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Measurements of cloud droplet size distributions and number concentrations at a mountaintop laboratory

Moein Mohammadi

Institute of Geophysics - Faculty of Physics - University of Warsaw

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Measuring cloud droplets microphysical properties:

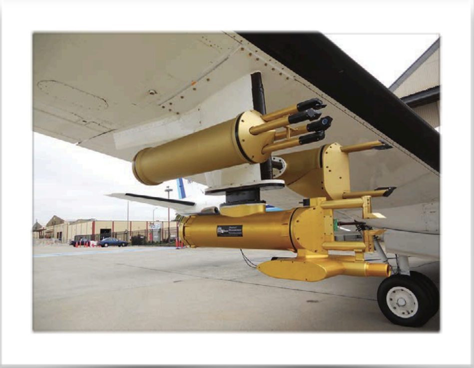
1. Remote sensing:

   Data collected by satellites, radars and radiometers

2. In situ sampling:

   A. Airborne

   B. Ground-based



In situ sampling instruments:

1. Spectrometers
2. Imaging devices:
    A. Holography
    B. Shadowgraphy

Spectrometers:

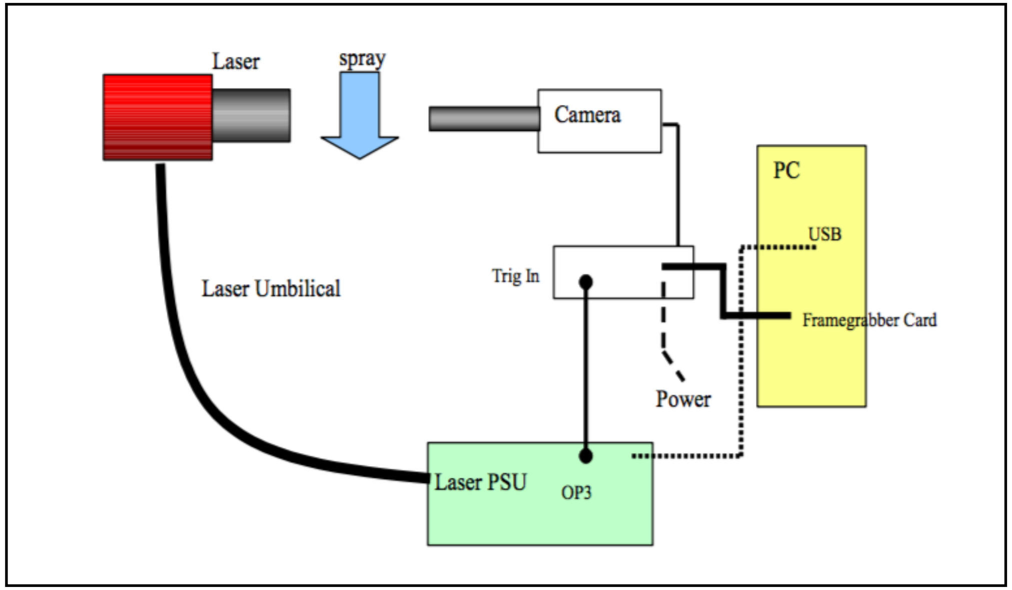
Forward Scattering Spectrometer Probe (FSSP)	Cooper (1988)	Gerber et al. (1999)	Coelho et al. (2005)
Cloud Droplet Probe (CDP)	McFarquhar et al. (2007)	Lance et al. (2010)	Lance et al. (2012)
Cloud & Aerosol Spectrometer (CAS)	Lance (2012)	Glen & Brooks (2013)	Barone et al. (2019)
Phase Doppler Interferometer (PDI)	Bachalo & Houser (1984)	Chuang et al. (2008)	Kumar et al. (2019)

Imaging instruments:

HOLODEC and HALOHolo	Fugal & Shaw (2009)	Schlenczek (2017)	Lloyd et al. (2020)
HOLIMO, HoloGondel and HoloBalloon	Hennenberger et al. (2013)	Beck et al. (2017)	Ramelli et al. (2020)
Cloud Particle Imager (CPI)	Lawson et al. (2001)	Connolly et al. (2007)	Woods et al. (2018)

VisiSize D30

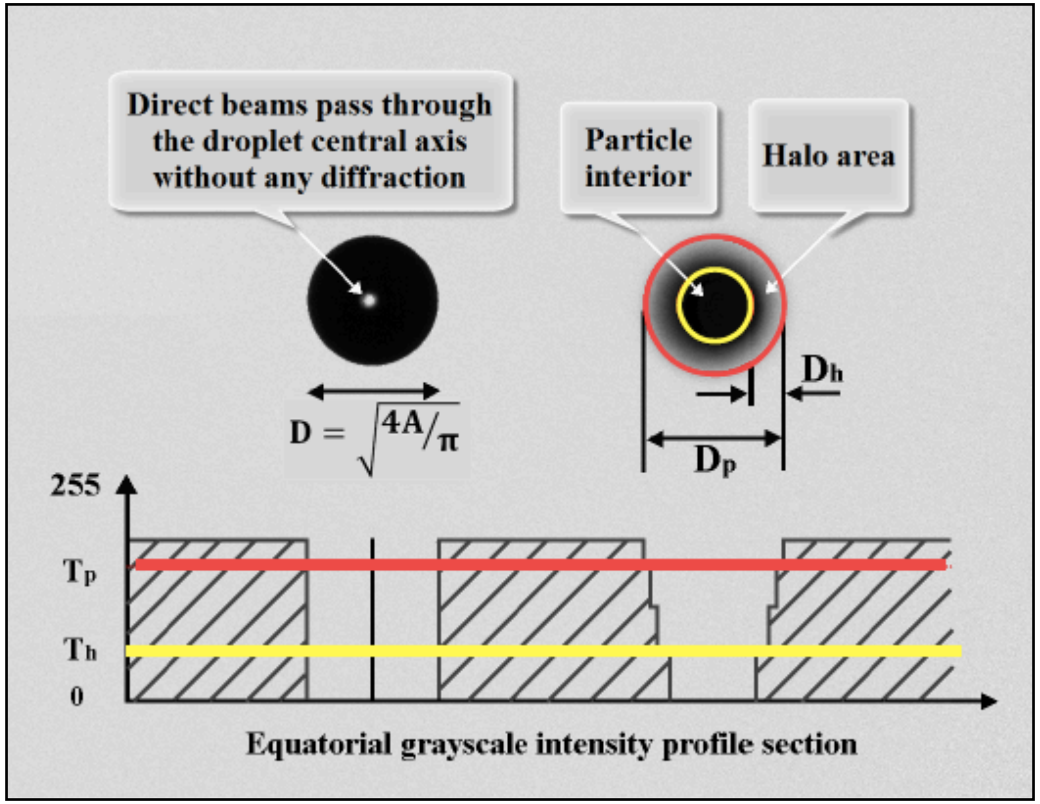
- A shadowgraph instrument by Oxford Laser Ltd.
- Originally for diagnosis of industrial sprays
- Droplets/particles sizing & velocimetry
- Spherical/non-spherical + In-focus/out of focus



Schematic representation of VisiSize D30 setup

Figure reproduced from (Kashdan et al., 2003)

- **Particle/Droplet Image Analysis (PDIA)**
  Kashdan et al. (2003, 2004)



Thresholding method showing droplet shadow image and intensity profiles for in-focus droplet (left) and defocused droplet (right).

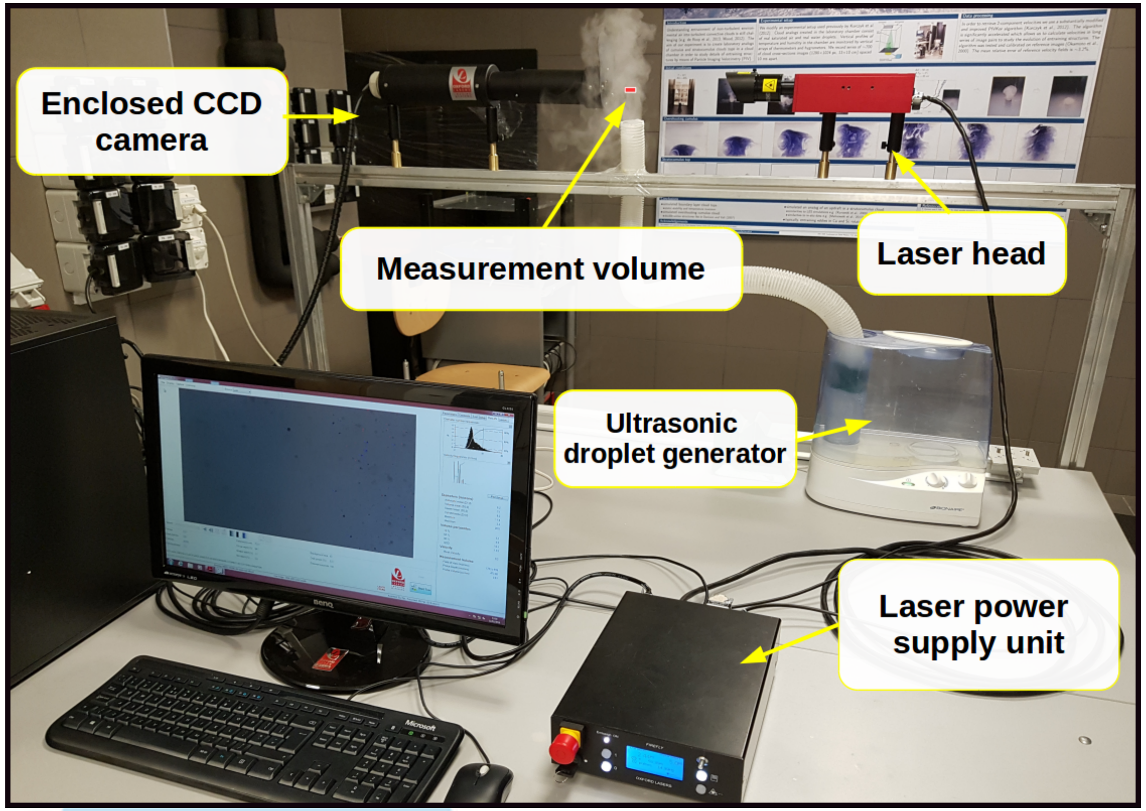
System overview

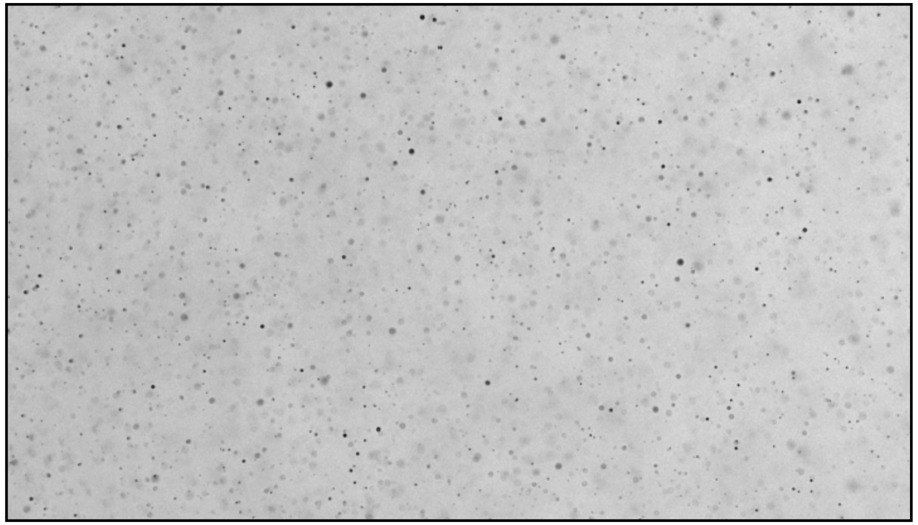
VisiSize D30 specifications			
Camera chip [pix × pix]	1952 × 1112		
Camera pixel [µm]	5.5		
Frame rate [fps]	30		
Wavelength [nm]	808		
Laser pulse duration [µs]	0.1–5.0		
Lens setting	×1	×2	×4
Magnification	1.49	2.97	6.12
Effective pixel size [µm]	3.69	1.85	0.90
Resolution [µm]	6.9	3.7	2.0
Field of view [mm × mm]	7.20 × 4.10	3.62 × 2.06	1.75 × 1.00
Depth of field [mm]	50.0	16.6	5.2
Sample volume [cm^3]	1.48	0.123	0.0092
Volume rate [$cm^3\,s^{-1}$]	44.3	3.71	0.28

Properties of the VisiSize D30 system for three different lens magnification settings provided by Oxford Lasers Ltd.

