

## ***Interactive comment on “Measuring Droplet Fall Speed with a High-Speed Camera: Indoor Accuracy and Potential Outdoor Applications” by C.-K. Yu et al.***

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Anonymous Referee #2 Received and published: 3 February 2016

Response: We appreciate Reviewer#2's comments, which help us improve the manuscript. A set of responses to your comments is provided below.

General comments Paper describes most of all results of indoor experiments concerning measurements of droplet fall speed with a High-Speed Camera (HSC) and their accuracy. At the end results obtained for outdoor conditions are also reported and discussed. However presented results for outdoor experiments are limited to 29 drops

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only collected during 2 storm events. For sure the motivation of study is clear and formulated in following sentence: “The acquisition of accurate rain drop fall speed measurements outdoors in natural rain represents a long-standing and challenging issue in the meteorological community.” Despite the rapid progress in electronics and optoelectronics this is still rather a goal to be met than a reality. I would only add that: “Acquisition of accurate rain drop fall speed measurements outdoors in natural rain by means of moderate cost and easy to use devices represents a long-standing and challenging issue in the meteorological community.”

Response: In this revision, this sentence (The acquisition of accurate rain drop. ...) in the abstract has been revised as the reviewer suggested.

I have to also admit that in general the manuscript is well constructed and clearly written. However after manuscript reading I have to raise the fundamental question concerning the novelty of presented study. The detailed literature review of droplet fall speed (DFS) is summarized by the following sentence: “However, none of these previous published works has addressed the possible application of the HSC to the investigation of atmospheric DFSs (page 5, line 13)” I have a doubt concerning the accuracy of this particular statement having in mind references used in manuscript and some other scientific communications. First of all, video disdrometers based on single camera (1 DVD) and double cameras (2 DVD) are already in use and commercially available at JOANNEUM RESEARCH Forschungsgesellschaft mbH. It could be only discussed if this advanced and costly equipment is affordable for all meteorological community. Problems reported in manuscript are already solved in this kind equipment or could be considered as minor in contrast to the issues of fast recorded frames processing, reduction of splash and turbulent wind effects on orifice of devices and supporting optimal cameras and light arrangement for in field measurements. Nevertheless fall velocity, front and side view of every single particle could be acquired by the 2 DVD.

Response: In this revision, the sentence (However, none of these previous...) )

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has been reworded for clarity. In addition, the authors understand that any instrument/technique has its own strength and weakness. The HSC is not designed nor intended to replace optical disdrometers like a PARSIVEL or 2DVD for measurements of fall speeds and drop size distributions. The strength of the proposed HSC method is its high precision without a need of assumptions implicit in the algorithms required to automatically determine drop sizes and velocities, which in turn can effectively mitigate the sampling uncertainties (such as splash contamination, margin fallers, and coexistence of several particles inside the light sheet) if the experimental setups can be appropriately designed. Conversely, a drawback of the HSC technique, as will be explained in our responses below, is related to the time-consuming work during the experimental period. This article represents a feasibility study to understand the specific degree of accuracy of DFS measurements made with a HSC and to evaluate its potential for measuring DFSs in the outdoor environment. Results from the study provide a unique reference in terms of the description of a sensor (i.e., HSC) and its methodology and processing which is a first, necessary step to achieve scientific goals using atmospheric measurements in the future.

Having in mind the journal to which manuscript was submitted I would also suggest to refer to following paper: Garrett, T. J., Fallgatter, C., Shkurko, K., and Howlett, D.: Fall speed measurement and high-resolution multi-angle photography of hydrometeors in free fall, *Atmos. Meas. Tech.*, 5, 2625-2633, doi:10.5194/amt-5-2625-2012, 2012. This particular paper is focused on snowflakes measurements but MASC is based on the idea of HSC image processing, it is capable to measure also other types of hydrometeors and finally some studies of device accuracy are presented. Finally note that in both devices: MASC and 2DVD use of multiple cameras, mounted at different angles solves the problem of focal zone discussed on page 16 and presented in fig. 9.

