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# Compact MicroLED-Based Lensless Microscope for Real-Time Airborne Cloud Droplet Sensing

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**Summary:**
We present a microLED-based lensless microscope, an imaging system that is compact, lightweight, energy-efficient, and capable of capturing airborne microdroplets. It consists of a microLED as a light source and a CMOS image detector and operates based on inline holographic microscopy. The microscope records holographic images of airborne microdroplets, which are then reconstructed using a Fourier-transform-based backpropagation algorithm. During testing, a microdroplet dispensing system was used to generate droplets with controlled sizes. The results showed that the LED-based lensless microscope could capture clear microdroplet images. After reconstruction, the images were comparable to those obtained using a lens-based camera. Based on the results, the proposed lensless microscope is suitable for monitoring airborne water droplets in both controlled laboratory environments and real-world field conditions.

**Keywords:** airborne droplets, lensless microscopy, microLED, meteorology

## Background, Motivation and Objective

The study of airborne droplets is increasingly important in atmospheric science and climate research [1]. Cloud behavior depends strongly on droplet size distributions rather than solely on liquid water content (LWC) [2]. Therefore, accurate in situ measurements of droplet size distributions and LWC are essential for investigating aerosol–cloud interactions using both airborne and ground-based platforms.

Experimental studies are typically conducted either in controlled laboratory environments or under real-world field conditions. Laboratory setups require compact imaging systems that can operate within confined spaces such as environmental chambers.

In contrast, field measurements require lightweight, portable devices suitable for deployment on towers, drones, or other mobile platforms. Conventional optical systems are often limited in these scenarios due to their size, complexity, and power consumption.

To address these challenges, we developed a microLED-based lensless microscope that enables compact and energy-efficient imaging of airborne microdroplets.

## Description of the setup

The LED-based lensless microscope consists of a microLED light source and a CMOS image detector, operating according to the principle of inline holographic microscopy, in which the sample is positioned between the illumination source and the detector. This configuration enables the recording of interference patterns generated by the interaction of light with the sample, which can later be computationally reconstructed. The microLEDs used in this work were developed in-house, emitting at a wavelength of 450 nm and featuring a pixel size of 20 µm. As the image sensor, a Basler monochrome CMOS camera was employed, with an active sensing area of 7.68 mm × 4.32 mm and a pixel pitch of 2 µm, providing high spatial sampling of the recorded holograms.

Image reconstruction is carried out using a Fourier-transform-based backpropagation algorithm, which enables the retrieval of high-quality images from the captured holographic patterns, achieving sub-micron spatial resolution [3]. The use of microLED illumination eliminates the need for high-power sources and complex optics, resulting in an energy-efficient system. Moreover, the dimensions of 4 cm × 4 cm × 4 cm and a

mass below 50 g make the system compact and suitable for both laboratory and field applications.

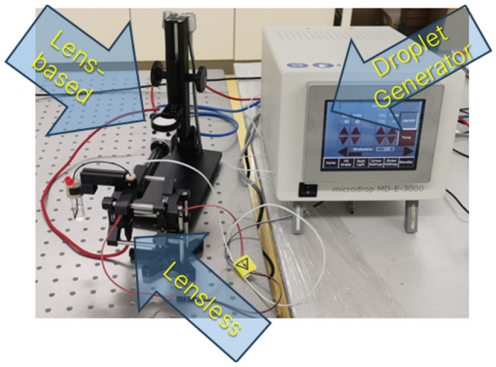



*Fig. 1. The lensless microscope and lens-based imaging system were integrated to enable simultaneous image acquisition as a validation step. Furthermore, the strobe mode of the microdroplet generator was synchronized with the light sources of both the lensless microscope and the lens-based camera.*

## Results

In this experiment, a dispensing system, MD-E-3000 from Microdrop Technologies, Norderstedt, Segeberg, Germany, was used to generate droplets with well-defined sizes. The LED-based microscope was positioned horizontally to provide sufficient space for the microdroplet dispensing tip between the CMOS detector and the microLED (Fig. 1). During calibration and measurements, a lens-based camera was used to image microdroplets generated by the same dispensing tip used in the lensless microscope experiments. To synchronize the measurements and ensure that both imaging systems recorded the same microdroplets, the strobe output controlled by the droplet generator was connected in parallel to the microLED of the lensless microscope and to the illumination source of the lens-based camera.

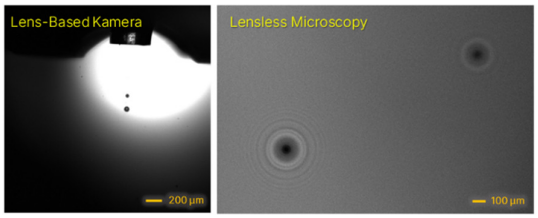



*Fig. 2. The lensless microscope was capable of capturing droplet images in strobe mode. The droplet positions shifted accordingly when the frequency or strobe delay was adjusted, consistent with the observations obtained using the lens-based camera.*

The results demonstrate that the lensless microscope can capture clear images of microdroplets. After applying the backpropagation reconstruction process, the LED-based lensless microscope produced images comparable to those obtained using the lens-based camera (Fig. 2). Based on the microdispenser parameters, namely a driving voltage of 80 V and a pulse duration of 60 µs applied to the piezoelectric nozzle, together with the calibration and synchronization of both imaging systems, the dispensing tip was found to generate droplets with a diameter of between 50 µm and 70 µm ± 5 µm.

Based on these results, it can be concluded that the proposed lensless microscope is suitable for monitoring airborne water droplets. Its compact and lightweight design makes it a promising candidate for droplet monitoring in both controlled laboratory environments and real-world field measurements. Therefore, the system enables lensless microscopy to be used as a portable tool that can be mounted on drones, kites, or even radiosondes for micro-meteorological studies (Fig. 3). This allows real-time measurements to be performed at various locations, e.g., mountainous sites such as Zugspitze, Schneefernerhaus, or Jungfraujoch in Switzerland, supporting long-term studies and sensing-stability evaluations.

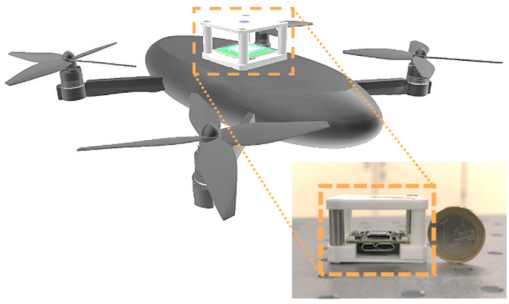


*Fig. 3. Illustration of a lensless microscope on a drone to provide useful data for in-situ cloud microphysics studies.*

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