A Disdrometer based on ultra-fast SPAD Cameras

A. Berthoud[1], S. Burri[1], C. Bruschini[1], A. Berne[1], and E. Charbon[1,2]
[1]EPFL, 1015 Lausanne, Switzerland
[2]Delft University of Technology, 2628 CD Delft, The Netherlands

***Abstract** – We present a new environmental application of SPAD imagers, namely the continuous and real-time measurement of size and shapes of hydrometeors. Details of the set-up and results obtained with a first 32x32 pixel prototype based on the RADHARD2 chip [1] are illustrated. Real-time operation at very low light levels, 6000 frames per second and 1:100 average data reduction are amongst the most significant achievements.*

INTRODUCTION: A disdrometer is an instrument designed to characterize the size (and shape for the most modern ones) distribution of hydrometeors (raindrops, snowflakes and hailstones). The resulting data help interpret weather radar images, as part of weather forecasts, and improve understanding of precipitation microphysics. Parameters of interest are fall speed, size/volume, shape [2] (ellipsoidal, possibly changing over time [3]) of hydrometeors.

DESIGN CONSTRAINTS: The top fall velocity is ~10m/s, while the target diameter is in the range 0.1–10mm. In addition, a disdrometer must be designed for autonomous and continuous outdoors use, often in very harsh conditions.

STATE-OF-THE-ART: Imaging based techniques play an important role in the literature [4]-[5]. Recent implementations include the use of multiple line-scan cameras [6] attaining resolutions of 0.1mm with a sampling area of 100cm^2. In general, it is important to achieve (1) high speed, (2) high dynamic range and sufficient SNR ratio, and (3) sufficiently high saturation levels to enable strong illumination.

PROTOTYPE: We have opted for a SPAD based imager, to achieve our main goals of sensitivity, speed, low power consumption, portability, and potentially low final system price. SPADs are a class of APDs operating above breakdown, in so-called Geiger-mode (Fig. 1). An initial disdrometer implementation has been achieved with an existing RADHARD2 (RH2) system, comprising a CMOS chip and an FPGA for rolling-shutter acquisition at 6000fps (Fig. 2). A micrograph of the chip, whose core is represented by a matrix of 32x32 30µm pitch pixels, each equipped with an independent counter, is shown in Fig. 3 [1]. The acquisition system is connected to a PC via USB.

SET-UP AND PROCESSING: The RH2 camera observes the raindrops as they fall through an intake slid and pass in front of a LED illuminator (Fig. 4 depicts the initial set-up used for lab test, Fig. 5 the final system layout). Processing is organised in a three-step hierarchical approach. First, we accumulate 1-bit frames so as to increase the pixel resolution to several (programmable) bits, typically 4. Second, using an event-driven technique, we recognize the presence of a hydrometeor in a frame, thus filtering those frames that do not contain any objects. A frame average is calculated, and only those frames above an empirically determined threshold are kept, resulting in less than 1% of the frames being stored. Third, the filtered stream is subsequently analyzed in the PC.

RESULTS: The first lab tests involved glass spheres of 2mm mimicking medium-large hydrometeors (Fig. 6). A typical image sequence of real raindrops is shown in Fig. 7. In order to train the system to recognize the raindrops within a range of possible geometries, RH2 follows a precise calibration procedure, involving determination whether the drop is in the focal plane, or its actual size, carried out using the drops as lenses [7] (Fig. 8). Once this calibration phase is completed, it becomes possible to estimate the actual diameter D of the raindrop (Fig. 9-Fig. 10). Several measurement campaigns have been carried out on real rainfall events. The raindrop is identified using standard pattern matching, where the training set is a known raindrop sequence and the reference patterns are the drop *soma* and its boundary (Fig. 11).

PLANS FOR THE FUTURE: The RH2 chip will be replaced with a larger format device, and the R/O electronics adapted. We also plan to move many of the functionalities from the software to the firmware level, and use machine learning techniques to make the training set transparent.

References

[1] L. Carrara et al., “A Gamma, X-ray, and High Energy Proton Radiation-tolerant CMOS Image Sensor for Space Applications”, *ISSCC* 2009, pp. 40-41, Feb. 2009.

[2] K. V. Beard and C. Chuang. A new model for the equilibrium shape of raindrop. *Journal of the*

Atmospheric Sciences, 44(11):1509–1524, 04 1986.