Laboratory experiments (Warsaw)

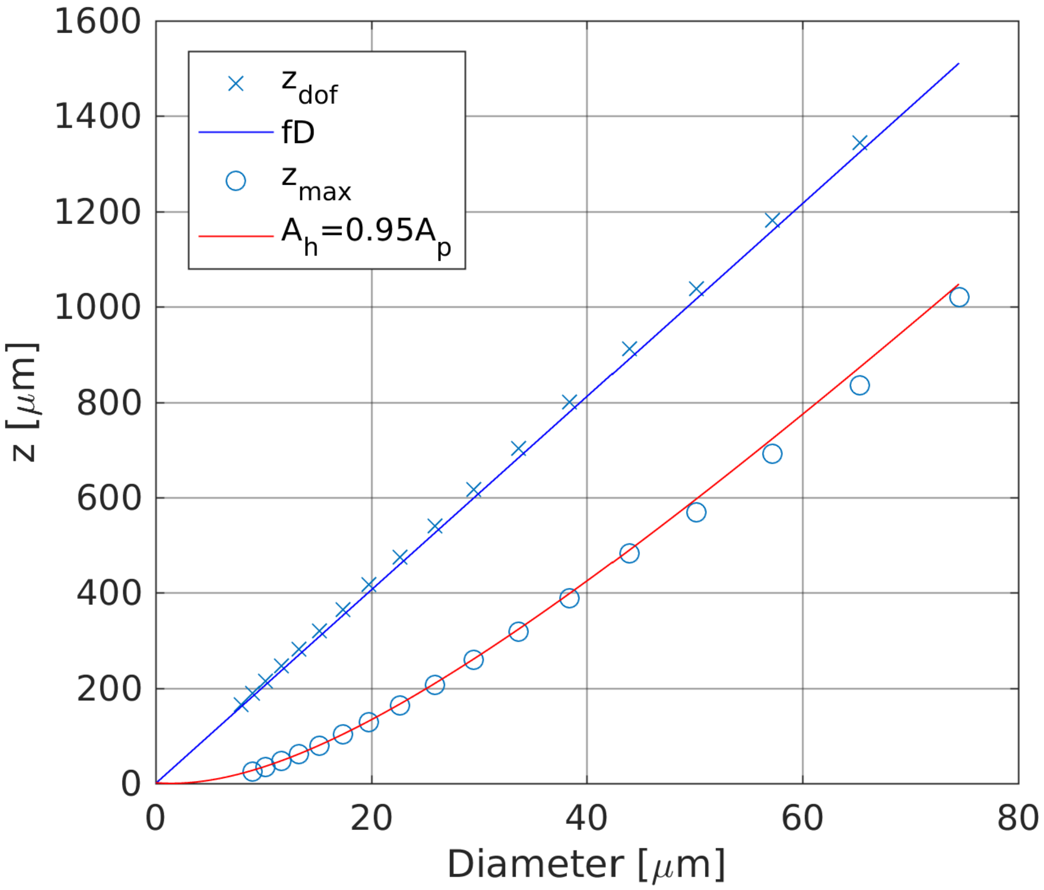
- Series of long run tests, obtaining size distributions of a cloud of small water droplets of ~10 μm diameter, produced by means of an ultrasonic fog generator (Poly-disperse droplets)





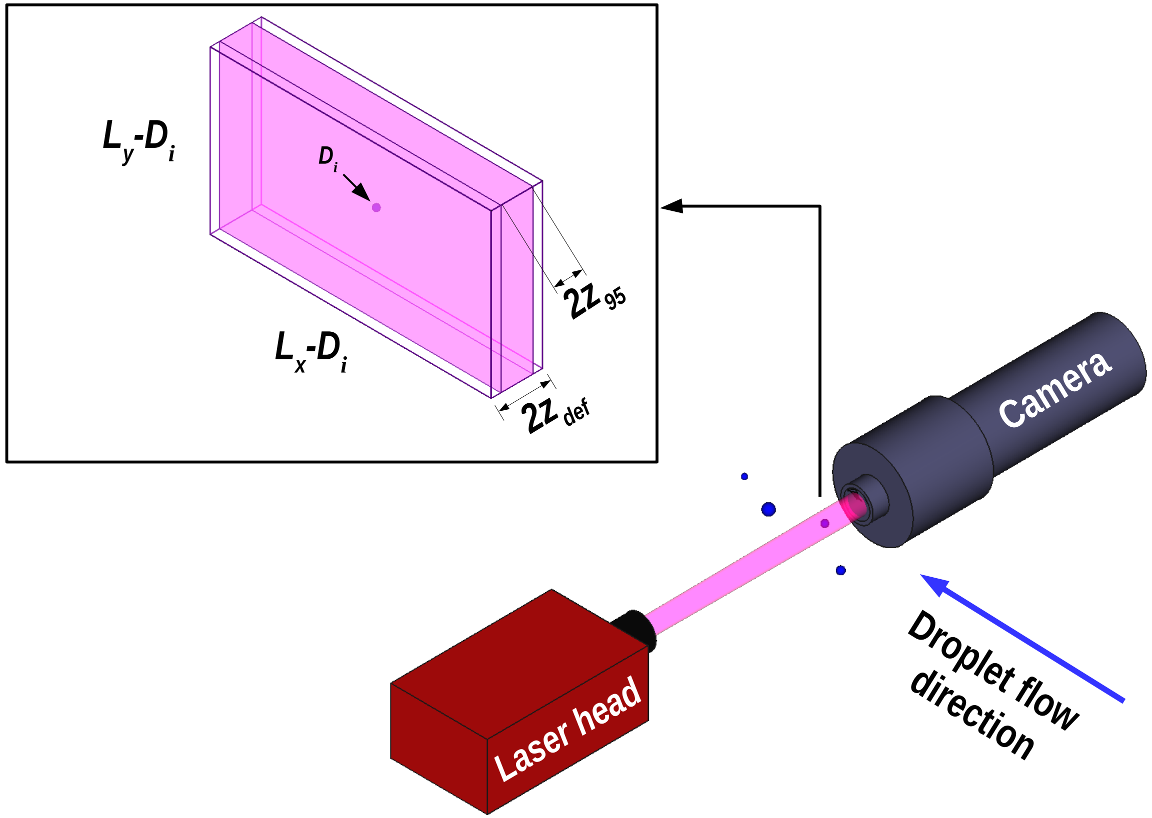
A typical shadow image of droplets produced by an ultrasonic droplet generator, taken with a camera lens magnification setting of x2

Laboratory experiments (Warsaw)



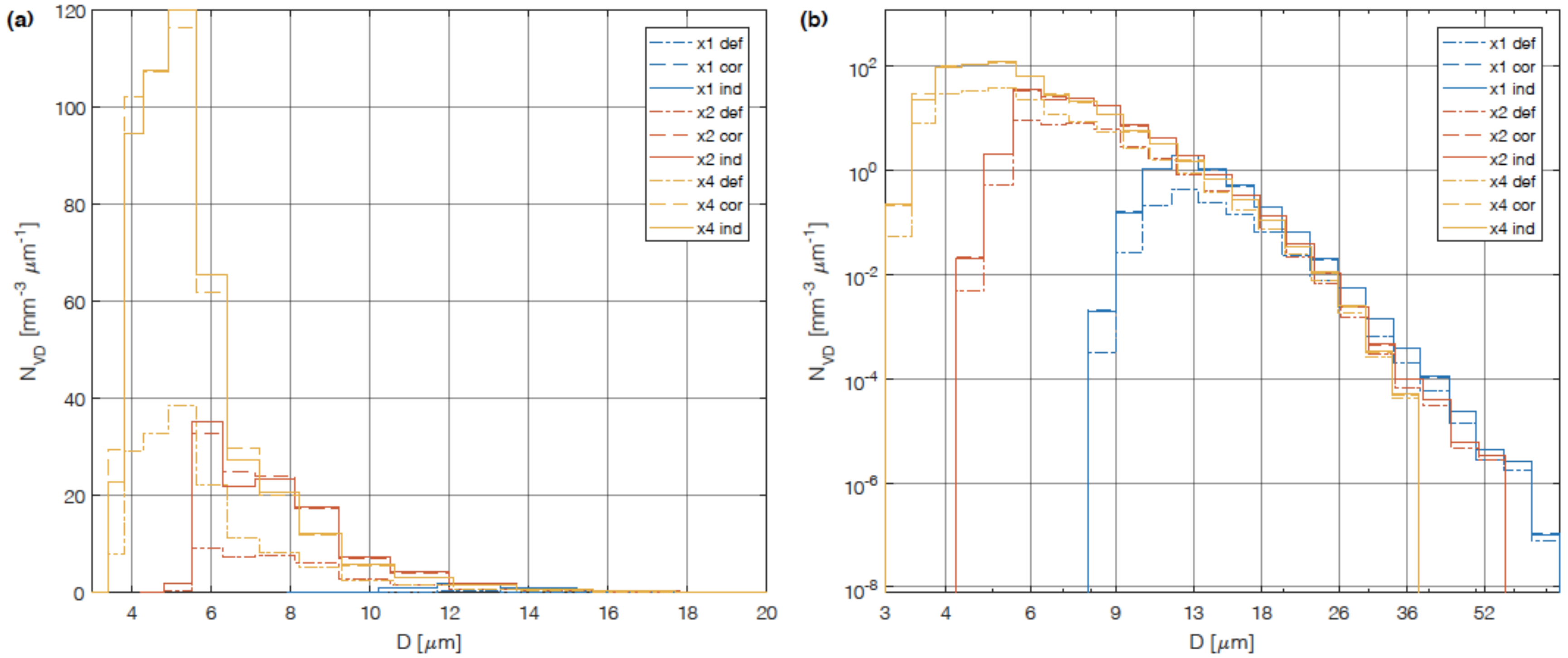
Maximum range of defocus distance (z) for each size bin: comparison between default values and experimental results for lens magnification setting x1.0

Laboratory experiments (Warsaw)