Response: Thanks to the reviewer for bringing the article of Garrett et al. (2012) to our attention. In this revision, we have cited this article in the Introduction section and also have emphasized the strength of MASC for solving the problem of focal zone occurring

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in our outdoor experiment described in section 6.

Changes in the manuscript: (Introduction) A growing number of optical instrument types have been proposed in the literature, such as the spectropuviometer (Donnadieu 1980; Hauser et al. 1984), the Particle Size and Velocity disdrometer (PARSIVEL, Löffler-Mang and Joss 2000), the two-dimensional video disdrometer (2DVD, Schönhuber et al. 1997; Thurai et al. 2013), the Hydrometeor Velocity and Shape Detector (HVSD, Barthazy et al. 2004), and the Multi-Angle Snowflake Camera (MASC, Garrett et al. 2012).

(Section 6) For example, a falling drop with motion in a direction perpendicular to the focal plan will feature transition from blurred to clear images (vice versa) within the view frame. To solve this problem, multiple cameras with different viewing angles may be deployed in the future, in a manner similar to the instrumental design of the so-called MASC described in Garrett et al. (2012).

Specific comments Page 9, lines 17-19. Why the size error is equal to +/- 0.040-0.045 mm? Should it not be a product of multiplying 2 (or 4, ie. 2 pixels for upper and 2 pixels for bottom droplet edges) by 0.028 mm?

Response: Sorry for the confusing. In this revision, this part of the text has been revised for clarity.

Changes in the manuscript: It is noteworthy that the method of detecting drop outline is generally not a key factor to influence the accuracy of size determination. Instead, relative dimension of the pixel size (i.e., image resolution) and drop size is more critical for the size determination. Given the pixel size of 0.028 mm, the minimum resolvable length for the drop image, it is reasonable to consider a potential uncertainty for determining each horizontal pixel row of the drop equal to 2 pixels. To obtain a maximum (minimum) possible drop size, all of the horizontal pixel rows constituting the drop are increased (decreased) with 2 pixels when integrating the drop volume from each horizontal pixel row. A range of size error may be evaluated by calculating the deviation

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of the originally estimated drop size from the calculated maximum/minimum drop size, which is equal to 0.040-0.045 mm.

Page 10, lines 15-16. Please check, most probably should be: 0.00056-0.01064 mm and 0.002-0.038 m/s

Response: Revised as suggested.

Page 14, lines 8-12. Most probably instead magnitudes of the  $V_e$  - magnitudes of  $V_e$  percentile should be used.

Response: Revised as suggested.

Page 16, lines 14-15 – Why not to compare to 2DVD (as claimed by manufacturer: vertical velocity accuracy better than 4

Response: We agree that the 2DVD fall speed measurements would probably have higher accuracy, compared to other optical disdrometers. However, to our knowledge, the actual degree of the accuracy (or typical errors) of fall speed measured by 2DVD has not been reported in the journal articles or in the formal publications. So, it is difficult for us to make a convincing or direct comparison of their accuracy with the HSC-derived velocity measurements.

Page 16, lines 16-18 page 15 lines 6-8. Why only larger drops were studied? Parsivel records droplets of diameter smaller than 1.75 mm up to about 0.2 mm.

Response: In the indoor experiment, the larger drops, such as the 14 drops selected for the comparison between HSC and PARSIVEL, were generated by using hypodermic needles. These drops were released one by one with some time ( $\sim 10$  s) in between, corresponding to each sampling duration of PARSIVEL. Therefore, when a drop was captured by HSC (i.e., passing through the focal plane) in a certain time, it is possible for us to check if the drop was also measured by PARSIVEL at that time. For smaller drops ( $< 2$  mm), they were generated by the sprinkling method so it is almost impossible to identify a specific drop captured by HSC from a large population of drops within each

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sampling interval of PARSIVEL.

