TNA User Report

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Project title	Exploring the limits of the Michigan Technological University (MTU) holographic droplet detection system HoloPi
Name of the accessed chamber	LEAK-LACIS
Number of users in the project	1
Project objectives (max 100 words)	This study aims to explore the applicability of MTU's holographic droplet detection system "HoloPi" at the Leipzig Aerosol Cloud Interaction Simulator (LEAK-LACIS). HoloPi is a digital inline holography system for measuring size, shape and three-dimensional spatial distribution of condensed phase particles larger than several microns in diameter. The lower detection limit is of particular interest. Increasing the resolution (< 5 µm) would allow to look on cloud microphysical processes like cloud droplet activation. Because it allows for the generation of cloud droplets under well-defined and reproducible conditions in a turbulent environment, LEAK-LACIS is an ideal infrastructure for carrying out such investigations.

Description of work (max 100 words):	During the 10 granted access days, we determined the lower detection limit of the digital inline holography system "HoloPi", including a specific magnifying lens. We compared the results with the theoretical resolution estimation. Afterwards we did several cloud droplet activation experiments with various aerosol particle sizes, number concentrations and supersaturations. All experiments were carried out at the Leipzig Aerosol Cloud Interaction Simulator (LEAK-LACIS).

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[1] Physics; Chemistry, Earth Sciences & Environment; Engineering & Technology; Mathematics; Information & Communication Technologies; Material Sciences; Energy; Social sciences; Humanities.

[2] UNI= University and Other Higher Education Organisation;
RES= Public Research Organisation (including international research organisations and private research organisations controlled by public authority);
SME= Small and Medium Enterprise;
PRV= Other Industrial and/or Profit Private Organisation;
OTH= Other type of organization.

[3] UND= Undergraduate; PGR= Post graduate; PDOC= Post-doctoral researcher; RES= Researcher EXP= Engineer; ACA= Academic; TEC= Technician.

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Trans-National Access (TNA) Scientific Report

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The report will be made available on the eurochamp.org website. Should any information be confidential or not be made public, please inform us accordingly (in this case it will only be accessible by the European Commission, the EUROCHAMP-2020 project partners, and the reviewers). Please include:

- Introduction and motivation
- Scientific objectives
- Reason for choosing the simulation chamber/ calibration facility
- Method and experimental set-up
- Data description
- Preliminary results and conclusions
- Outcome and future studies
- References

Instructions

Name of the PI: Neel Uday Desai
Chamber name and location: LEAK-LACIS chamber, Leipzig, Germany
Campaign name and period: HoloPi18, 22.02. – 07.03.2018
Text:

Introduction and motivation

With digital inline holography, it is possible to measure size, shape, three-dimensional spatial distribution, and motion of condensed phase particles larger than several microns in equivalent diameter. The holographic method offers the advantages of a well-defined sample volume size that is not dependent on particle size. Given typical droplet number densities, this enables estimation of the full droplet size distribution from a single hologram (Fugal and Shaw, 2009). Furthermore, the holographic measurement technique provides the spatial distribution of droplets, and therefore information on the geometry of cloudy-clear-air interfaces and droplet inertial clustering (Beals et al., 2015; Lu et al., 2008). For example, the holographic measurement technique is also applied in aircraft in-situ cloud measurement studies.

However, due to technical issues (e.g., minimum pixel size on the CCD camera, laser wavelength) it is challenging to determine cloud particles in a size range of a few micrometres (<5 µm). With an increased resolution, it would be possible to observe cloud microphysical processes which occur on smaller spatial scales like cloud droplet activation (especially in a turbulent environment).

Michigan Technological University's (MTU) holographic droplet detection system "HoloPi" is a holographic instrument used to measure both, cloud droplet size and spatial distributions for the MTU Pi chamber (Desai et al. 2018). At the Pi chamber, the maximum resolution is about 7 µm. This is due to the large working distance between the lens and the measurement volume. In order to determine maximum possible resolution of the HoloPi system, it is necessary to evaluate it in a chamber where the working distance is much smaller, because the resolution increases with decreasing working distance.

Scientific objectives

During this research campaign, we tried to answer the following questions:

1. Determination of the lower detection limit of the holographic system HoloPi: What is the lowest particle size we can resolve? Does it compare with theoretical estimation? Can the resolution be increased by use of specific magnifying lenses?
2. Statistics for rare cloud droplet events: Can we determine e.g., meaningful cloud properties (mean droplet radius, LWC, etc.) for rare cloud droplet events?
3. Distinction between spherical supercooled droplets and ice crystals: Can we observe a difference between small liquid droplets and small ice crystals?