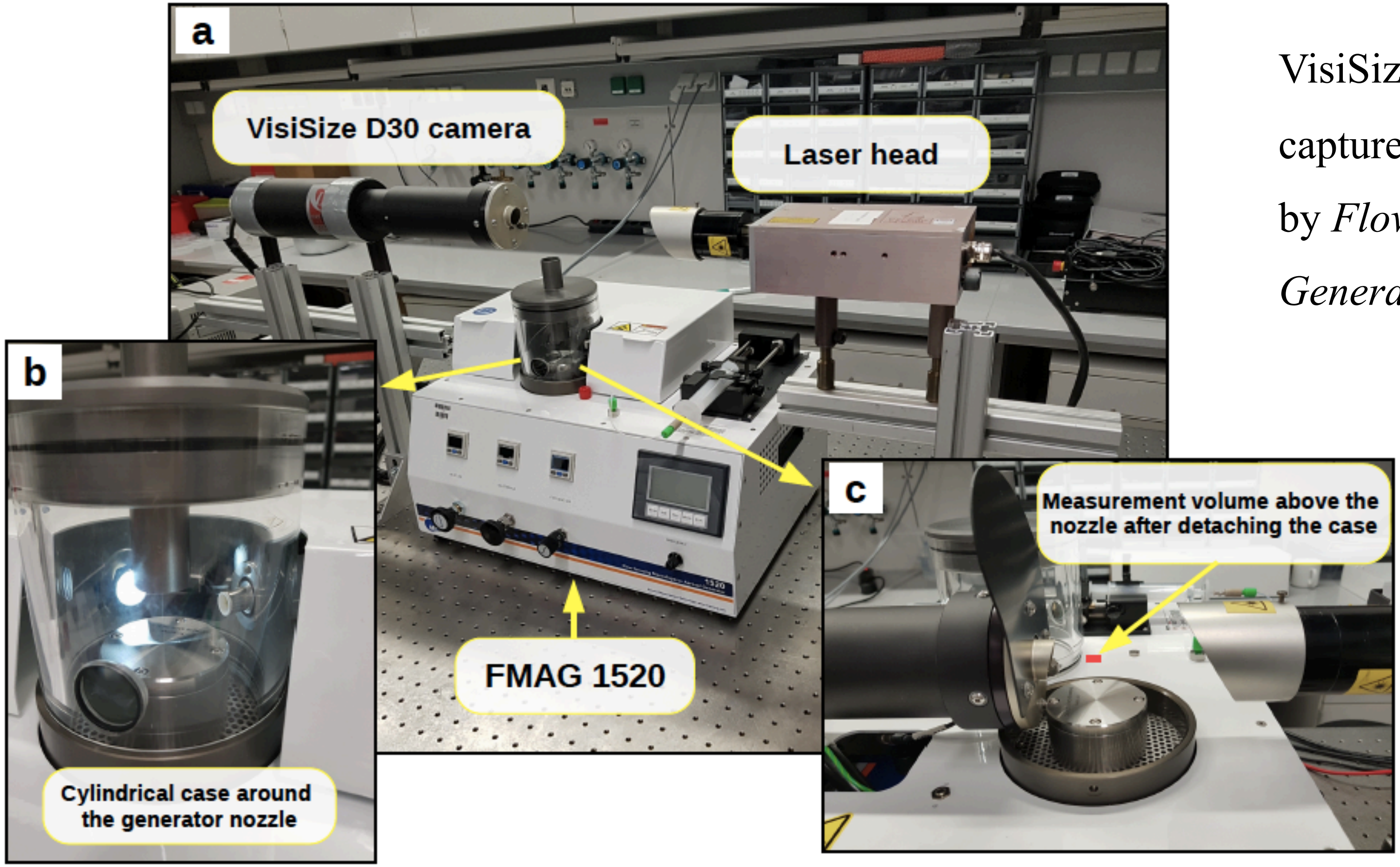
Schematic illustrating difference between the default and the corrected sample volume having the same field of view, $S = (L_x - D_i)(L_y - D_i)$, but differing in depth of field (z_{def} vs. z_{95}).

Laboratory experiments (Warsaw)



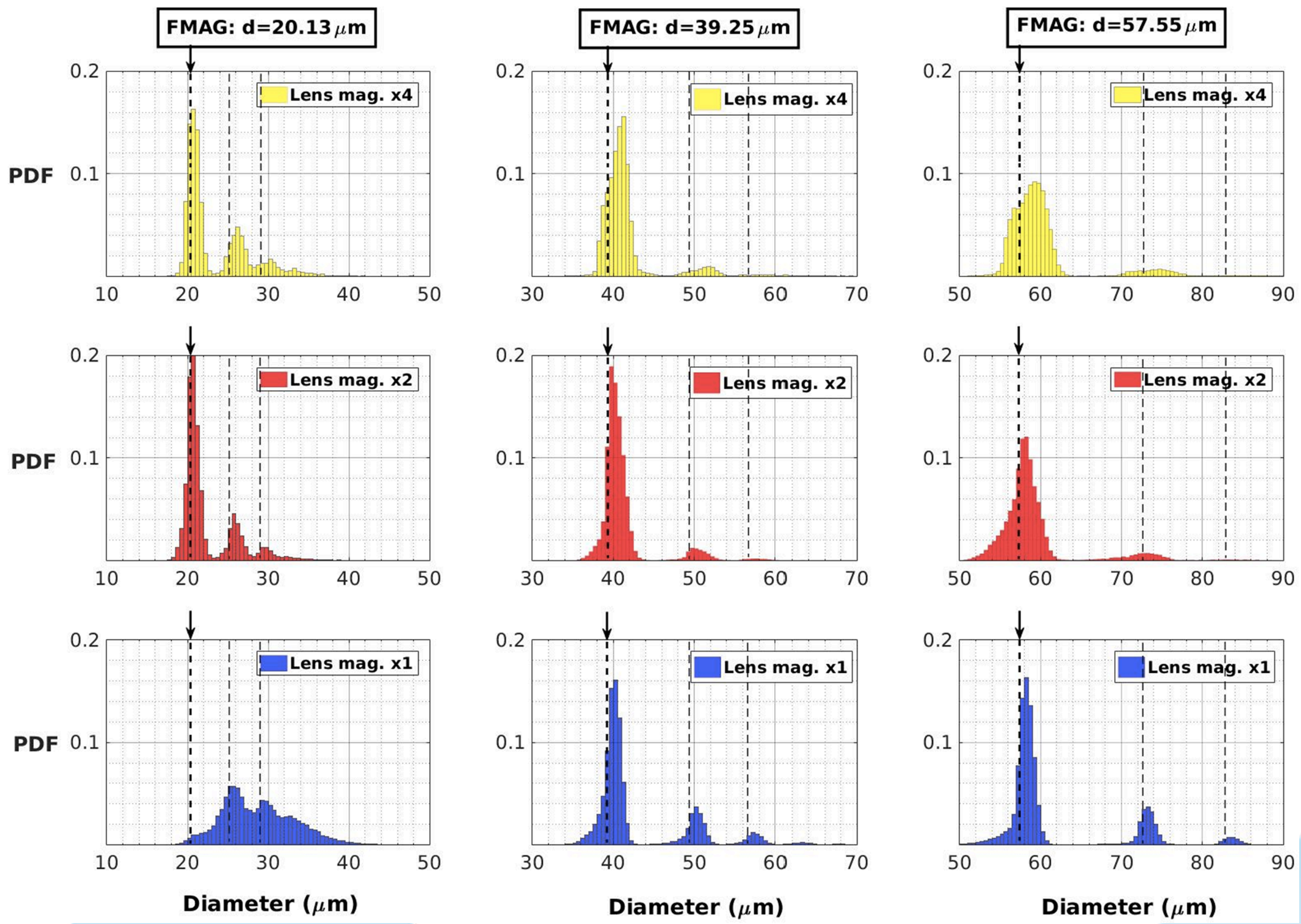
Comparison of droplet size distributions obtained with three methods, default (def), corrected (cor) and individual (ind), in the course of the three measurement series differing in lens magnification settings. Same data plotted in (a) linear and (b) logarithmic scale.

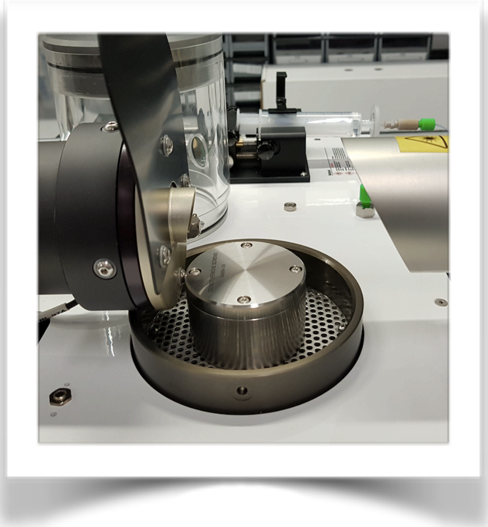
Laboratory experiments (Goettingen)



VisiSize D30 mounted as such to be able to capture water droplets (D ~ 20-70 um) produced by *Flow Focusing Mono-disperse Aerosol Generator 1520 (FMAG 1520)*

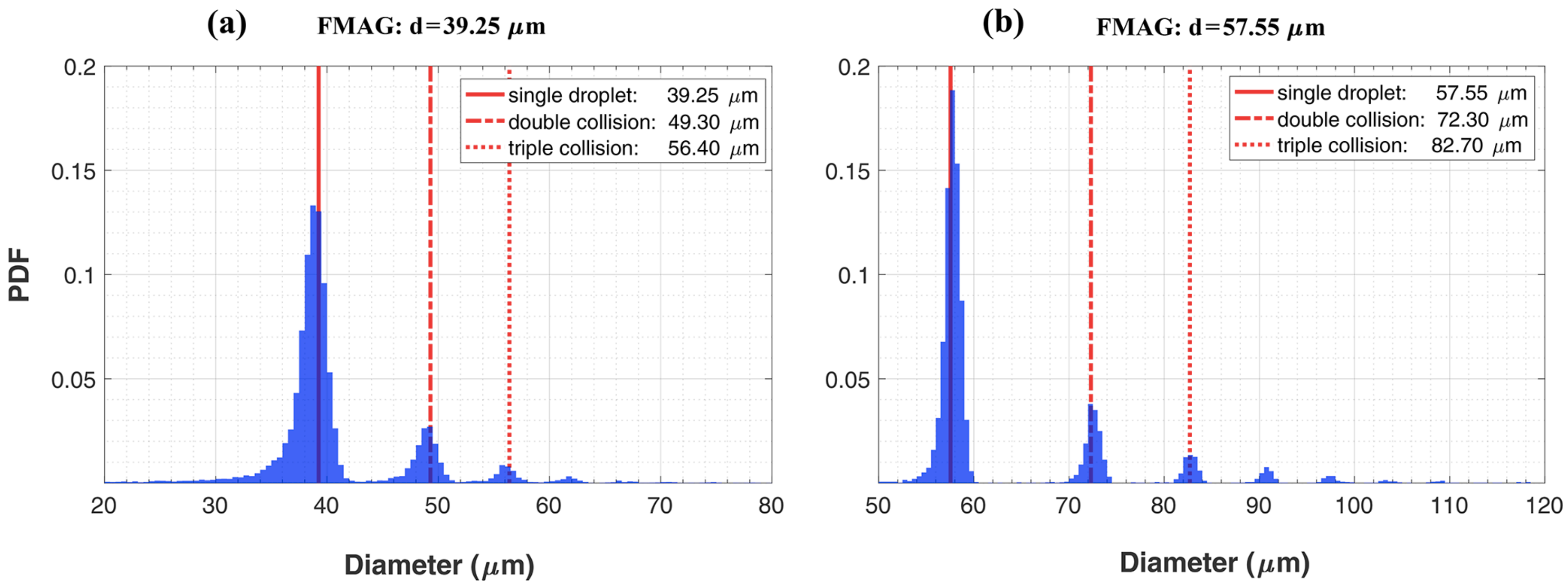
Laboratory experiments (Goettingen)