[3] F. Y. Testik, A. P. Barros, and L. F. Bliven. Field observations of multimode raindrop oscillations by high-speed imaging. *Journal of the Atmospheric Sciences*, 63:2663, 2003.

[4] M. Löffler-Mang and J. Voss. An Optical Disdrometer for Measuring Size and Velocity of Hydrometeors. *Journal of Atmospheric and Oceanic Technology*, 17:130, 2000.

[5] J. R. Saylor and N. A. Sivasubramanian. Edge detection methods applied to the analysis of spherical raindrop images. *Applied Optics*, 46(22):5352, 2007.

[6] A. Kruger and W. Krajewski. Two-dimensional video disdrometer: a description. *Journal of Atmospheric and Oceanic Technology*, 19:602, 2002.

[7] B. K. Jones, J. R. Saylor, and L. F. Bliven. Single-camera method to determine the optical axis position of ellipsoidal drops. *Applied optics*, 42(6):972, February 2003.

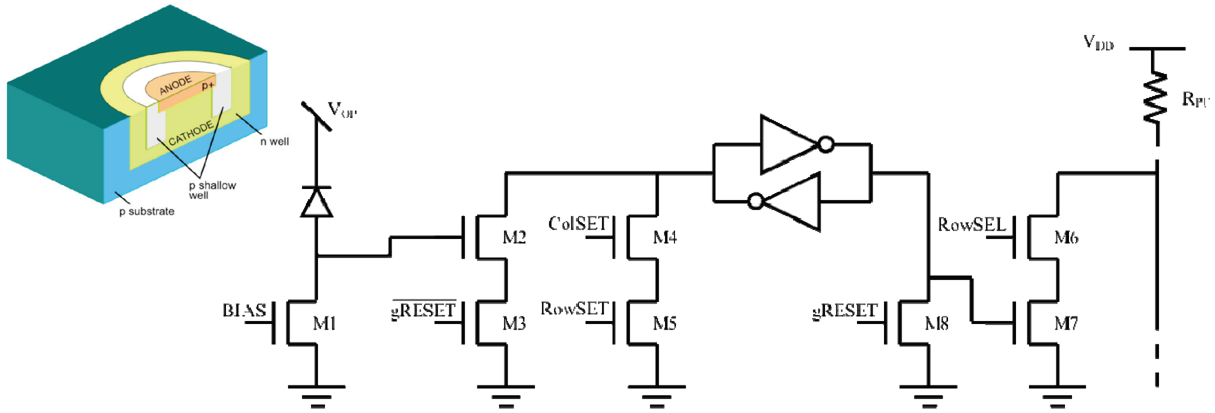


Fig. 1 RADHARD2 pixel: schematic diagram with passive quench and recharge circuitries (left), pulse shaping and an embedded counter (right) [1]. Inset: SPAD cross-section, conventional CMOS process.

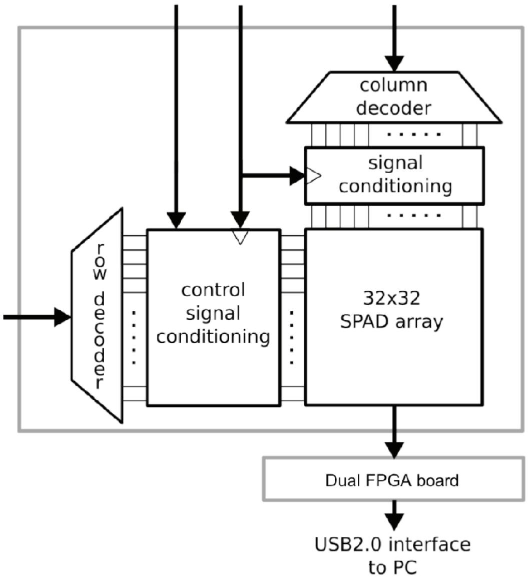


Fig. 2 RADHARD2 block diagram [1]. The chip is read out in rolling shutter mode as a sequence of 1-bit 32x32 pixel frames.