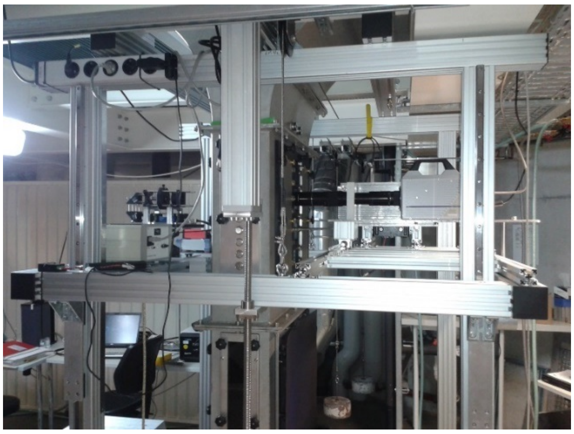
To deal with these three objectives, 15 access days were requested. However, only 10 access days were granted because the European Commission imposes a limit with respect to the percentage of TNA-funding provided to researches from non-EU countries. Consequently, the third objective was not dealt with in the framework of this TNA activity.

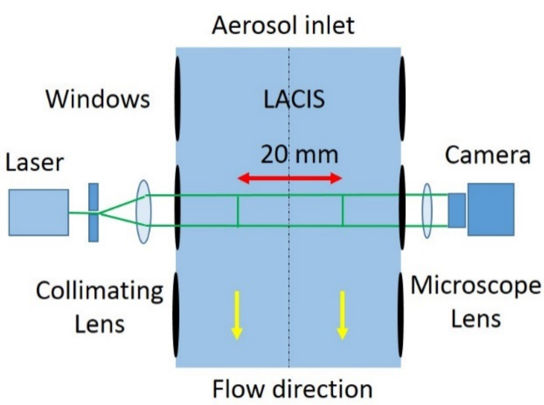
Reason for choosing the simulation chamber / calibration facility

Testing the highest resolution of the holographic system needed a facility with small working distance and small cloud droplet sizes. The LEAK-LACIS facility is an ideal infrastructure for carrying out the investigations, as it allows for the generation of small cloud droplets under well-defined and reproducible turbulent conditions with a very well-suited range of droplet sizes and concentrations.

Method and experimental set-up

The digital inline holographic system consists of a collimated Crystal Laser Systems (CryLaS) 532-nm laser and a high-speed digital camera (Photron Fastcam SA2) together with a K2-Distamax Lens. The laser beam passes through the LACIS chamber and undergoes diffraction when it encounters cloud droplets. The camera with a resolution of 2048 x 2048 pixels and a framerate of up to 1000 fps then receives the diffracted light. The individual pixel size is 10 µm. However, since at least two pixels are





required to confidently distinguish a particle/droplet from the background image, the lower detection limit without any further magnification is (at least) 20 µm. The detection limit was improved by installing a magnifying optics with a magnification of 12.5. The optics consists of a telephoto lens and a 2x magnification lens (NTX Tube 2x).
Fig. 1 HoloPi at the measuring section of LACIS. (Left) Image of the assembly. (Right) Schematic of the assembly. The measurements were taken within a 20 mm distance near the center of the chamber.

For the experiments at LACIS, the digital inline holographic system "HoloPi" was placed downstream of the aerosol inlet with the focal plane of the camera being 10 mm from the center of the chamber towards the camera (Fig. 1). LACIS is a closed loop turbulent wind tunnel featuring a continuous total volume flow of about 10000 l/min. The cross-sectional area of the measuring section is 0.8 m x 0.2 m resulting in a flow velocity of about 1 m/s. In the experiments two saturated particle free air flows of different temperature on either side of the center line (Fig. 1) are turbulently mixed together with a third flow of about 1 l/min containing aerosol particles. In the mixing zone, a region with supersaturated conditions occurs, resulting in cloud droplet activation and growth. The thermodynamic conditions (temperature, dew point) during the experiments are precisely controlled. Consequently, the supersaturation ratio is also well known.
Before doing the experiments, HoloPi was installed (day 1) and calibrated using a USAF resolution target (days 2 and 3). The lower detection limit was determined and compared to the theoretical values. The characterization of HoloPi was followed by a series of measurements at different particle and thermodynamic properties (days 4-10, Tab. 1). Particle number and size, as well as the temperature gradient between the two saturated flows were varied, resulting in different saturation ratios. In contrast, the flow velocity was kept constant for both flow branches at 1.3 m/s in all experiments. After one day of experiments with ammonium sulfate particles ($(NH_4)_2SO_4$), particles were aerosolized from an aqueous sodium chloride solution (NaCl). This was done because of the larger hygroscopic growth factor of NaCl particles. Cloud droplet activation experiments were carried out at low (1000 cm^{-3}) and high (5000 cm^{-3}) concentration, respectively.