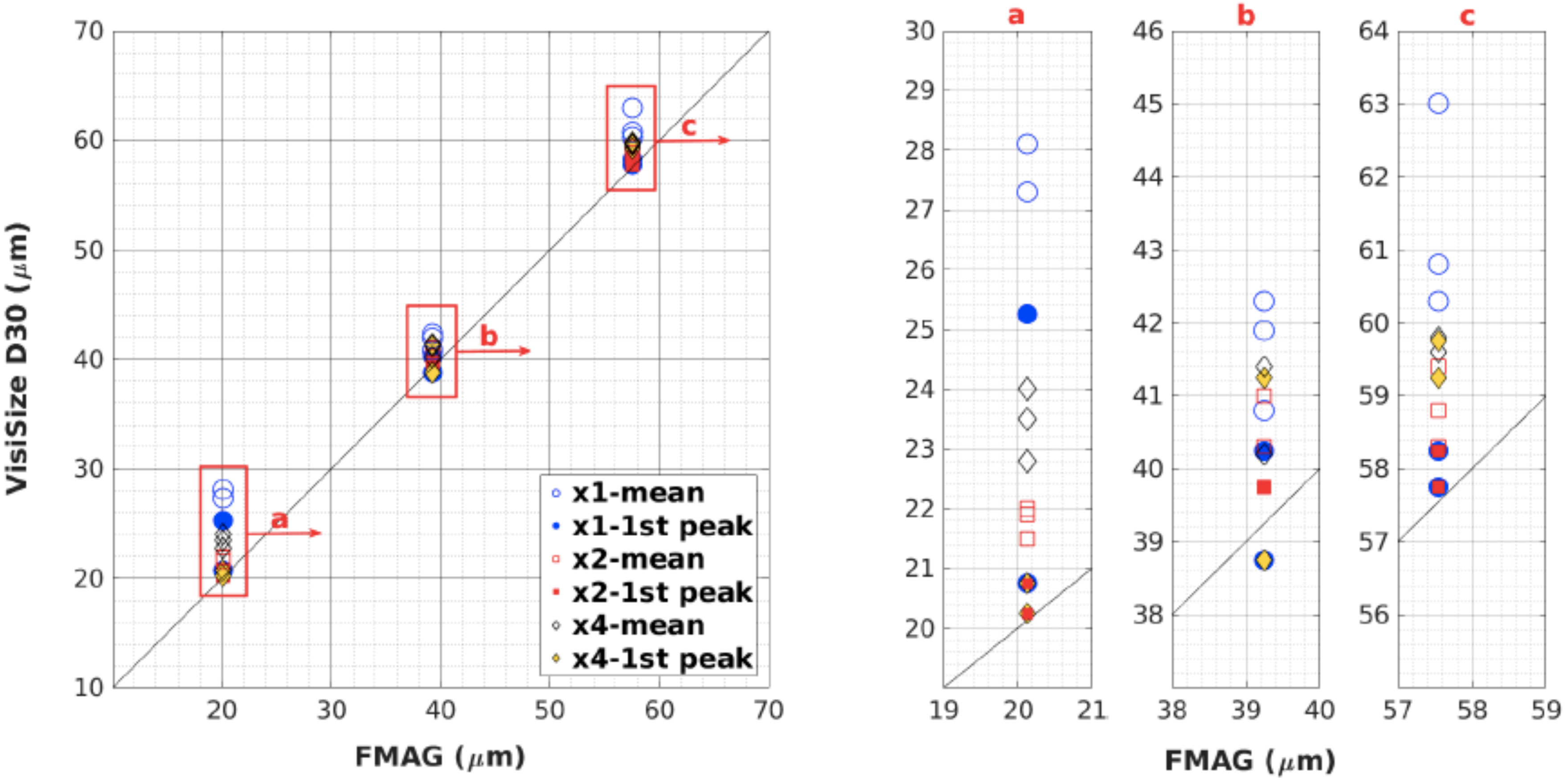
The VisiSize D30 was located above the exit of the FMAG in order to measure outgoing droplets in the configuration without the case (~ 4.5 cm distance)

Laboratory experiments (Goettingen)



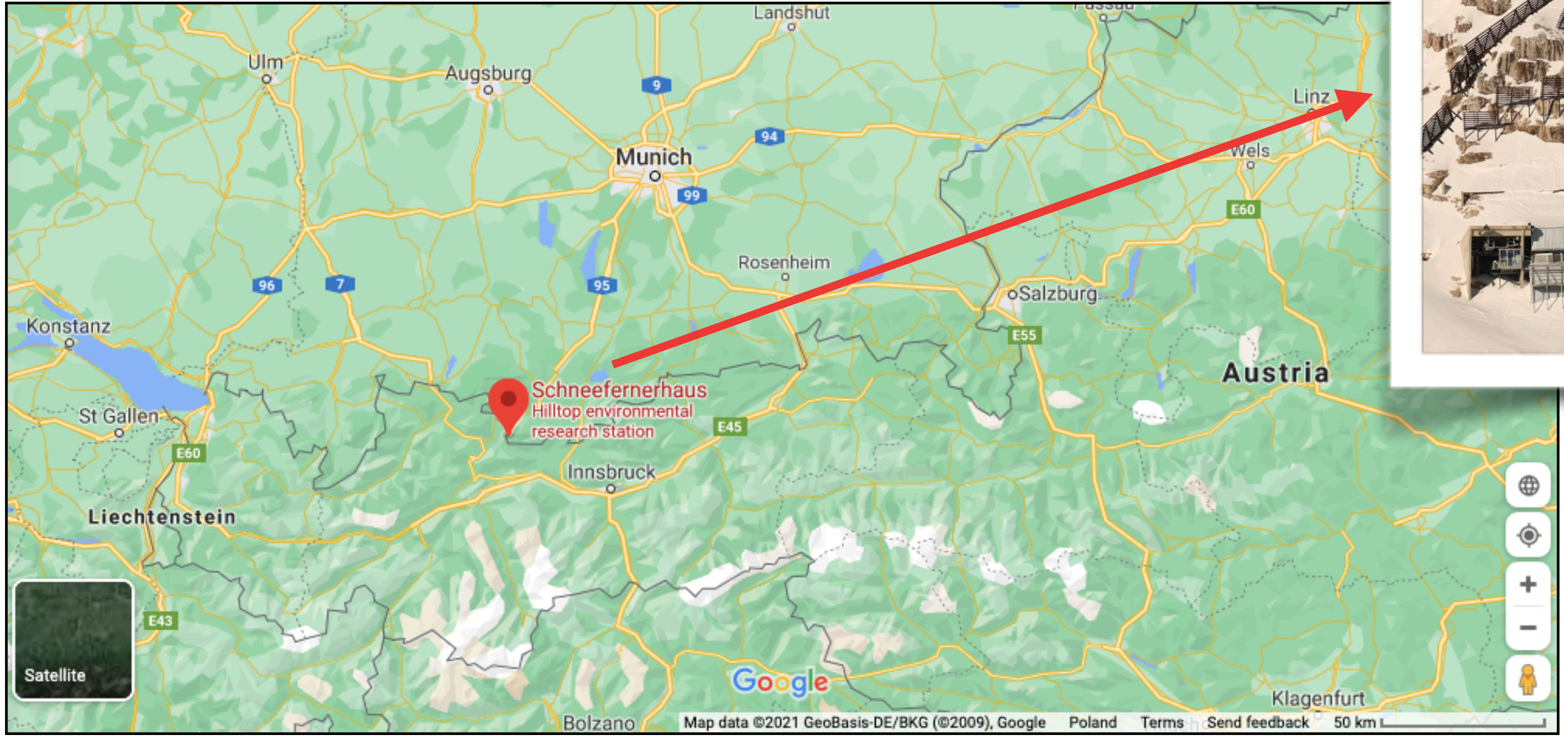
The VisiSize D30 was located above the exit of the FMAG in order to measure outgoing droplets in the configuration with the case (~ 18.5 cm distance)

Laboratory experiments (Goettingen)



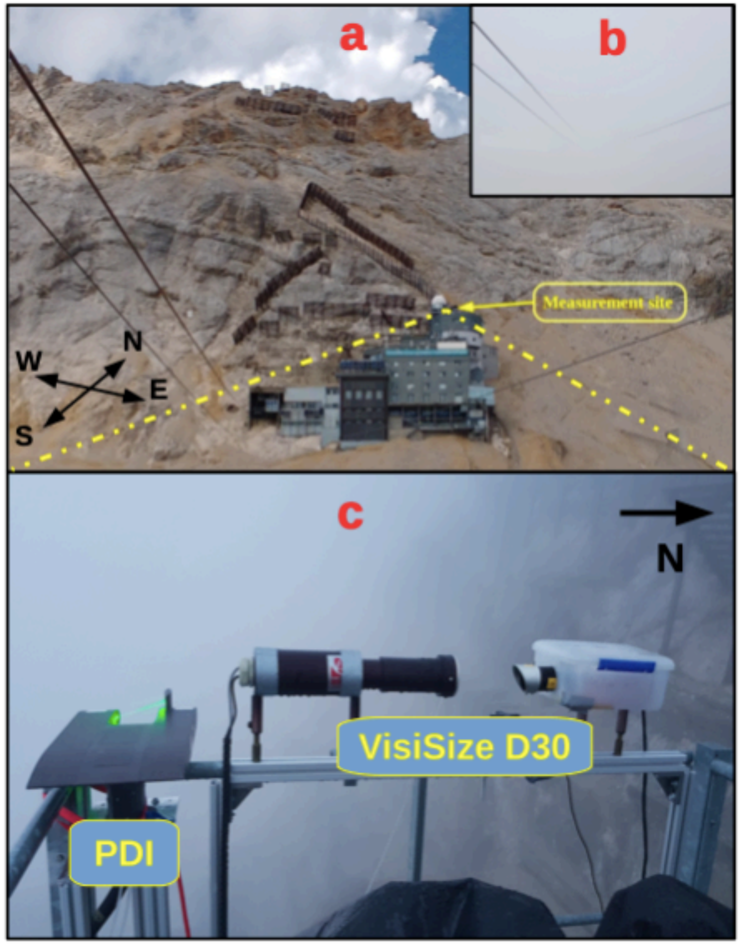
Comparison of droplet sizing using the VisiSize D30 and the FMAG. Scatter plot illustrates the position of the first peak in the size histogram and the arithmetic mean diameter with respect to the FMAG-generated droplet size for different lens magnification settings (left). The red boxes (a, b, c) in the scatter plot are enlarged in the panels on the right. Each pair of points (filled and empty) represents a single measurement.

Schneefernerhaus observatory:



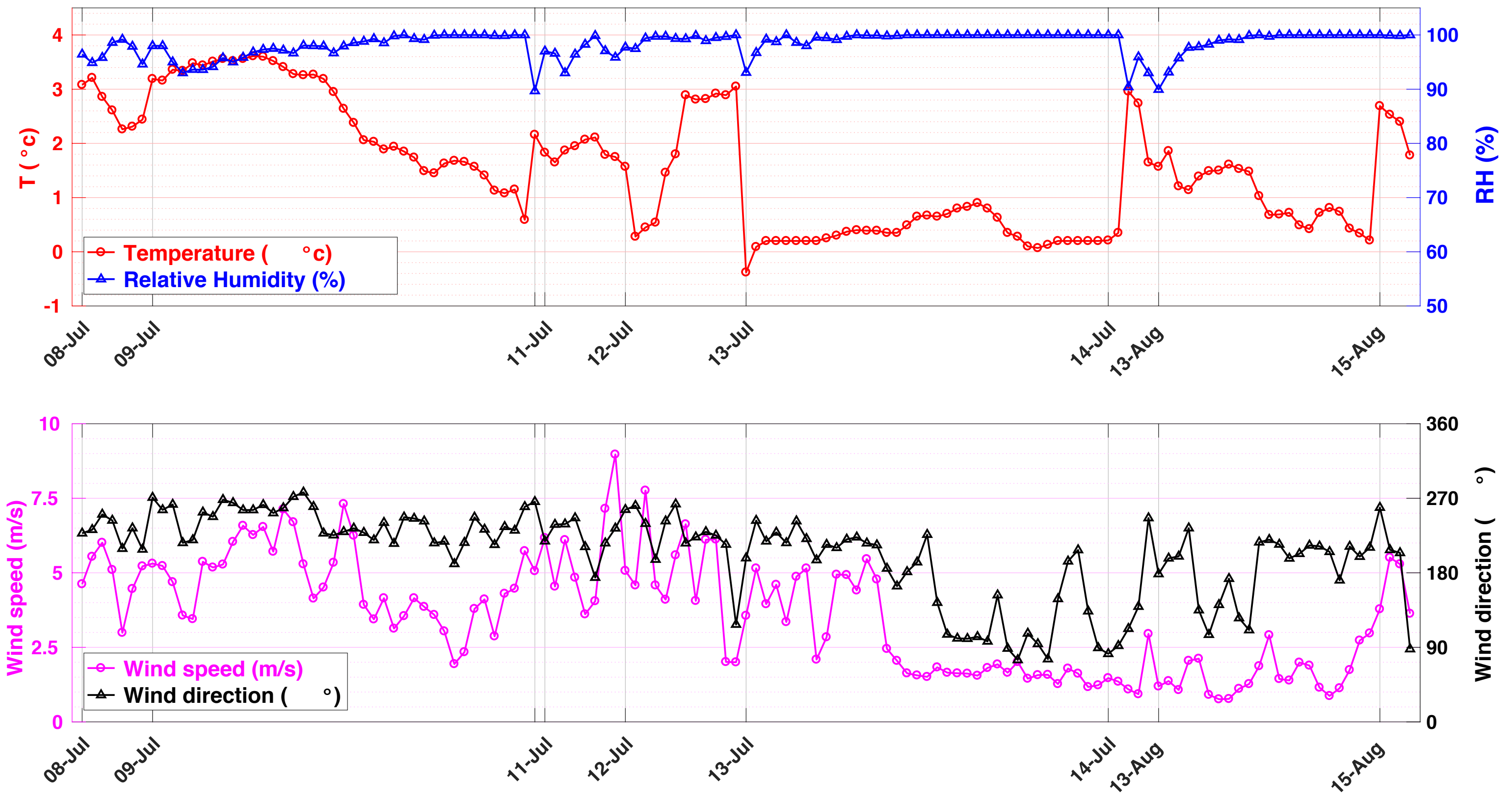
Environmental research station (Umweltforschungsstation Schneefernerhaus) [UFSobservatory] located just below the peak of mountain Zugspitze at ~2650 m a.s.l. in German Alps.

