A Hologram Imager Instrument for Ground Plane Measurements of Hydrometeors

Ville A. Kaikkonen* and Anssi J. Mäkynen†

*Centre for Measurement and Information Systems, University of Oulu, Kajaani, Finland
†Optoelectronics and Measurement Techniques Laboratory, University of Oulu, Oulu, Finland

Abstract—**This paper presents a holographic hydrometeor imager aimed for in-situ measurement of falling hydrometeors. The hydrometeor imager is based on in-line holographic imaging, which enables larger imaging volumes than can be achieved using traditional imaging techniques. By numerically reconstructing holograms containing the hydrometeors, detailed images of rain drops and snowflakes with resolutions of tens of micrometers are acquired, as well as the local 3D position of individual hydrometeors inside the measurement volume. The reconstructed in-focus images of hydrometeors are analyzed using conventional image analysis techniques to extract the properties of individual hydrometeors. The imaging equipment is described and the results from the first field measurement are presented.**

Index Terms—**digital holography, image analysis, laser, radar, snowflake, meteorology**

I. INTRODUCTION

Large coverage area measurements of rainfall and snowfall are increasingly important, for example, for water resources monitoring, road and air traffic condition monitoring, and natural hazard estimations. Remote sensing or sensor networks can be used for this task. With existing methods, snowfalls are more challenging to measure than rainfalls. Especially in radar remote sensing of snowfalls, accurate reference measurements of snowflake geometries and their properties in situ would be needed to reduce the uncertainty of the radar measurements [1], [2].

Image based instruments have been presented for measuring hydrometeors, such as the two-dimensional video disdrometer (2DVD), the snowflake video imager (SVI) and the multi-angle snowflake camera (MASC), but either the resolution or the size of the imaging volume is constrained in all these instruments [3]–[5].

Digital holographic imaging found use in many biological and biomedical applications, and within the last ten years the potential of holographic imaging based measurements has also been recognized in meteorological applications, especially in studies of cloud physics [6], [7]. With holographic imaging, a larger depth-of-field is achieved than with traditional macro and micro imaging systems. Thus imaging small objects which appear in random locations, inside a large volume, is not as impractical for holographic imaging as it is for traditional imaging techniques. In-focus images of the objects can be acquired by a numerical back propagation of a digital hologram. In addition, after back propagation, the individual focus distance for each object is acquired, which when combined together with the vertical and horizontal position of the object in the field of view, every object's 3D position can be measured. After the reconstruction of holograms containing hydrometeors, in-focus silhouette images of opaque hydrometeors are acquired. From hydrometeors which are transparent or have transparent parts, inner structures which either scatter the light or contain structures with different refractive indices can also be observed.

Although we are developing a fully automated imaging and analysis system for hydrometeor imaging, in this article we focus mainly on the holographic imaging instrument. In the following sections a holographic imager for recording macroscopic hologram images of free falling hydrometeors on the ground plane is described. First, we describe the components and the mechanical design of the instrument. Next we present the main image processing steps used for automated measurement of hydrometeors, and last we show the results of the first field measurements followed by discussion and future visions.

II. THE HOLOGRAPHIC HYDROMETEOR IMAGER

The hydrometeor imager presented in this paper is our second generation model based on an in-line holographic imaging setup, also known as Gabor holographic imaging. Our first device has been described in previous work [8]. These two models differ both in mechanical and electrical design. The model described in this paper utilizes a separate laser driver circuit to produce pulsed illumination. The laser diode has power of 20 mW and a wavelength of 637 nm. The mechanical design is compatible with Basler Aca-series cameras. The housed camera model is an Aca-1300-gm-30 equipped with a 1.3 megapixel CCD (Charge Coupled Device) area scan sensor and gigabit Ethernet (GbE) connection. The sensor has 1296 x 966 pixels, and the pixel size is 3.75 by 3.75 microns. The camera objective is a 50mm/F1.4 C-mount lens, which provides a 4.5:1 demagnification and results in a maximum measurement volume of approximately 22 x 16 x 200 mm (W x H x L). The length of the measurement volume can be limited using the plastic protective hoods mounted on top of the camera and light source housings. The computer housed in the instrument is an Advantech MIO-2261 series single board computer running on a Windows 8 operating system. The computer is equipped with a dual-core processor,

4 GB of DDR3 memory and a GbE connector, the dimensions of the board are 70 by 100 mm. The instrument runs on 12 VDC and typical power consumption is below 20 W.

