarding the signal-to-noise in the signal bursts. Fig. 2 shows what looks like noise on the Doppler burst, but it is not. It is due to the interaction of the Picoscope sample frequency and the Doppler frequency. A peak of one frequency at the same occurrence of the other frequency may be a peak and peak, but it could be a positive in one and a negative in the other. This can be excessive if there are only a few of the amplitude steps within the signal burst. For the Doppler burst shown in Fig. 2 this is not a problem as the displayed voltage levels, 31, are considerably greater than the minimum resolution. However, if there are only 10 or less voltage steps in a Doppler burst then the burst centre could be far from the weighted average mark. This is particularly the case for small drop sizes. Also, a close up of the Channel A and Channel B signal edges, show that the small difference could be controlled any unseen characteristics in Channel A. This would also affect the location of the Channel A mark. Thus, the voltage level and voltage steps should be set to reduce the potential shift in the delay measurements.

The signal bursts captured by the Picoscope are transferred to the computer and stored. The signal bursts are then read by the software and the capture checked of a second signal burst occurred and the limits where there is no crossing of a second signal burst and/or noise levels. Once the signal burst limits are set, the pedestal within the signal burst is determined by using a first-in-first-out smooth technique. The pedestal is then subtracted from the signal burst leaving the amplitude centred at zero volts. The positive side is separated along with the inverted negative side. The centre of each side is determined by a weighted average. The two-time locations are averaged to obtain the mark of that signal burst. The time difference between the A and B marks yield the delay time between A and B.

In order to determine measurement accuracy, a small part of the program was added that would remove the delays on B and C signal bursts to zero when compared to A. A uniform random number generator would then pick a droplet size from the droplet range. The conversion of delay to droplet was inverted to yield the A:B and A:C delays for the selected droplet size. B and C signal bursts are then adjusted in time to set the calculated delays for the time between A mark and B mark, and between A mark and C mark. This approach was used on the signal bursts obtained by the PDA because the marks, especially B mark did not satisfy the A:C/A:B ratio set by the mask. The program was set to a 1-to-20- micron droplet size range, and the 668 array was processed. Since each droplet size was known, the comparison with the droplet size obtained by the program yields the measurement error for each droplet.