UFS-2019 campaign



Cloud field experiment at UFS camp: (a) The UFS view from Zugspitzeplat station on a sunny day, pointing the measurement site on the 9th floor balcony; (b) The same view while UFS is immersed in clouds; (c) Main measurement instruments: VisiSize, and PDI probe mounted next to each other while clouds are reaching UFS from the west side

Data collection



Local weather conditions at UFS , obtained from recordings by German Weather Service, Deutscher Wetterdienst (DWD), during the measurement campaign including Temperature, Relative Humidity, Wind speed and direction. (Wind coming from north represented by 0 as well as winds from east, south and west by 90, 180, and 270 respectively)

Data collection

Droplet Size Distribution (DSD) & Droplet Number Concentration (DNC) measurements with:

- VisiSize D30
- PDI-FPDR probe (Artium Tech.)

Total VisiSize measurements: 450

(Live/captured - size/velocity modes with different lens magnifications during 12 days with cloud/rain/snow events)

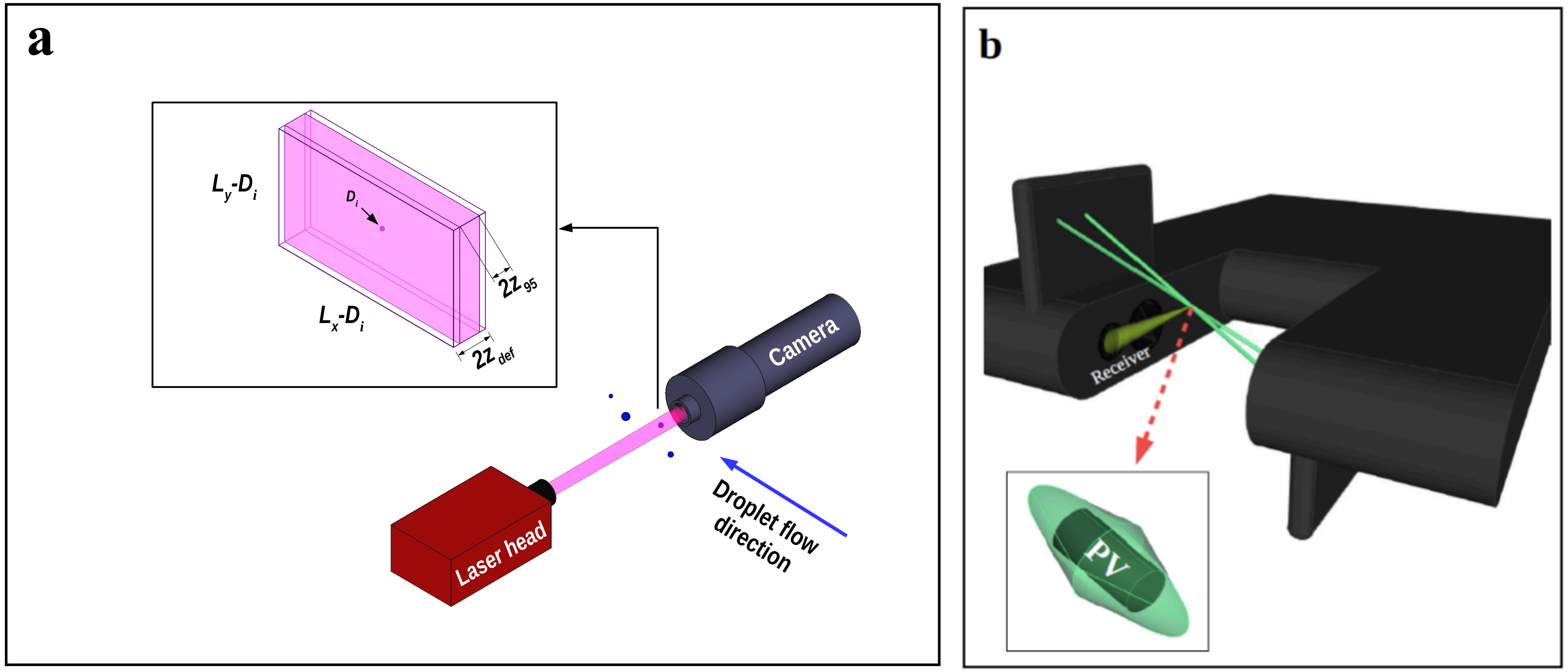
Selected measurements: 133

(with PDI results available through whole ~ 15 min of each experiment)

		VisiSize measuring mode	
		Diameter	Velocity
VisiSize camera lens magnification setting	X2.0	85	18
	X4.0	25	5

Data collection

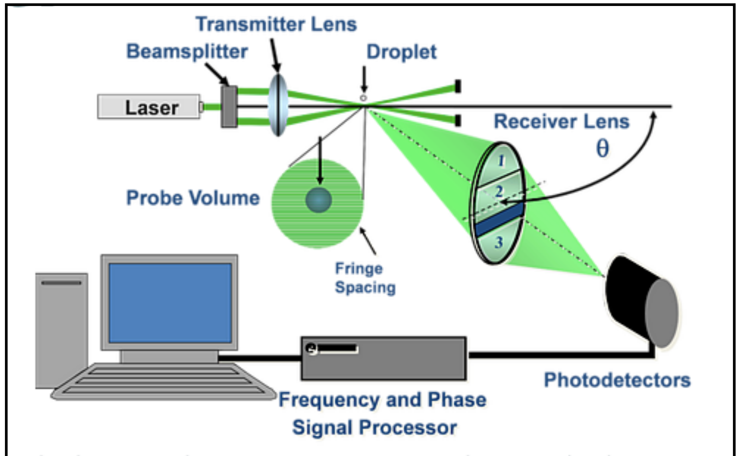
Schematic presentation of **VisiSize** Sample volume vs. **PDI** probe volume:



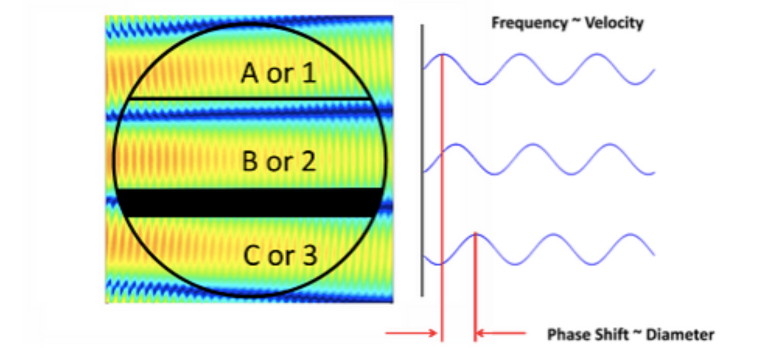
Schematic representation of (a): VisiSize setup and a magnified sample volume around droplet, comparing default and modified depth of fields (z_{def} vs. z_{95}); (b): PDI probe with the magnified illustration of the cylindrical probe volume (PV) within the intersection of laser beams where the light from the passing droplets is scattered into the receiver.

PDI (Phase Doppler Interferometer):

- Sizing & velocimetry based frequency & phase shift of scattered light
- www.artium.com & Chuang et al. (2008):



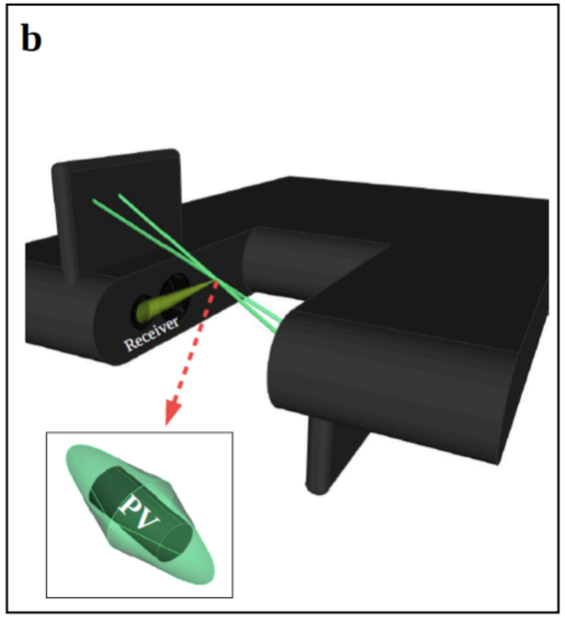
Configuration of a basic phase Doppler interferometer (PDI) system.



Calculated interference fringe pattern with the segmented receiver placed over the pattern showing how the fringe spacing can be measured using the phase shift information.

Probe Volume (PV):

- The intensity of scattered light from a droplet depends on its size and position within the intersection beams.
- The probe volume for droplets changes based on the size, so in order to compensate for it, a PVC (probe volume correction) factor is used by the software equal to the ratio of Probe area for the biggest size bin to each size bin.
- There is an effective minimum diameter (D_{min}) which droplets smaller than that can not be detected even if they pass through the Probe central axis (with the highest light intensity).
- D_{min} value for each measurements calculated by the PDI software.