A. Mechanical construction and dimensions

In-line holography is the simplest to realize of all the holographic imaging methods. Therefore it is also possible to use a relatively simple mechanical design, which has to withstand the challenging environments where the hydrometeor measurements are to be made. The components of the instrument are housed inside an anodized aluminum cover, with window fittings and end caps machined from plastic, shown in Fig. 1. The instrument head is designed to be rotating in the wireless configuration, and the system is powered through a rotating electrical connector. In this configuration, a wing is installed on the side of the instrument so that the device automatically turns the longer side of the measurement volume towards the wind direction.

The camera and light source housings on the top are tilted away from the center of the instrument to prevent any accumulated snow on the instrument reaching the measurement volume. The instrument can be mounted on a 60 mm diameter pillar. The dimensions of the instrument without the pillar are height 62 cm, width 65 cm and length 20 cm.

B. Hologram recording

In an in-line hologram recording configuration, the light source is aimed directly towards the camera. An in-line hologram is formed on the camera sensor when the highly coherent light from the laser scatters from the objects between the light source and the camera, and interferes with the unscattered part of the light from the laser Fig. 2.

The light source consists of a laser driver, a laser diode and collimating optics, which produce a collimated 26 mm diameter beam at the exit of the lens system. As the outcoming collimated beam has a very low divergence, the imaging

system almost has a unit magnification across the whole measurement volume. The camera objective is installed together with a spacer ring in a way that the collimated beam illuminates the whole sensor and the focus of the camera objective is on the protective glass located in the light source housing.

The recording of the holograms is controlled in a LabView environment in a graphical user interface (GUI), where camera settings and preprocessing parameters can be set. The typical parameters to be set for a measurement are the recording frame rate, the threshold value for empty hologram detection and the number of holograms selected for a background subtraction.

As the first step of the imaging sequence, the camera triggers the laser diode driver which produces a 1 µs long light pulse to illuminate the hologram. The length of the light pulse is short enough to limit the movement of the free falling hydrometeors to less than one pixel, during the hologram exposure, up to 15 m/s fall speeds. The camera sensor has a global electronic shutter and it can be set to a short enough time to suppress the effect of ambient light on the hologram. Holograms can be recorded with a maximum frame rate of 30 frames per second (fps) and the digital holograms are saved as grayscale images in portable network graphics (PNG) file format. The recorded holograms are buffered on an onboard hard drive, and further processed in the preprocessing step.

C. Hologram preprocessing

Only a fraction of the recorded holograms contain any objects of interest, and therefore only the holograms containing hydrometeors and the ones needed for the background subtraction should be kept. As the instrument runs round-the-clock and the stream of the hologram images can reach data rates up to 135 GB per hour with the maximum frame rate, preprocessing of the hologram images is needed in order to keep the data buffer size and the data communication requirements of the instrument at a reasonable level. A computationally light and robust method, to distinguish the holograms which contain meaningful information, should be included in the preprocessing step to handle the data flow.