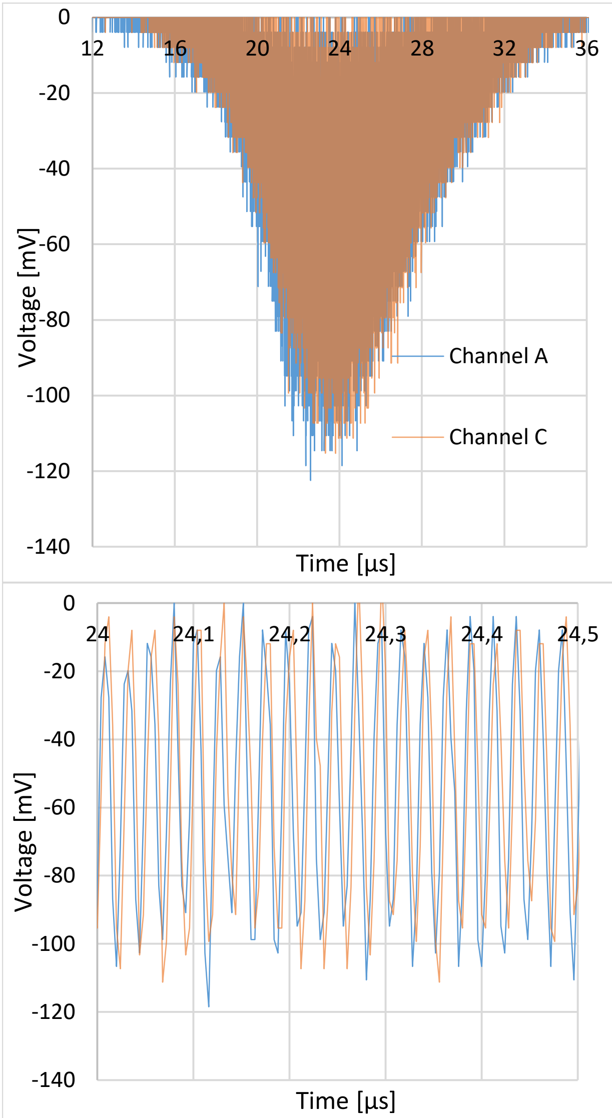

Fig. 2 Doppler Burst acquired by the PDA system. Top: The whole burst, bottom: detail in the time resolved signal.

The average error was +/-0.5 microns in both A:B and A:C droplet sizes. The processing time was 15 seconds to acquire the results and measurement errors for all 668 droplets. The computer was a standard PC with an i7 core processor, an M.2 P**CI**e SSD drive, and the Windows 10 operating system.

The processing of the Doppler burst of Channel C is shown in Fig. 3. In the first stage, a) the PM signal is simply inverted from the negative level to a positive level. In b) the pedestal has been determined and shown overlaying the signal burst as a red line from a 300-sample smooth. The view of the separated positive and negative halves as described above is shown in c). In this case the red pedestal plot was from a 100-sample smooth. Areas below 70% of the peak amps have been removed to reduce noise, and the peak amplitude has been set to 1.0. The change in amplitude makes it easier to match the characteristics of the signal bursts. The positive data are in black and the inverse negative data are green. The weighted average technique is used to determine the central time location for each, and the average of the two marks become the mark to be used with the A mark to determine the A:C delay.

The signal processing program has been recently increased by adding two different cycle techniques to determine what their measurement accuracies were. As mentioned above, the time technique has the advantage of no limits regarding delays, and the cycle technique has the advantage that noise, assuming high signal peak levels, does not cause problems. The objective was to use the time delay technique to determine the delays and the cycle techniques to verify the measurements. Running the same 668 array data, the measurement accuracy in all three techniques was +/- 0.5 microns over the range 1 to 20 microns.

3.2 Droplet size estimations

The time differential between the burst signals from apertures A and B, and A and C, yield the delays that are then converted to the A:B droplet size, and A:C droplet size. The conversion equations are determined by using the optical characteristics of the PDA system and the uniform random number generator to input a known two delays and droplet size into the signal bursts obtained from the spray. (The actual delay of the centroid is set to zero in the A, B, and C signal bursts. Then the B and C signal bursts shifted in time based on the random droplet size.) The measured delays are then plotted, one set for A:B and the other for A:C. The equalizations can be determined for droplet size versus delay. The signal processing software has two routes. The prime one is to take the signal bursts as they come and use the weighted average to determine where the mid-point is. If the three signal bursts are not identical, the location in time of the weighted average can change, yielding measurement errors – with no way to determine how much or why. In order to determine if the software is correct, was to add a second route. The signal bursts from the A/D convertor have the centroids based on the delays found (as in route 1). In order to control the measurement, the B and C signal bursts are shifted in time to match the centroid in A, i.e., no delays at all. A uniform random number selects a droplet size, and the A:B and A:C delays calculated. The B signal burst is now shifted to the A:B delay obtained between the A and B centroids. Likewise, the C signal burst is now shifted to the A:C delay obtained between the A and C centroids. The resulting signal bursts are then entered into the same signal processing path as route 1. The difference is that the delays are known and if the measurements yield the same delays, the software is working correctly, and processing errors determined over