DNC computation:

- Probe Area:

$$PA(D) = \beta\omega\sqrt{log(\frac{D}{D_{min}})}$$

$$PA\ (Dmin) = 0$$

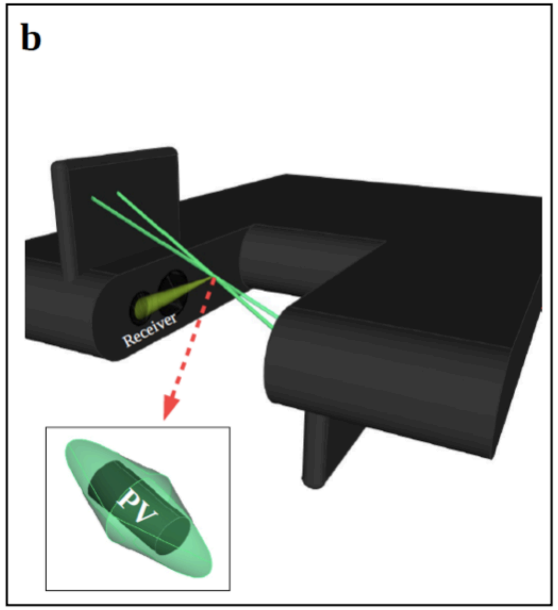
- DNC:
  - Swept volume:

$$DNC_{SV} = \frac{1}{(PA)(t_{Tot})}\sum_i \frac{n_{c(i)}}{\overline{|v_i|}}$$

$$\overline{|v_i|} = \frac{\sum_j |v_{i,j}|}{n}$$

  - Transit time:

$$DNC_{TT} = \frac{1}{t_{Tot}}\sum_i \frac{\sum_j Tt_{i,j}}{PV_i}$$



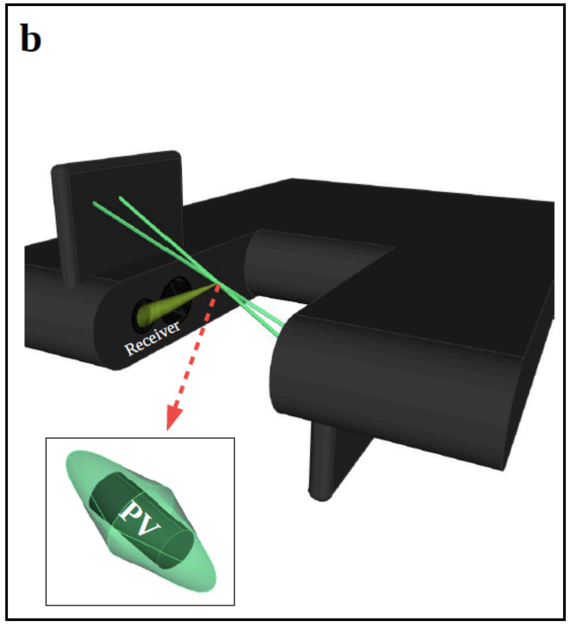
DNC modification and applying filters:

- Corrected Swept method:
  - Bin centres for PA, and mean velocity in smaller time window
- Individual method:

$$V_j = PA_j|v_j|\tau_j$$

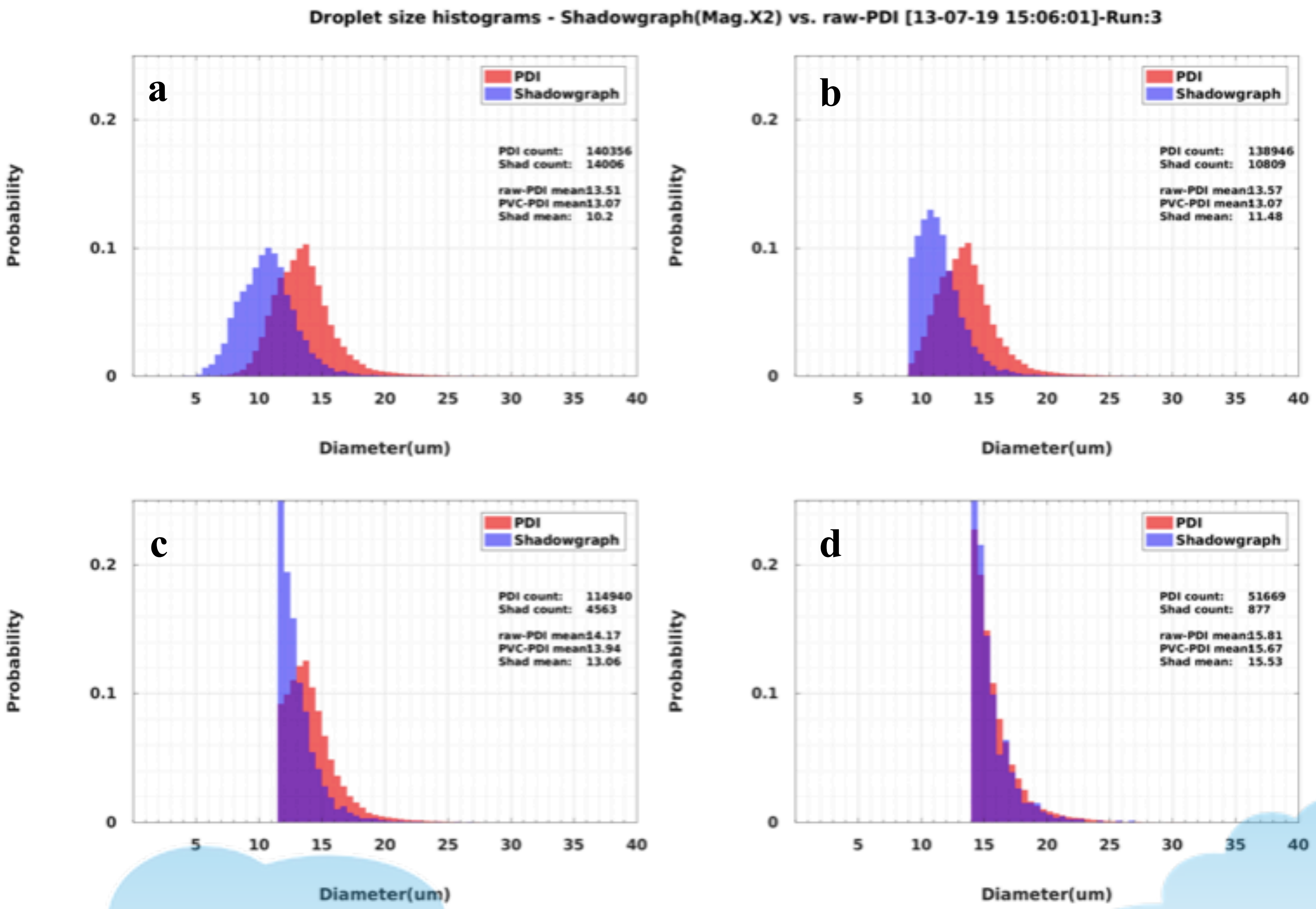
$$\tau_j = \frac{t_{j+1} - t_{j-1}}{2}$$

$$DNC_{ind} = \frac{n}{\sum_j V_j}$$



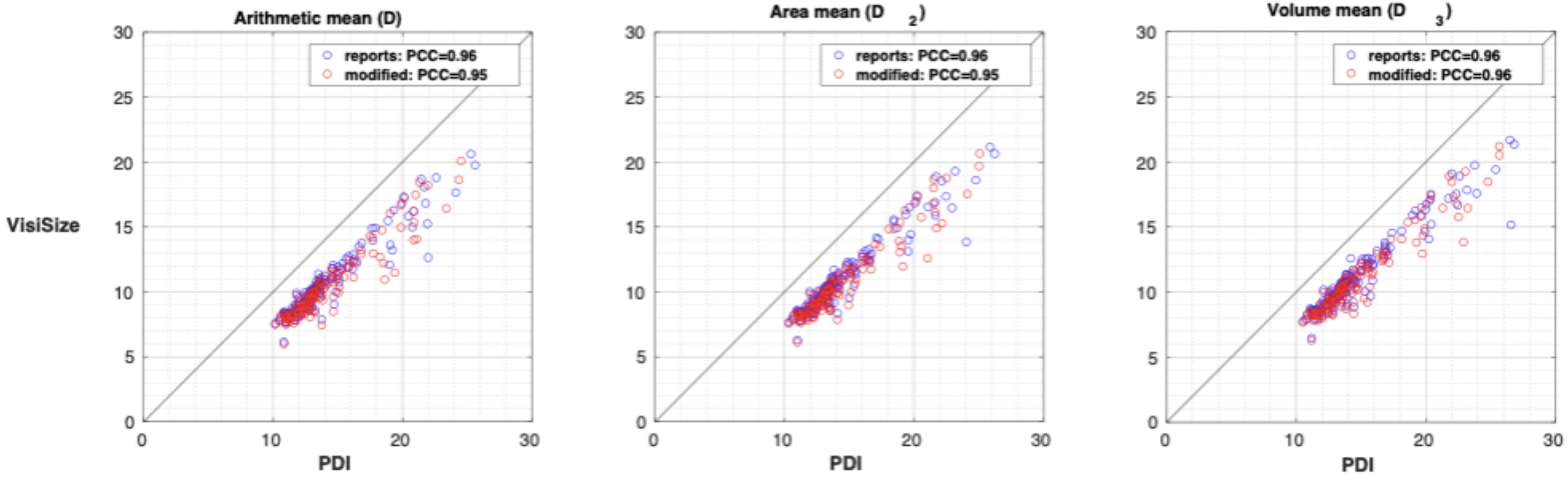
- Repetition filter on simultaneously detected drops
- D_{min} cut-off on data

Results



- Normalised size distribution histograms of cloud droplets collected by two instruments during a measurement on 13.07.2019 [15:06– 15:21].
- Droplet size ranges which have been analysed in each plot: [**a**] whole range, [**b**] d>9 um, [**c**] d>11.5 um, [**d**] d>14 um.

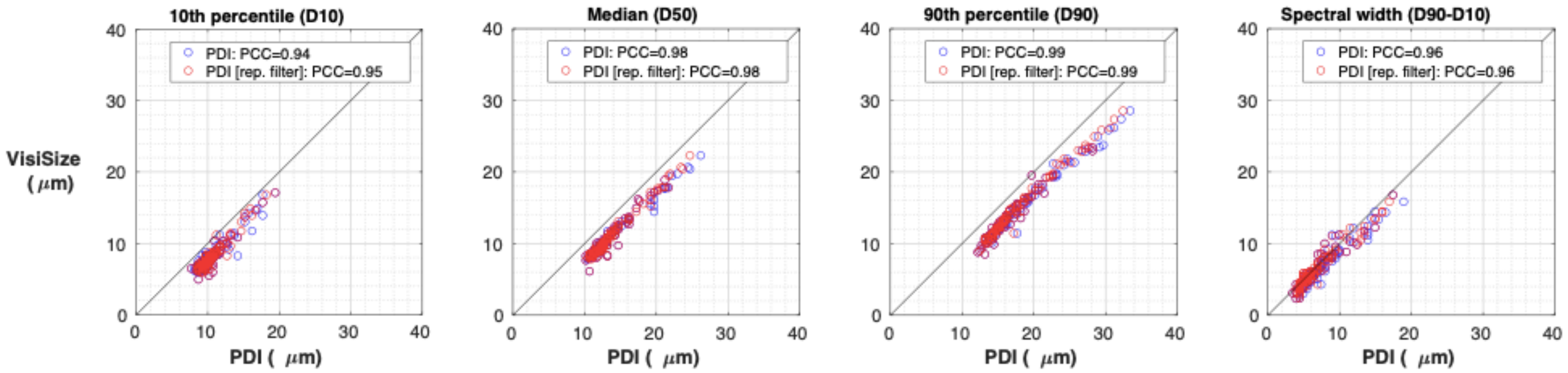
Results



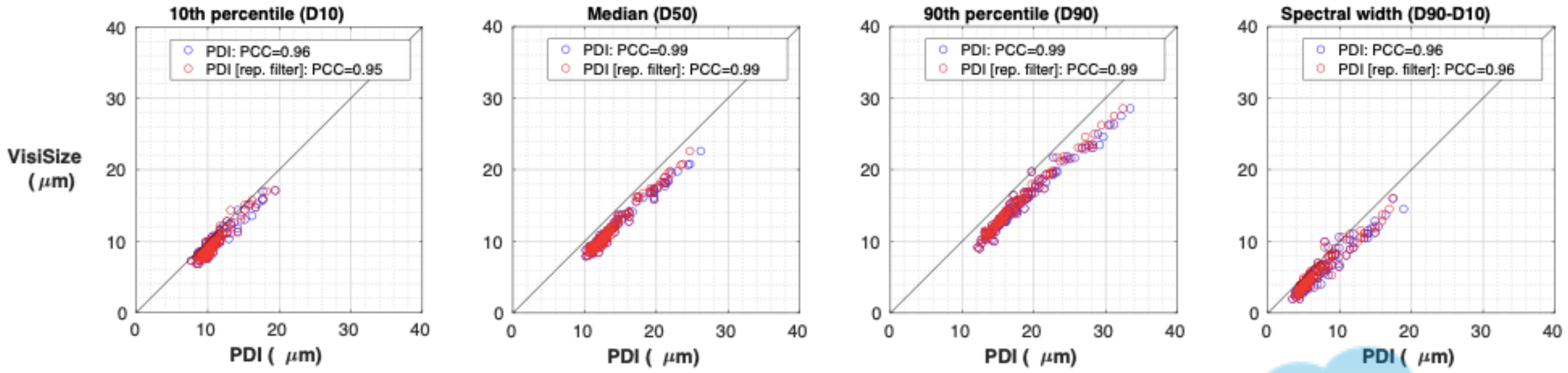
- Comparison between VisiSize and PDI probe regarding droplets mean diameter.
- The blue circles: reported data in each single measurement of about 15 minutes long during cloud events,
- The red circles: after applying modifications on reports : for VisiSize modifying SV,

  for PDI probe applying the repetition filter (replacement of all droplets detected simultaneously with a single mean value.