To address this task, a simple and fast algorithm based on the subtraction of the most recent hologram image from the previously saved hologram has been developed. The resulting image after the subtraction is analyzed using a user defined
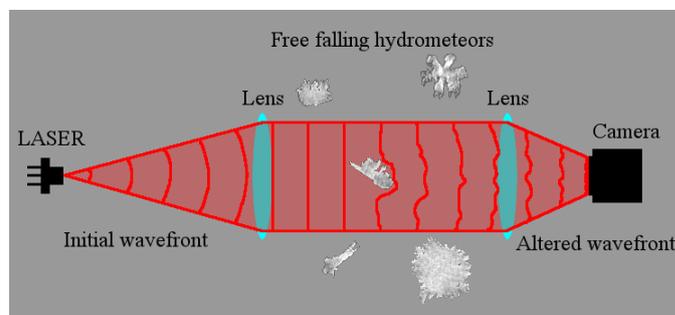

Fig. 1. A photo of the holographic hydrometeor imager installed in the measurement field in Hyytiälä, Finland. A magnification of the instrument head found in the lower right corner.

Fig. 2. An illustration of the holographic recording principle.

intensity threshold value, and marked either as 'true' if the threshold value is exceeded, meaning an object is found, or as 'false' if there are no pixels exceeding the threshold value. The background removal in the reconstruction phase is done by calculating a median image from the neighboring holograms of a detected hologram containing hydrometeors. For this reason, only the files marked as 'true' and their neighboring files are needed to be sent to the server for reconstruction and analysis.

D. Data communication

After the preprocessing, the hologram images containing hydrometeors and corresponding background images are sent to a server for reconstruction and post processing. The instrument can send the data to a server both wirelessly and wired. The data connections can be implemented in mobile telecommunications networks or in either wired or wireless local area networks. An external antenna for the wireless communication is mounted on the top of the central pole of the instrument.

The holograms are sent to a server running on a Windows operating system using the File Transfer Protocol (FTP) network protocol. A single server can receive and process holograms from multiple hydrometeor imager instruments.

E. Hologram reconstruction and analysis

The recorded holograms are processed in the server in the Labview and MATLAB environment using the holoViewer toolbox [7]. Before back propagation, the background is removed from the hologram in order to erase all the static objects which are not of any interest, such as dust on the protective window and optic surfaces Fig. 3.

When reconstructing a hologram containing hydrometeors, an image stack along the depth direction is formed, and all the depth planes containing in-focus hydrometeors are searched. The hydrometeors found are then analyzed using conventional image processing methods in order to extract descriptive properties of individual hydrometeors such as size, perimeter, area, and 3D position, for example. The resulting in-focus images of the hydrometeors after reconstruction correspond to traditional in-focus grayscale images. At present, the focusing is still done manually, but automated focusing and analysis is currently under investigation.

III. FIELD TESTS AND MEASUREMENTS

The resolution of the instrument is demonstrated by reconstructions of holograms of a USAF1951 test target. When the pixel size of the camera is multiplied by the imaging optic's demagnification factor of 4.5, an effective pixel size of 16.9 microns results in the object plane, which is also the size of a pixel in the final reconstructed image. The holograms of the test target were recorded in Hyytiälä, Finland, after the instrument was set in the field. The holograms were taken at both ends of the measurement volume, limited by the adjustable protective hoods to distances of 62 mm and 173 mm from the window in the light source housing. From Fig. 4, it can be seen that the horizontal and vertical elements from group 4 in the test target are visible with a decent contrast up to element number 4, in both, which corresponds to a line width of 22.1 microns.

The first field measurements were made in Hyytiälä starting from 14th March 2014. Both rain and snowfall events were recorded during the spring time. The instrument was found to be running stably during the whole spring. In Figs. 5-8, different sized hydrometeors are shown as grayscale images after the hologram reconstruction. Only the background subtraction was performed in the reconstruction process, no additional processing of the images was made.

IV. DISCUSSION

The holographic hydrometeor imager instrument was described, and the very first results from this new instrument were presented. This instrument was designed based on the experience gained from the first prototype, and the aim was to make it lighter, more compact and more cost effective than the previous version.