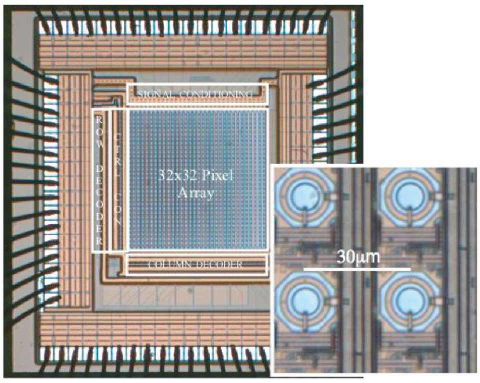


Fig. 3 Photomicrograph of RADHARD2, a 32x32 parallel-counting pixel array implemented in 0.35µm CMOS technology. [1]

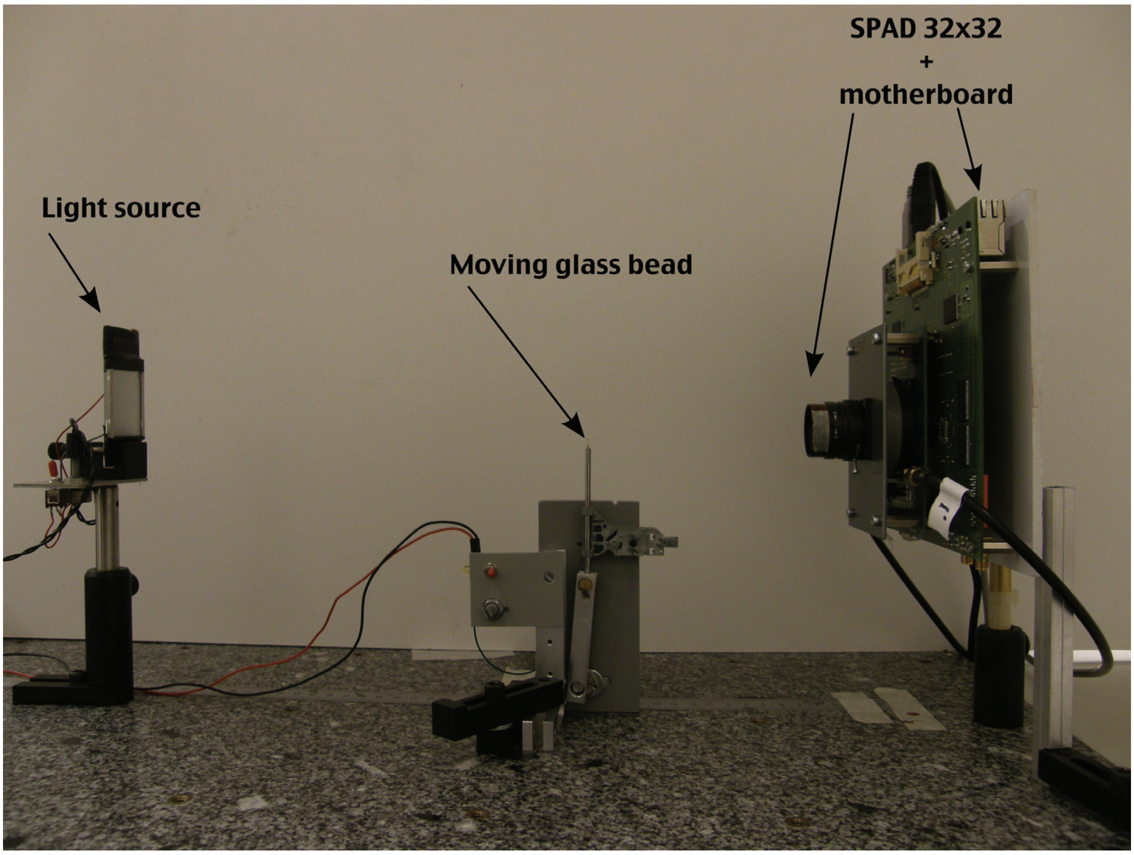


Fig. 4 Initial disdrometer set-up for lab bench tests using a moving glass bead to mimic a falling drop.