Results

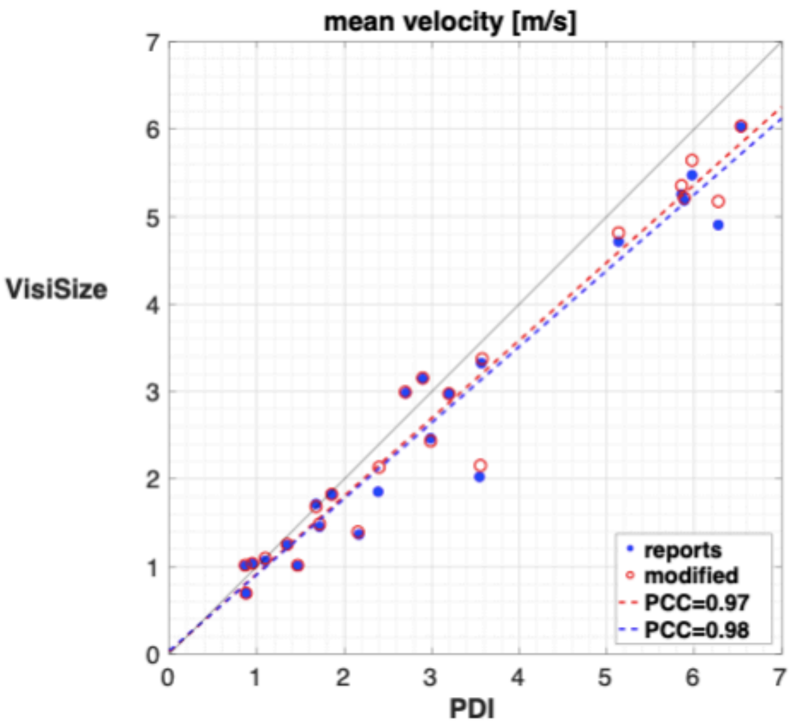


after Dmin-cutoff:



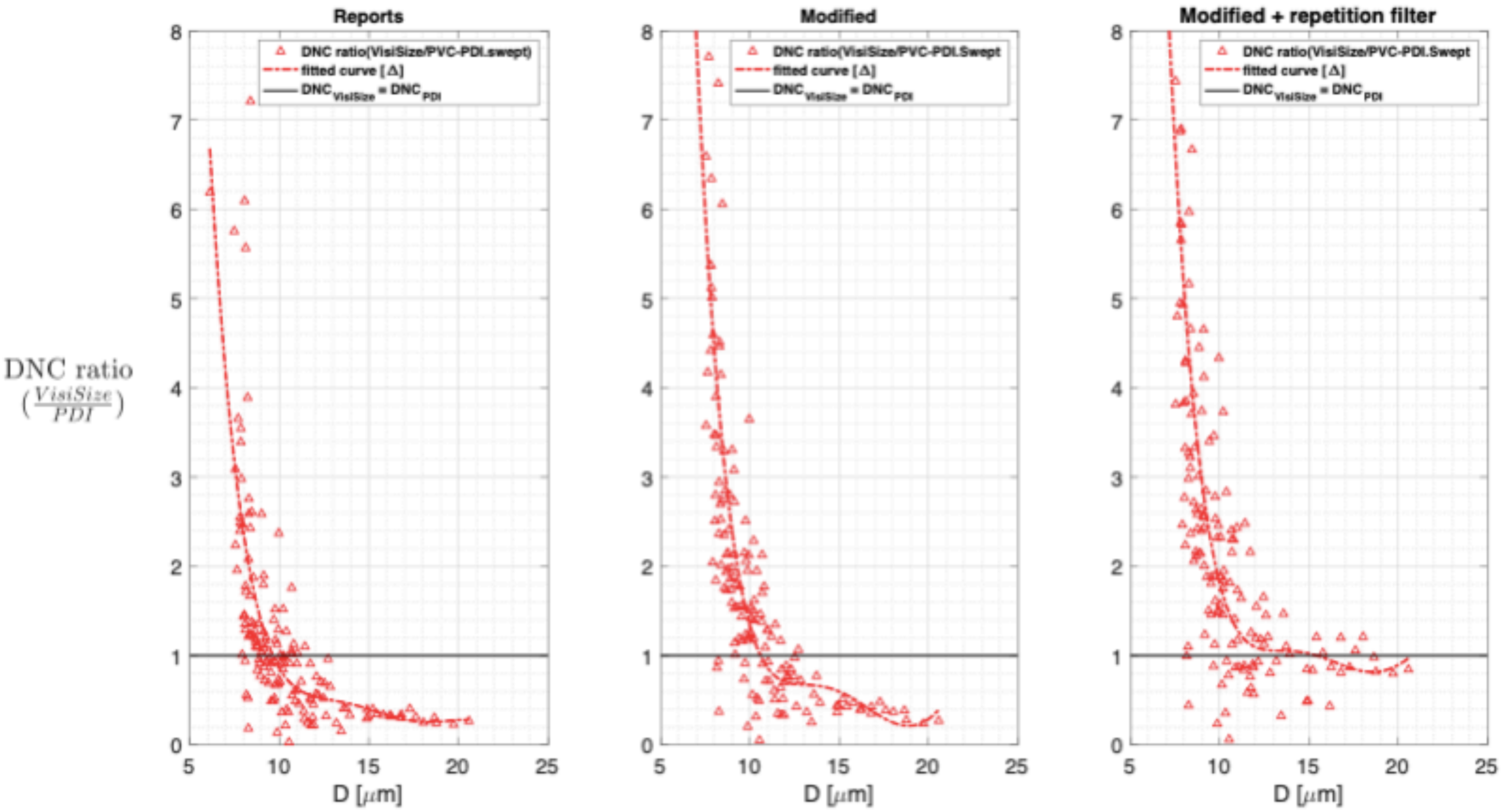
- Comparison between VisiSize and PDI probe regarding droplets different size ranges.
- The blue circles: reported data in each single measurement of about 15 minutes long during cloud events,
- The red circles: after applying modifications on reports : for VisiSize modifying SV, for PDI probe applying the repetition filter (replacement of all droplets detected simultaneously with a single mean value.

Results



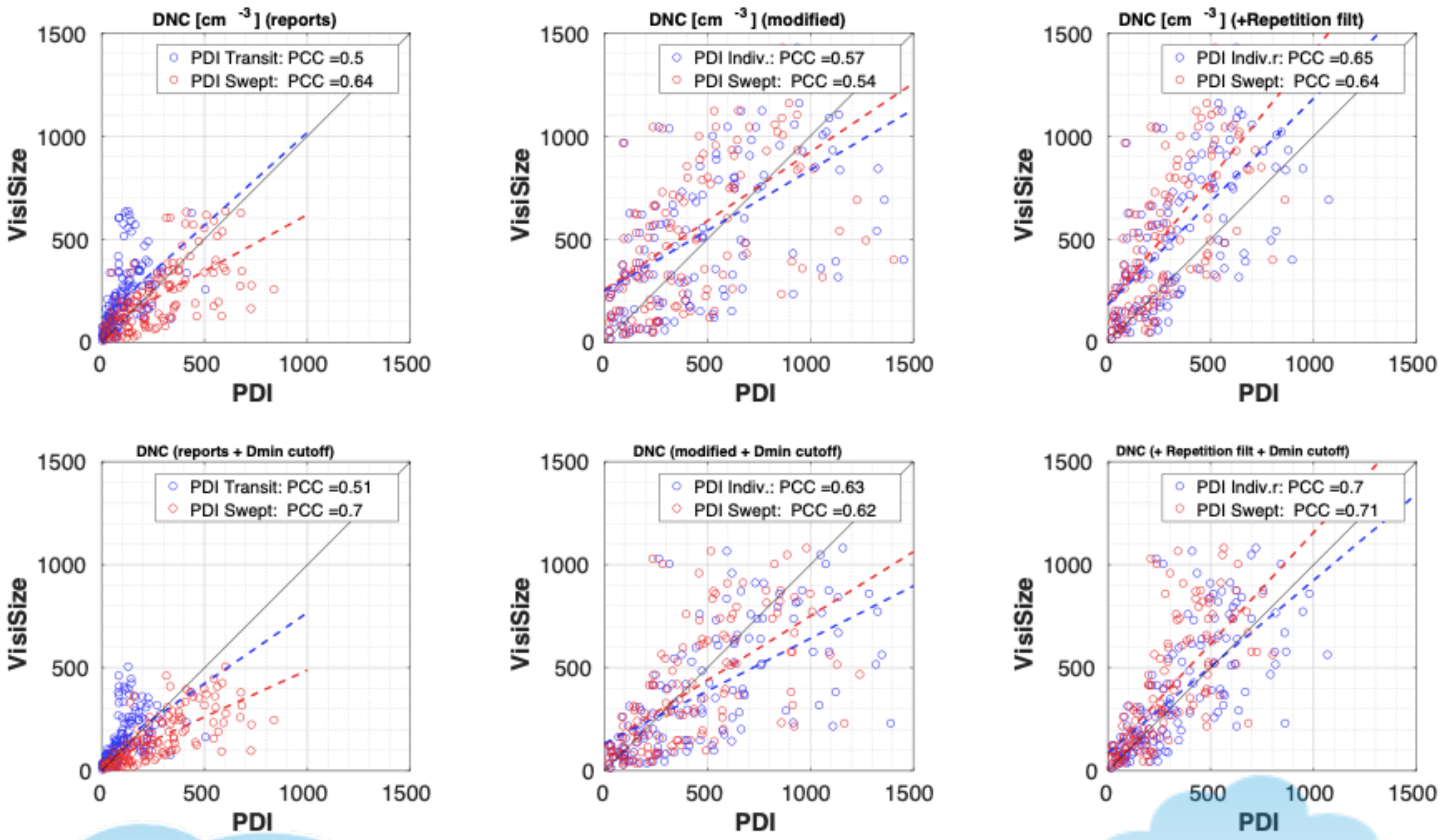
- Comparison between VisiSize and PDI probe regarding droplets mean velocity.
- The blue circles represent the instruments reported data in each single measurement of about 15 minutes long during cloud events.
- The red circles are obtained after applying D_{min} cut-off on the whole data of both instruments, which removes all droplets detected below the default minimum detection range of PDI software.