The instrument could be designed to have an even longer measurement volume to improve the measurement area coverage, but as the objects in the hologram should block only a small amount of the light reaching the sensor, the density of flakes could be too high during heavy snowfalls and degrade the image quality drastically.
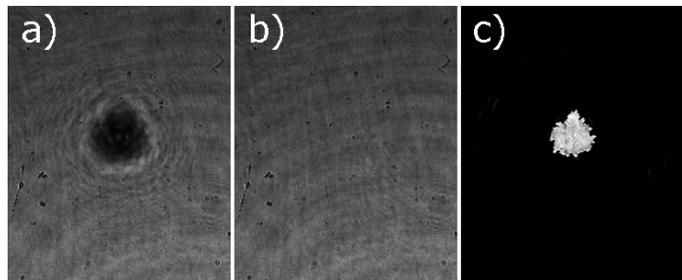

Fig. 3. Fig. 3. Image set describing the hologram processing, from left to right, a) recorded hologram of a hydrometeor, b) background hologram, c) a numerically reconstructed and focused image of the hydrometeor in a).
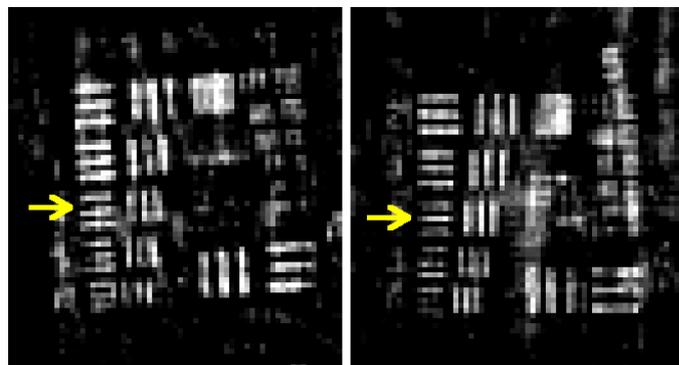

Fig. 4. Reconstructed images of the USAF 1951 test target at both ends of the measurement volume. The arrow in both images is pointing to the element 4 of the group 4 of the test target.
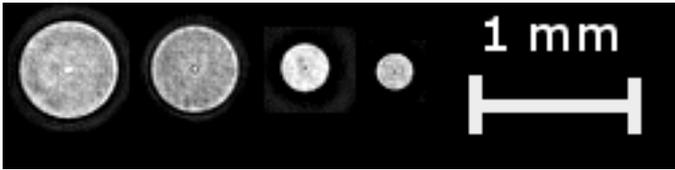
Fig. 5. An image collage of raindrops after hologram reconstruction, captured in Hyytiälä on 8th and 9th May 2014

Despite the relatively high computational power needed for reconstructing the images compared to direct imaging methods, the reconstruction utilizing parallel processing cards has reduced the processing time greatly in recent years, making holographic system also suited for applications needing nearly real time results.

At the moment the hologram imager instrument can be set to collect data in a server. Automated reconstruction and properties extraction are currently being developed. So far we have recorded over one million holograms from Hyytiälä, and comparisons with other instruments in the field will be made after the data analysis has been fully automated. In future, the possibility for automated classification of the hydrometeors should also be investigated [9], [10]. The sampling speed of the instrument is not high enough to record all of the fastest falling hydrometeors. As rain and snowfalls are dynamic events, with temporal and spatial variations, higher frame rates should be utilized in future to record holograms of all the hydrometeors falling through the measurement volume [11].