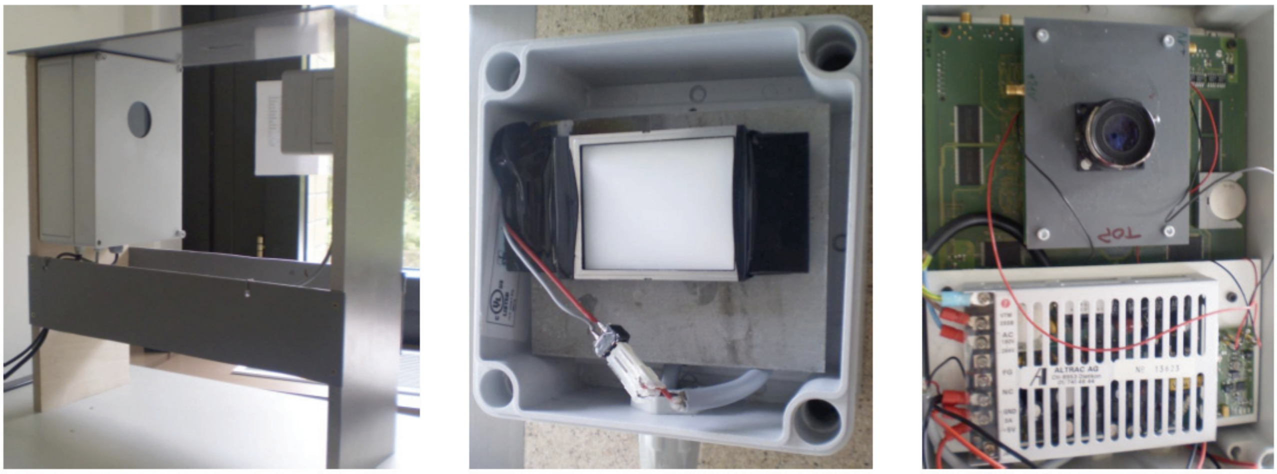


Fig. 5 Final system layout. Left: disdrometer housing. Centre: Light source in its protection case. Right: Sensor, motherboard and power supply

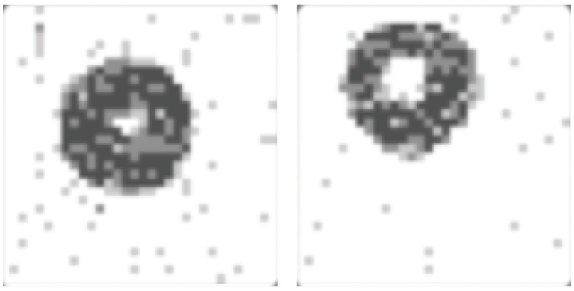
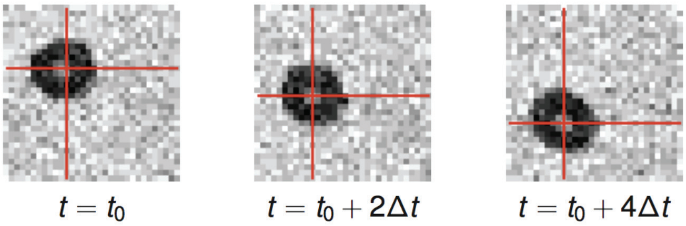


Fig. 6 Image of a glass sphere captured by RADHARD2 (left, set-up of Fig. 4). Water drop observed by RADHARD2 under the same conditions (right, set-up of Fig. 5). The intensity resolution was 4 bits in all experiments.



$t = t_0$ $t = t_0 + 2\Delta t$ $t = t_0 + 4\Delta t$

Fig. 7 Sequence of raindrops captured by RADHARD2 running at a 6kfps. The centre is determined and thus the velocity of the fall may be determined. In this case the estimated velocity was of 3.4m/s.

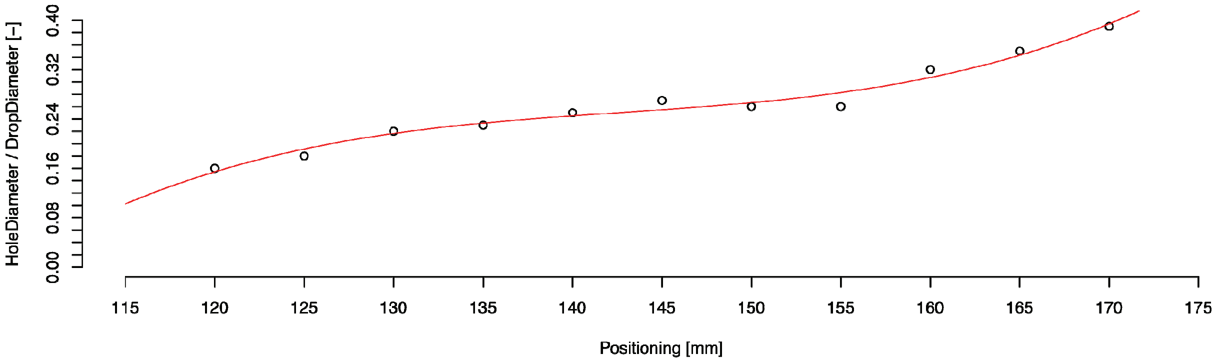


Fig. 8 Use of raindrops as lenses for calibration purposes: (*soma* diameter)/(drop diameter) ratio as a function of the drop location along the intake slid. The horizontal axis shows the distance of the raindrop to the main lens. The relation is cubic as shown by Jones [3]. (NB: soma: white hole in the drop image centre.)