Changes in the manuscript: The comparison between HSC and PARSIVEL size and velocity measurements for 14 of the larger rain drops ( $D > 1.75$  mm) illustrates the quantization of the PARSIVEL measurements (Fig. 8). These drops are selected for presentation because they were simultaneously observed by both the HSC and the PARSIVEL. It should be noted that in our indoor experiment, the larger drops ( $> 2$  mm), such as the 14 drops, were generated by using hypodermic needles as described in section 2. They were released one by one with some time ( $\sim 10$  s) in between, corresponding to each sampling duration of PARSIVEL. Therefore, when a drop was measured by HSC (i.e., passing through the focal plane) in a certain time, it is practical to check if the drop was also captured by PARSIVEL at that time. For smaller drops ( $< 2$  mm), they were generated by the sprinkling method so it is almost impossible to identify a specific drop captured by HSC from a large population of drops within each sampling interval of PARSIVEL.

Page 16, lines 8-11. Does it mean that threshold values could vary between day and night and over the day due to solar radiation differences? If so, this should be commented as another severe complication of outdoor applications.

Response: In fact, the determination of the drop size is not very sensitive to the threshold of brightness difference we choose. For example, if we use a slightly lower (say 33) or higher (say 37) threshold, it causes a rather minor difference in the drop size ( $< 1.5$  %) compared to that using the original threshold value. This is one of the advantages for the proposed method. In addition, the threshold appears to have a consistent value for a wide spectrum of drop sizes collected from a given experiment. In this revision, we have emphasized this point in section 3.

Changes in the manuscript: It is noteworthy that if we use 24 or 28 as a threshold (cf. Fig. 3), it causes a rather minor difference in the drop size (within 1.5 %) compared to that using the threshold value of 26. The determination of the drop size is not very

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sensitive to the threshold we choose.

Page 18 lines 6-8. This sentence is not clear. Note that several drops namely 9 drops were collected simultaneously on 25 June 2014 at 15:13:03 UTC. The question is how many drops simultaneous could we examine especially if a view frame is 29x29 mm<sup>2</sup>? Could we expect some saturation problems at higher rainfall rates? How much time do we need to process the frames? Is it possible to process them on-line?

Response: In this revision, this sentence has been reworded for clarity. A number of factors including hardware/software settings (the recording frame rate and size of storage memory, for instance) and the characteristics of natural rain (concentration and duration, for instance) can influence the number of raindrops collected by the HSC. In addition, the HSC technique is also related to the time-consuming work during the experimental period, such as the visual and subjective selection of target drops for each recorded period of HSC and the data transfer of these selected drop images from the HSC's temporary storage memory to the hard disk drive of the working computer. These constraints lead to a limited number of water drops that can be actually collected for post-analysis. However, fortunately this weakness can be mostly solved by developing an automatic procedure of judging whether the drops are inside the focal zone and/or by a suitable upgrade in the software/hardware to speed the process of data transfer. These improvements are expected to greatly help strengthen future applications of HSC to the statistical studies of natural DFSs. We are currently undertaking these research and testing works to increase the efficiency of data collection for HSC.

Changes in the manuscript: It is noteworthy that the velocity measurements of HSC, as discussed in this article, are expected to possess good reliability because they are derived on the basis of tracking individual, specific rain drops (Testik et al. 2006).

Page 18 lines 9-10. Most probably too optimistic having in mind 2 DVD and MASC devices.

Response: In this revision, this sentence has been reworded for clarity.

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Changes in the manuscript: Various sampling uncertainties can be effectively mitigated in the proposed high-speed imaging technique.

Tab. 1. How the rainrate R was estimated? Was it a reading from Parsivel? Please, comment row 9 where you report droplet parameters for rainrate R equal to 0.

Response: The rain rates shown in Table 1 is provided by the Vaisala weather transmitter (this information has been added in the table caption), not from the reading of PARSIVEL. Because the minimum detection of rainfall intensity for Vaisala is 0.1 mm h<sup>-1</sup>, it is possible that we can still capture some rain drops during weak rainfall even if the rainfall reading from the Vaisala is equal to zero. This is exactly the case for row 9 indicating a zero rain rate.

Technical corrections Page 14 line 13 most probably bonds instead bond

Response: Corrected as suggested.

Page 15 line 21 most probably allowed instead allow

Response: Corrected as suggested.

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