Results



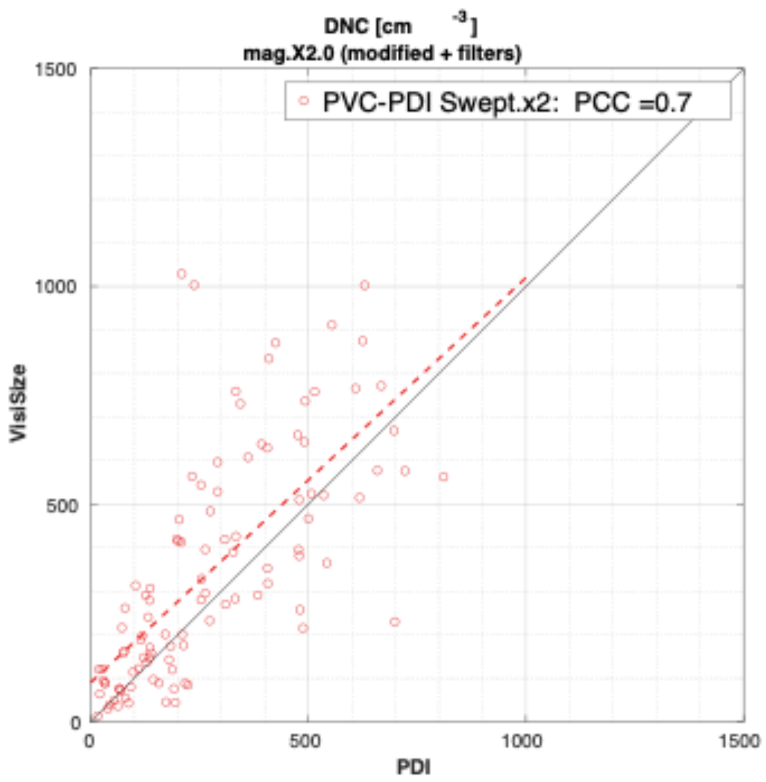
- VisiSize to PDI DNC ratio changes with mean droplet sizes through the measurements.
- Left panel: report data, middle panel: results after SV modification applied, right panel: additionally applying D_{min} cutoff & repetition filter (on PDI).
- Each red triangle: a single measurement of approximately 15 minutes long.
- Fitted curves on scatter plots are shown with dashed lines, and 1:1 ratio with a black horizontal line.

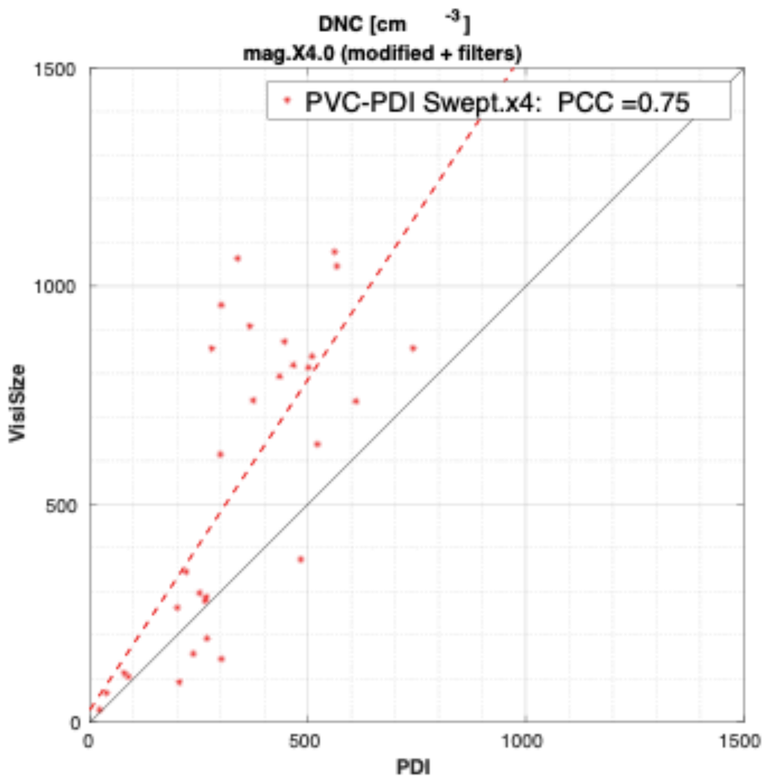
Results



- Comparison of DNC results between the VisiSize and PDI probe.
- The different colors represent different methods for PDI probe, and the dash lines shows the linear least square regression for each scatter plot companied by the PCC value within the legends.
- From left to right the plots illustrating: reported data, data after SV modifications, modified data after applying repetition filter on PDI results.

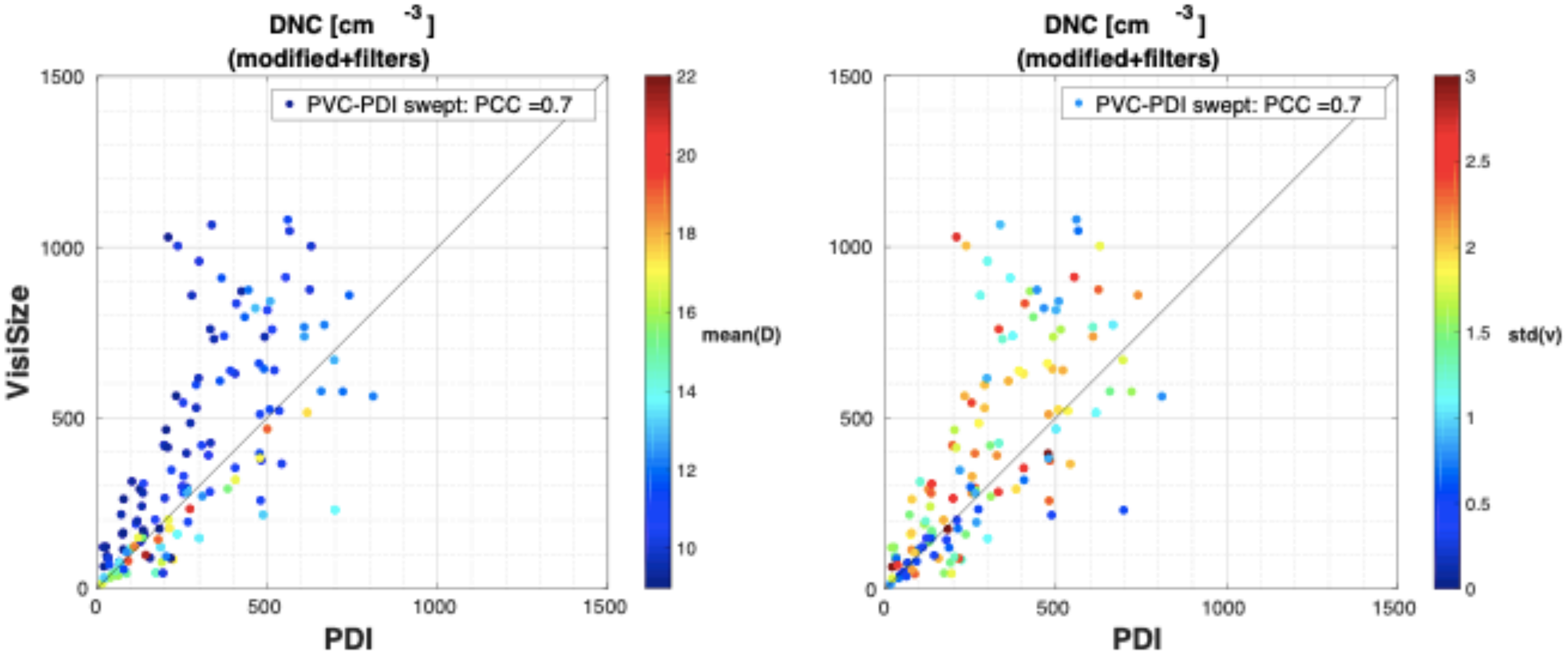
Results





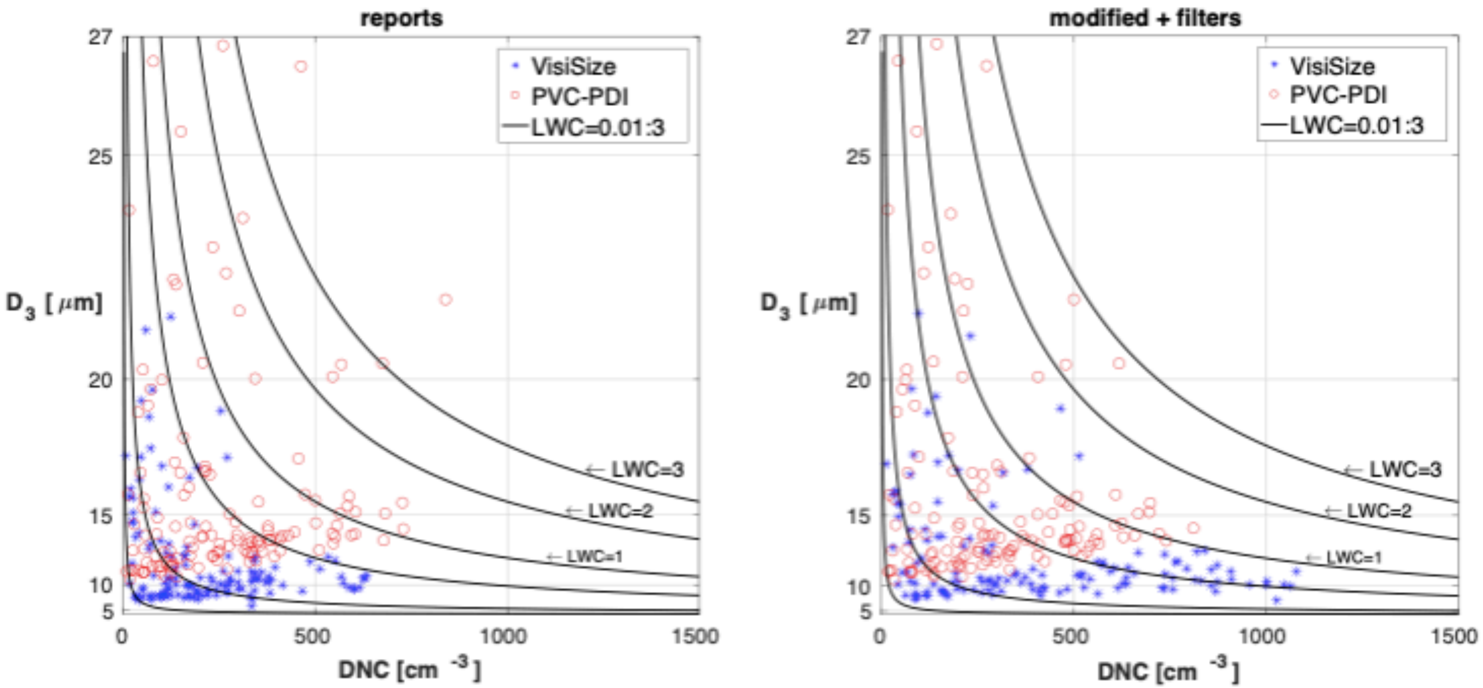
- Comparison of DNC results between the VisiSize and PDI probe based on different camera lens magnification setting used by VisiSize (x2: circles on left plot, x4: starts on right plot)
- The Probe Volume Correction (PVC) applied on PDI swept method, and the dash lines shows the linear least square regression for each scatter plot companied by the PCC value within the legends.

Results



- Comparison of DNC results between the VisiSize and PDI probe based on droplets mean diameter and velocity standard deviation spectra.

Results



- Intercomparison between cloud droplets volumetric mean (D_3), number concentration (DNC) and liquid water content (LWC) based on results from two instruments: VisiSize and PDI probe.

Summary

- DSD and DNC of cloud droplets studied after a series of field experiments in summer 2019 at UFS observatory in the German Alps.
- VisiSize D30, a commercial shadowgraph instrument used for the first time for sizing and velocimetry of cloud droplets there, along with a Phase Doppler Interferometer (PDI) probe.
- Analysis of simultaneously collected data from the two instruments, and applying modifications to the original algorithms illustrate a reasonable agreement regarding the droplet sizing and velocimetry between them for diameters larger than 13 μm.
- Discrepancies observed concerning the DNC results, especially in smaller sizes. Further investigation allowed the attribution of discrepancies to different optical performance of the sensors regarding small droplets, and to high turbulent velocity fluctuations relative to the mean flow, resulting in an uncertain estimate of volume of air passing through the PDI probe volume.

Acknowledgments

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THANK YOU FOR YOUR ATTENTION!

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