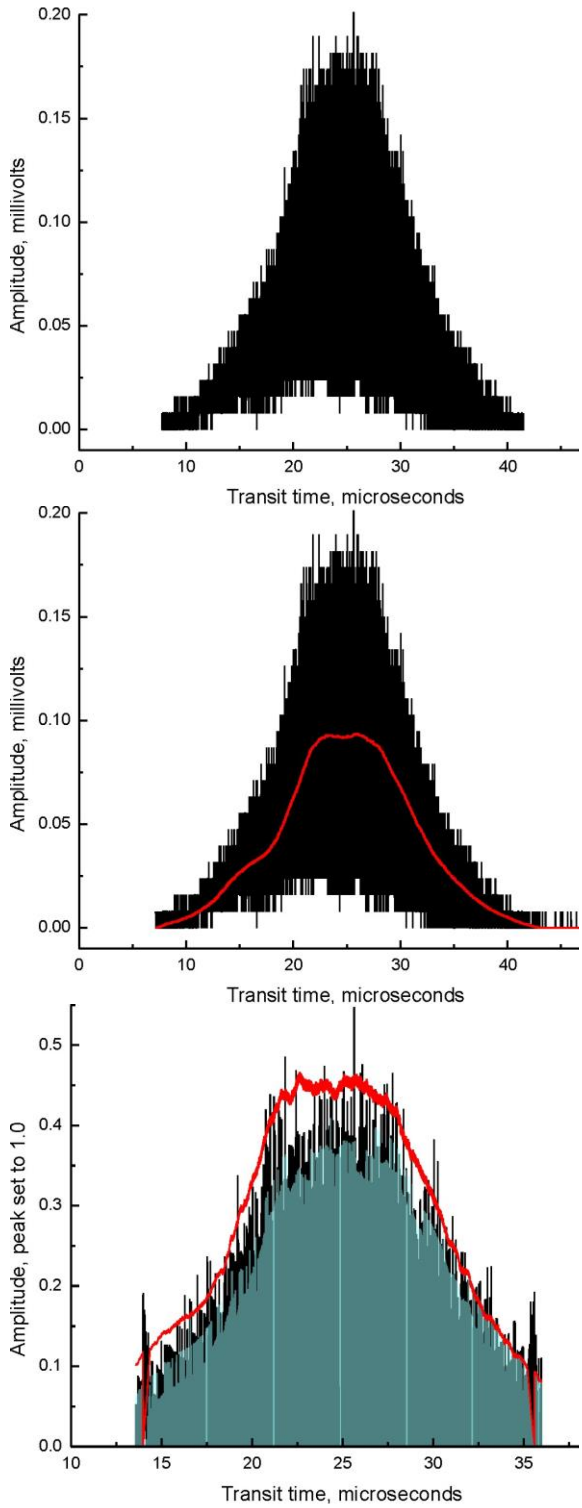

Fig. 3 From top: a) original inverted burst, b) The overlay of the pedestal on the signal burst, c) processed burst.

the entire 1–20 micron range in a droplet by droplet method. The software was run with synthetic signals – data set with uniform random droplet size was generated. Illustrative results in the form of dropsize histogram are shown in Fig. 4. Dropsize histogram of the measured data set that was acquired by the BSA processor is given in Fig. 5. Since the histogram in Fig. 4 was obtained for uniform random droplet size, it is not directly comparable to the BSA data.

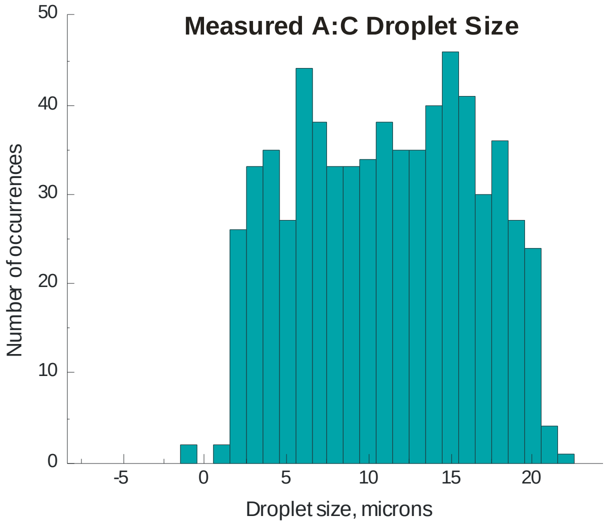

Fig. 4 The resulting size histogram.

