Digital holographic disdrometer for precipitation monitoring

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Abstract. The paper proposes and discusses the optical design and design features of a digital holographic disdrometer that combines the advantages of optical and 2D video disdrometers. The developed device has a measuring area size more than 100 cm$^2$, the size range of the analyzed particles is up to 20 mm, the resolution is 15 μm and allows you to receive and analyze images of hydrometeors.

1. Introduction

An instrument designed for determination of drop size distribution, velocity, amount of litho- and hydrometeors and their classification is named a disdrometer. It is used for monitoring precipitation properties, for example, in atmospheric physics and agrometeorology.

Historically, the impact disdrometers for measuring drop kinetic energy were widely spread. The acoustic disdrometers have higher accuracy and are capable of measuring the size distribution, kinetic force and precipitation intensity [1]. The hydrometeors are classified by indirect ways (for example, by comparing their fall velocity and size). Modern optical disdrometers can measure particle sizes from 0.1 mm to 30 mm, with an accuracy of 5% (starting from 15 microns), they have high sensitivity and their measuring area size up to 40 square centimeters. The specific properties are the following:

- Hydrometeors are classified by indirect ways [2].
- It is expected that only one particle is present in the area of precipitation measurement which limits the maximum intensity of precipitation being investigated.
- Insects may influence the measurement results.

More complicated 2D video disdrometers models (2DVD) are equipped with two high speed line scan cameras and they watch 10 $\times$ 10 cm$^2$ common area, the pictures of hydrometeors are classified directly, and their resolution is approximately 10 times worse (about 170 μm) compared to the optical disdrometers [3, 4].

The challenge is to develop an instrument possessing all the advantages of 2DVD with the resolution comparable to an optical disdrometer. One of the solutions is to apply digital in-line holography (DIH). As a single hologram contains the information about 3D volume, any cross-section of the volume can be reconstructed numerically at various distances from the image sensor by post
processing [5]. Next, we present the features of the holographic scheme, the effect of image volume depth on the resolution and a description of the prototype of the digital holographic disdrometer that we created.

2. Depth of field comparison for DIH and an ordinary imaging technique

It is known, that the resolution \( r \) and the field depth (DOF) of an optical system is in reverse proportion to lens numerical aperture \( NA \):

\[
r = \frac{1.22\lambda}{2NA},
\]

where \( \lambda \) is the wavelength of the light source, \( NA = n \cdot \sin \alpha \), \( n \) is the refractive index, \( \alpha \) is the maximum angle under which the light from the object enters the lens.

Typically the depth of field is limited from both sides and can be calculated as

\[
h_0 = \pm \frac{\lambda}{4n \cdot \sin^2\left(\frac{\alpha}{2}\right)}.
\]

Next, let us consider the factors influencing the resolution and depth of the image volume for in-line holographic setup depicted on figure 1. Here the objects (4) and (6) are lightened by collimated beam (7) from laser source. The diffraction pattern is refracted by lens (3) and registered by image sensor (1).

![Figure 1. The scheme for DIH registration.](image)

1 – image sensor; 2 – focused image of the second object; 3 – lens; 4 – first object; 5 – virtual image of the sensor; 6 – second object; 7 – collimated laser beam.

It is more convenient to consider the beam path from each objects up to the virtual image sensor in front of the lens rather than behind the lens. In this case the size of the virtual image sensor \( S' \) is equal to the field of view (FOV) size and could be evaluated using the formula of thin lens, for instance.

Then the effective pixel size on the hologram plane is

\[
\Delta \eta = \frac{FOV}{N},
\]

where \( N \) is the resolution of the image sensor.

The enlarged view of the right side of the scheme for DIH registration is depicted on figure 2. Aperture angles here are \( \alpha_1 \) and \( \alpha_2 \), they are the maximum angles, under which the beams from the first and second objects respectively can enter the lens. On the figure \( \alpha_1 > \alpha_2 \), that's why the numeric aperture of the lens in point (4) is more than in point (6). But the aperture angle of virtual image sensor \( \alpha_{S'} \) is less than \( \alpha_{S_3} \), because the distance \( l'_1 > l'_2 \). As a result, high spatial frequencies of the diffracted
pattern formed by first object will not be registered by image sensor, and this fact will decrease the resolution of the first object on reconstructions compare to second object.

![Figure 2. The enlarged view of the right side presented on figure 1.](image)

According to the equation (1) the best lateral resolution in case of DIH is limited by the following factors:

- numerical aperture $NA_O = n \cdot \sin \alpha$ of the objective lens, which decreases while the distance between the object and the input lens increases;
- numerical aperture $NA_S = n \cdot \sin \alpha_S$ of the image sensor, or numeric aperture of virtual image sensor when using the lens;
- the size of coherence area on the plane $S'$;
- maximum order of interference $m = \frac{\lambda}{\Delta \lambda}$, where $\lambda$ is wavelength, and $\Delta \lambda$ is the width of the spectrum of the light source;
- effective pixel size on the hologram plane $\Delta \eta$.