Date	**Material**	**Sizes [nm]**	**Temperature gradient [K]**	**Particle concentration**
27/02/2018	$(NH_4)_2SO_4$	400, poly.	10	low, poly.
28/02/2018	NaCl	200, 400, 500	10, 13, 16	low, high
01/03/2018	NaCl	100, 200	16	low, high
02/03/2018	NaCl	300	13	low, high
05/03/2018	NaCl	100, 200, 300	13	low, high
06/03/2018	NaCl	300, 400	10	low, high
07/03/2018	NaCl	300, 400	13	low

Tab. 1: Experimental overview of the cloud droplet experiments (days 4-10). Days 1-3 (22nd, 23rd and 26th March) were used to set-up and calibrate the digital inline holographic system (HoloPi). HoloPi was detached on 7th March (day 10).

Data description

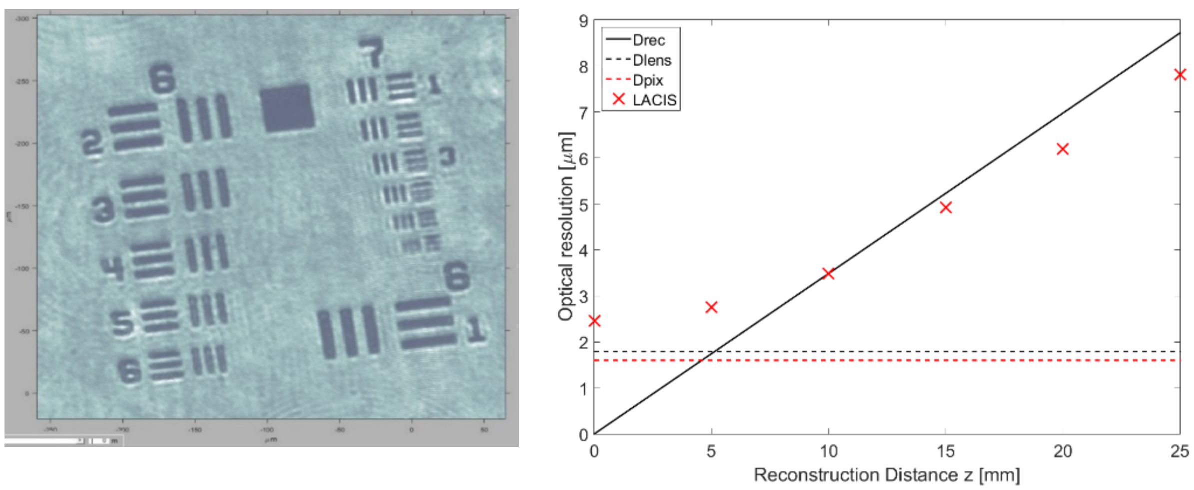
The holographic data were obtained in the form of digital images, which then were reconstructed numerically using the convolution method in Fourier space (Fugal et al. 2004). The reconstructed data were analyzed both, manually and using machine learning algorithms. For each experiment, 1000 images were recorded at a rate of 500 frames per second. On each image a certain number of droplets was detected for which the diameter and position were determined. At the end, droplet size distributions (i.e., droplet number as a function of droplet diameter) are obtained for each experiment by considering all images of a specific experiment.

Preliminary results and conclusions

1. Determination of the lower detection limit of the holographic system HoloPi:

The resolution was experimentally determined by inserting a USAF-1951 resolution target in the beam path. Because the optical resolution is also a function of the distance from the focal plane, the position of the USAF-1951 target was varied along the beam path. Fig. 2 shows the results of the resolution measurements. The lower detection limit was found to be 2.46 µm at the focal plane, increasing to about 7.9 µm at a distance of 25 mm.

Theoretically, the resolution was calculated following Henneberger et al. (2013). A magnification of 12.5 results in a theoretical equivalent pixel size of 0.8 µm and a total field of view of 1.65 x 1.65 mm^2. According to the effective pixel size, the corresponding lower droplet detection limit would be 1.6 µm. However, the effective resolution is also dependent on the lens and furthermore a function of wavelength, focal length and aperture. For this project, a laser with a wavelength of 532 nm and a lens with a diameter of 58 mm and a focal length of 80 mm was used. The calculated resolution of the lens (D_{lens}) and the effective resolution for reconstruction as function of the distance from the focal length