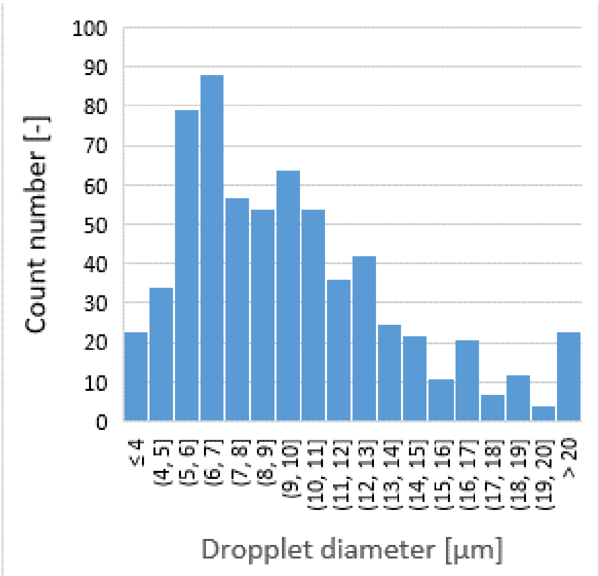

Fig. 5 Dropsize histogram as acquired by the BSA processor.

4 Conclusion

A processing part of a Monte Carlo simulation of Phase Doppler systems was used to determine droplet sizes from spray measurements. It was intended to replace the signal processing part of actual PDA system (Dantec fibre-based PDA system with a BSA signal processor and three channel receiver). The software was modified by adding a zero-crossing approach to measure the single cycle delays. The droplet sizes estimation was based on the time shift between signals from the three scattered light detection apertures.

Since the histogram obtained from the software was run with real signal bursts, with the delays set to known values as obtained from selected droplet sizes from a uniform random droplet size. The results are not comparable to the BSA data. It just illustrates that the signal processing software is working as expected and it could be used to process 'real-world' experimental signals. This is work in progress, and that signal problems should be removed with the upgraded A/D convertor. The alternative software-based signal processing approach will be widely usable with advantages of sizing non-transparent liquids (measurement in back-scatter mode), measurements above 2π for all scattering modes without a need to resolve between them and hypothetically also for multiple bursts.

Acknowledgement

This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic under the project LTAIN19044 funded from the program INTER EXCELLENCE (INTER–ACTION).

List of Symbols

f_0	Frequency shift by Bragg cell [Hz]
f_D	Doppler frequency [Hz]
T	Period of Doppler burst [s]
u_n	velocity component of particle motion normal to the fringe orientation [m/s]
s	fringe separation [m]
β	Scattering angle [°]
λ	Wavelength of the laser light
ψ	Elevation angle [°]
Φ	Parameter dependent on scattering mode [-]
$\Delta\varphi$	Phase shift [°]
Δt	Time shift [s]
θ	Angle of intersecting laser beams [°]

References

1. F. Lizal, J. Jedelsky, K. Morgan, K. Bauer, J. Llop, U. Cossio, S. Kassinos, S. Verbanck, J. Ruiz-Cabello, A. Santos, E. Koch, and C. Schnabel, European Journal of Pharmaceutical Sciences 113, 95 (2018).
2. J. F. Meyers, Graham Wigley NASA/TM–2020-5006713 (2020)
3. H.-E. Albrecht, M. Borys, N. Damascke and C. Tropea, Laser Doppler and phase Doppler measurement techniques. (ISBN 978-3-642-08739-4 ISBN 978-3-662-05165-8, DOI 10.1007/978-3-662-05165-8, Springer, Berlin; New York, 2003).