During a couple of snowfall events in Hyytiälä, the snow accumulated on the front of the window so that the view was partly blocked. We think this was, to some extent, because we had to fix the instrument for wired operation, and therefore during snowfalls in high wind, the instrument was not in the optimal position, and was exposed to accumulation. Changing the window mounts to a downwards tilted and flatter version would most probably help to diminish this unwanted effect.
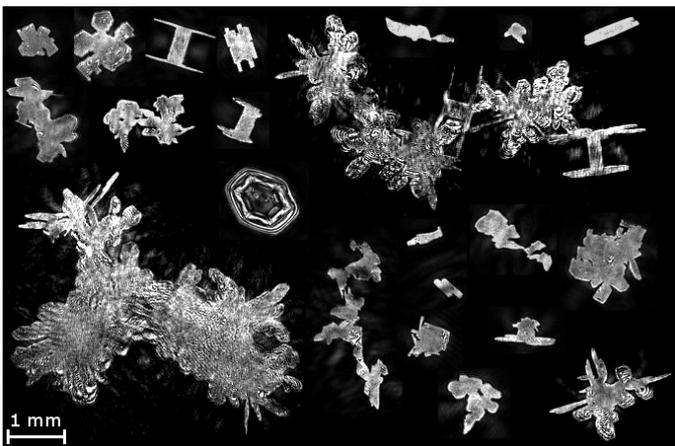

Fig. 6. An image collage of snowflakes after hologram reconstruction, captured in Hyytiälä on 20th March 2014 between 15.00 and 17.00 hours (UTC).
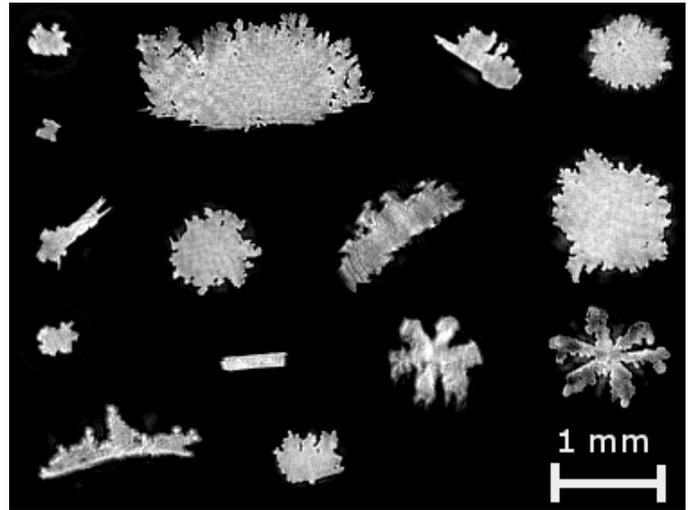

Fig. 7. An image collage of snowflakes after hologram reconstruction, captured in Hyytiälä on 18th March 2014 between 21.00 and 22.00 hours (UTC).
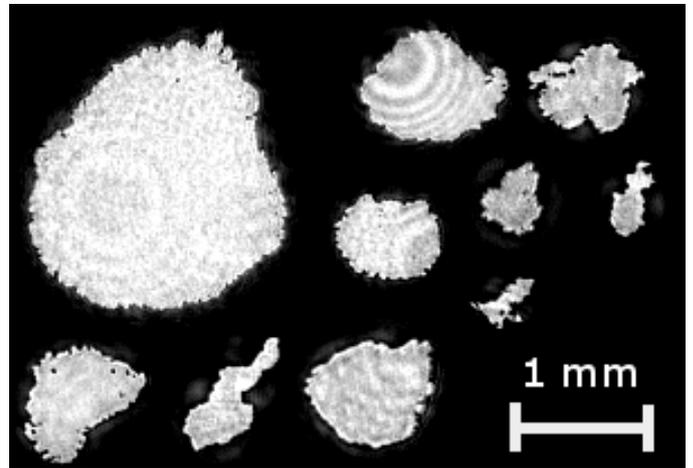

Fig. 8. An image collage of snowflakes after hologram reconstruction, captured in Hyytiälä, on 2nd May 2014 between 17.00 and 18.00 hours (UTC).

Other planned improvements for the instrument in the near future include adding heating to the light source and camera housing windows, and installing an improved laser controller.

Two new similar instruments are being put together at the moment, and will be installed for hydrometeor measurements in the fall in measurement fields in Finland.

V. ACKNOWLEDGMENT

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