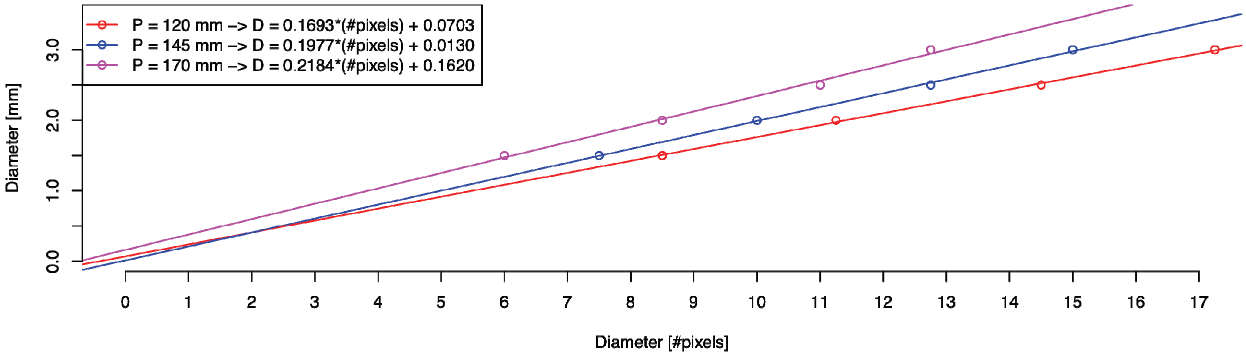


Fig. 9 Estimation of the raindrop diameter *D*, irrespective of distance of the raindrop to the main lens *p*. The accuracy of the estimation is given by the error of the linear fit.

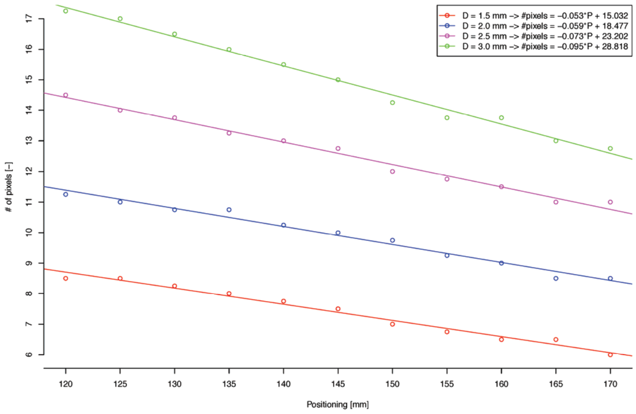


Fig. 10 Linear fit of raindrop diameter D in pixels vs the drop position on the optical axis for several values of the real drop diameter. The accuracy is given by the error of the fit.

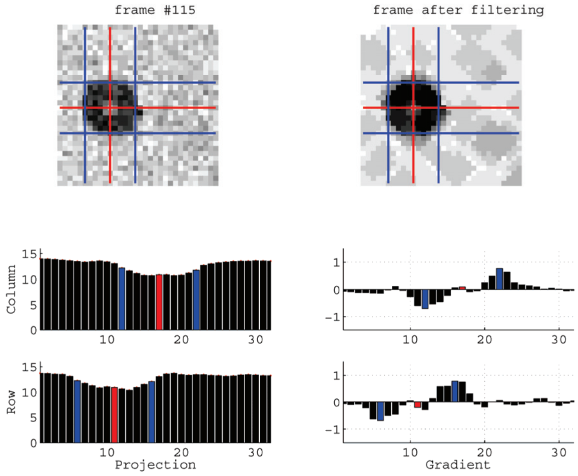


Fig. 11 Results after post-processing: raindrop raw image (top left), filtered image (top right). Bottom left: projection for each dimension, bottom right: gradient on this projection.