If the necessary resolution is equal $r$, then the numeric aperture should not be less than

$$NA_{\text{min}} = \frac{1.22 \lambda}{2r}, \quad (4)$$

and minimum acceptable aperture angle of lens and virtual image sensor $S'$ is

$$\alpha_{\text{min}} = \arcsin\left(\frac{NA_{\text{min}}}{n}\right). \quad (5)$$

If the lens has numeric aperture equal to $NA_{\text{min}}$, then maximum acceptable distance from input lens to the object $l_{\text{max}}$ (without decrease of resolution ability) is equal to the working distance of the lens. If the numeric aperture of the lens more than $NA_{\text{min}}$, then

$$l_{\text{max}} = \frac{d}{2 \tan \alpha_{\text{min}}}, \quad (6)$$

where $d$ is front effective aperture of the lens.

If the coherence area covers the whole field of view, the maximum distance with the resolution higher than $r$ between the object plane and virtual image sensor is given by

$$h_H = \pm \frac{\text{FOV}}{2 \tan \alpha_{\text{min}}}. \quad (7)$$
The results of the field depth comparison for DIH and an ordinary imaging technique are shown in table 1.

**Table 1.** Theoretical abilities for DIH and an ordinary imaging technique depending on the resolution.

| Resolution µm | $NA$ | $h_O$ mm | $h_H$ mm | $h_H / h_O$ | $FOV$ mm |
|---------------|------|-----------|-----------|--------------|-----------|
| 1             | 0.321| 0.005     | 3.02      | 608          | 2.05      |
| 2             | 0.161| 0.020     | 12.6      | 621          | 4.10      |
| 10            | 0.032| 0.510     | 318       | 624          | 20.5      |
| 13            | 0.025| 0.862     | 538       | 625          | 26.6      |
| 15            | 0.021| 1.15      | 716       | 625          | 30.7      |
| 20            | 0.016| 2.04      | 1270      | 625          | 41.0      |
| 100           | 0.0032| 51.0     | 31900     | 625          | 205       |

The calculation is made on the basis of the following initial data:

- The wavelength of the laser source is 527 nm.
- The size of the image sensor pixel is 5.5 µm.
- The size of image sensor is 2048×2048 pixel or 11.3×11.3 mm.

Since the size of measuring area of 2D video disdrometer is 10×10 cm, then the depth of field should be higher than 5 cm, and the optical resolution is generally limited and may not exceed 100 µm (see the last line of Table 1). Whereas when using holography with the same resolution, the size of the measuring area is approximately 600 times more. These peculiarities of the holographic registration method allow us to create digital holographic disdrometer with high resolution ability and sensitivity.

**3. A prototype of the digital holographic disdrometer**

The design of a digital holographic disdrometer is shown in figure 3.

**Figure 3.** The design of digital holographic disdrometer.

1 – laser source; 2 – beam expander; 3 – windows; 4 – polarizers; 5 – high-efficiency narrowband light filter; 6 – lens; 7 – video camera; 8 – heaters; 9 – temperature sensors; 10 – data storage and transmission unit; 11 – control unit; 12, 13 – boxes; 14 – protective visors.
The operation principle of the instrument is as follows: coherent laser beam (690 nm wavelength), passing through beam expander occurs in the space between the optical windows, thus forming a measuring volume, the size of which determines the sensitivity of the disdrometer. The larger the measuring volume and the size of the measuring area (the horizontal section of this volume), the higher the sensitivity.

The collimated beam scattered on the particles of precipitation trapped in the measuring volume forms a hologram, which is recorded by video camera through lens.

The use of narrowband light filter, the maximum transmittance of which corresponds to the wavelength of the laser source, significantly reduces the noise level, allowing to use a low-power laser source (for example, a laser diode), to increase the safety of its operation, to reduce power consumption and its cost.

A four megapixel video camera (Grasshopper 3) has the pixel size of 5.5 µm. A large aperture 50mm/F1.4 lens is attached to the camera and provides for the possibility to tune magnification in such a way that effective pixel size $\Delta \eta$ on the image sensor is equal to 14.3 µm. The front effective aperture of the lens is equal to 35 mm, this is more than field of view (FOV = 0.0143 × 2048 = 29.3 mm). According to the equation (7) the maximum acceptable distance between the object plane and virtual image sensor plane where the resolution higher than 14.3 µm is limited by the size of the FOV and equal to 523 mm, which corresponds to the limiting measurement area $52.3 \times 2.93 = 153$ cm$^2$.

Protective visors are needed to prevent precipitation particles from entering the optical windows. The distance between the visors allows us to limit the depth of the measuring volume so that the sampling area corresponds to 100 cm$^2$.

The prototype tests showed that its sensitivity is sufficient to measure precipitation with intensity of 0.02 mm per hour within 15 seconds.

4. Conclusions

The main features for the digital holographic imaging technique and the design of the developed prototype of the digital holographic disdrometer are considered. The basic dependencies connecting the DIH resolution and depth of the imaging volume are given. It is shown that when using the holographic registration scheme, the maximum depth of imaging volume is about 600 times more compared with the ordinary imaging technique. This allowed us to develop a digital holographic disdrometer having a high sensitivity due to the large sampling area (100 cm$^2$) and at the same time to get 14.3 µm optical resolution comparable to the resolution of optical disdrometers. Images of hydrometeors resulting from the reconstruction of a digital hologram can be used for further classification and measurement of precipitation.

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