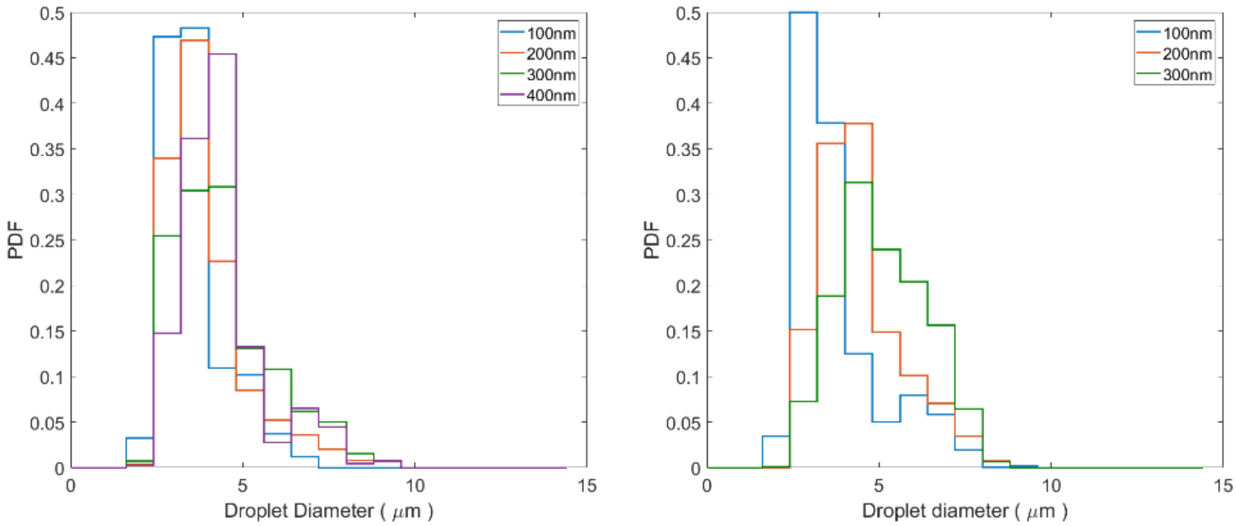


(D_{rec}) is plotted in Fig. 2. The fig. also shows that experimental and theoretical values are in a good agreement. It can be concluded that the determined lower detection limit of 2.46 µm at the focal plane is a great improvement by a factor of about 8 compared to the detection limit of the holographic system without any magnifying lens. It is also an improvement compared to the 7 µm, which can be achieved at the MTU Pi chamber (at a longer working distance).

Fig. 2: (Left) A hologram of the USAF resolution target. (Right) Resolution plot using the USAF-1951 resolution target. The black solid, black dashed, red dashed lines show the theoretical resolution limit due to the reconstruction distance, lens aperture and pixel size respectively (Henneberger et al. 2013). The red crosses indicate the observed resolution using the USAF-1951 resolution target.

2. Investigating rare cloud droplet events:

On days 4-10, cloud droplet activation experiments were done at the LEAK-LACIS facility. This means aerosol particles were activated and grew to form cloud droplets. Particle properties (particle size and number concentration) as well as the thermodynamic conditions (supersaturation ratio) were varied (see Tab. 1). The supersaturation was adjusted by varying the temperature difference of the two



saturated gas flows between 10 K and 16 K. Results for the experiments with a temperature difference of 16 K are exemplarily shown here (Fig. 3). Measured droplet sizes generally increase with increasing particle diameter. The differences between the different particle sizes are small, which can be explained by the kinetically limited dynamical growth after the cloud droplet activation. Furthermore, there was no significant difference between the low and high concentration experiments. This might be due to the comparatively low overall particle concentration. Because of the strong dilution, the competition effects between the droplets seem to be negligible.

Fig. 3: Probability Density Functions (PDF) of all the different aerosol input size distributions are plotted together for a 16K temperature gradient. Results are shown for low (1000 cm^{-3}, left) and high aerosol number concentration (5000 cm^{-3}, right).

In addition to the measurements with HoloPi, a white light optical particle spectrometer WELAS2300 (PALAS GmbH, Karlsruhe, Germany) was applied. WELAS2300 can measure particles between 200nm and 20 µm in diameter but with lower temporal (1s for WELAS 2300, 0.02s for HoloPi) and spatial resolution (a few millimetres for WELAS 2300, 20 µm for HoloPi). WELAS2300 was installed several centimetres downstream of HoloPi (to not disturb the gas flow and the HoloPi measurements). Both instruments were operated in parallel. Overall, the WELAS2300 data were found to be in a good agreement with the HoloPi results (not shown here).

Outcome and future studies

The HoloPi measurements at the LEAK-LACIS facility have provided a very valuable data set concerning the detection limit of HoloPi, as well as the activation of cloud droplets under well-defined turbulent and thermodynamic conditions. It was shown that the detection limit of the HoloPi system can be lowered down to values significantly below 5 µm by using a higher power magnifying lens and reducing the working distance between the lens and measurement volume. Here, the detection limit obtained was 2.46 µm and the spatial resolution was about 1.2 µm. Therewith, cloud microphysical processes like cloud droplet activation can be measured. Based on the promising results shown here, a future study might deal with distinction between liquid droplets and ice crystals.

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