Response Letter for Anonymous Referee #2

Overall Comments

Opportunistic sensing is an emerging crowdsensing technique for monitoring precipitation. Previous studies have suggested that delicate use of visual surveillance cameras allow the retrievals of rain drop size distributions as well as rainfall intensity. This study demonstrates that raindrop size distributions can be retrieved from an infrared surveillance camera as well. The topic is relevant for AMT readers, and the presented work is interesting. I have a few concerns as listed below.

Answer:

We appreciate for your valuable comments. As suggested by the referee, all the comments were considered in the revision of the manuscript.

Q1. The motivation of using infrared surveillance cameras is weak to me. Although no such work has been done, it does not necessarily mean that the presented work is promising in applications. Given many readers are in the meteorology community, they may wonder: Are infrared surveillance cameras widely distributed? Why and how should this approach be applied? At what conditions should we employ this technique? The authors may elaborate this point in Introduction or in Discussions.

Answer:

The surveillance camera (supporting infrared mode) considered in this study will not be able to replace traditional observation devices (rain gauge, radar, satellite, etc.). However, if these studies can be continued to secure robustness, it will be an excellent complement to the existing observation system in terms of spatio-temporal resolution and accuracy improvement.

The infrared surveillance camera mentioned in this study refers to a product in which an IR (infrared) light is additionally installed on a general camera. Infrared cameras emit near-infrared rays through an infrared emitter and receive the reflected light from the objects. Accordingly, there is an advantage in that raindrops that are invisible to the human eye can be detected. Most of the surveillance cameras currently installed have these functions. There are not many surveillance cameras that support infrared mode yet, but they are widely distributed. For example, in Korea, where the authors reside, the most frequently installed public surveillance camera model is Hanhwa Techwin SNO-6084R, which supports IR mode (Please see, https://product.hanwha-security.com/en/products/camera/network/bullet/SNO-6084R/overview/#).

The reasons for using the proposed method are as follows. Existing studies have focused on the time when video can be captured with visible light. Naturally, these methodologies are only applicable in daytime conditions. In other words, it is impossible to obtain input data without visible light using the existing image-based rainfall measurement method. However, when photographing using infrared rays, it is possible to obtain a rainfall image even when there is no general sunlight. Therefore, it is of great significance in terms of supplementing the limitations of existing studies.

Conditions and manner for using the proposed methodology are as follows. The method can be used under low illumination conditions. That is, when the amount of light is sufficient, the video may be sufficiently captured with visible light, and thus the IR mode is not required. However, when sunlight is insufficient, an image should be captured using a camera supporting the IR mode. If the IR mode is not supported, it is also possible to additionally purchase and install IR light to the normal camera to record the video under dark conditions. When using a camera that supports IR mode, it can be set to the auto mode provided by the camera manufacturer, or the operating time zone can be set to manual. In general, this auto mode has the sensitivity to illumination as an option. Therefore, if this sensitivity is well adjusted through trial and error, it is possible to acquire rainfall images under dark conditions. The manuscript was revised by reflecting the above-mentioned contents.

(Revised Manuscript, Lines 64-68)

However, the existing studies have focused on the time when video can be captured with visible light. It is impossible to obtain input data without visible light using the existing image-based rainfall

measurement method. Thus, these methodologies are only applicable in daytime conditions. However, when recording using infrared rays, it is possible to obtain a rainfall image even when there is no sunlight. No study has estimated the rain in dark conditions to our knowledge.

(Revised Manuscript, Lines 88-91)

In this study, an infrared surveillance camera was considered under dark conditions. Here, the dark condition refers to a condition in which raindrops cannot be captured by a general surveillance camera with visible light. Infrared cameras emit near-infrared rays through an infrared emitter and receive the reflected light from the objects. Accordingly, there is an advantage in that raindrops that are invisible to the human eye can be detected.

(Revised Manuscript, Lines 478-482)

In this study, DSD was estimated using an infrared surveillance camera; the rain rate was also estimated. Consequently, we could confirm the possibility of estimating an image-based DSD and rain rate obtained based on low-cost equipment in dark conditions. Though, the infrared surveillance camera considered in this study will not be able to replace traditional observation devices, if future studies can be continued to secure robustness, it will be an excellent complement to the existing observation system in terms of spatio-temporal resolution and accuracy improvement.

Q2. It appears to me that the algorithm used in this study is similar with previous works on visual images. The authors should clearly state the innovative point of the presented algorithm. For example, how were the previous algorithms adapted to fit the infrared application?

Answer:

Existing image processing-related studies regarded rainfall as noise that should be removed. However, recent studies, including this study, attempted to estimate rainfall using these noises. These studies used rainfall images to calculate rainfall intensity through techniques such as AI. However, unlike previous studies, individual rainfall particles were extracted through optical physics and image processing, and the distribution of them was compared with actual observation data from the PARSIVEL.

In addition, the algorithm presented in this study have the innovative points adapted to fit the infrared application comparing with the previous studies. Largely, 1) 2D kernel is additionally applied to improve the light smudging phenomenon that may occur in infrared video, and 2) only major raindrop is extracted for overlapping raindrops. The manuscript was revised to reflect these parts.

(Revised Manuscript, Lines 141-142)

Videos from infrared mode have usually a blur effect. Thus, the additional 2D kernel was applied to remove the pixels having blur.

(Revised Manuscript, Lines 333-335)

If the rain streaks overlap, the diameter of the raindrops can be estimated large. In this study, in order to reduce the overestimation of raindrop diameter, the main central axis coordinates of rain streaks in images were obtained, and main short diameter information was estimated.

Q3. Fig. 7. Where are those big particles from? If they are falling, they should have rather high velocities. But they could also be the results of lens contamination.

Answer:

The possibility of lens contamination mentioned by the referee is a very important part in analysis using camera image data. The authors were aware of this and used two methods as countermeasures. The first method is to fundamentally block lens contamination. In other words, it is to install a shield on the surveillance camera itself. The next method is to take only an image of an uncontaminated part, and this meaningful part of the image is called a region of interest (ROI). The camera's resolution is 1,080 pixels for the height and 1,920 pixels for the width, but the images were cropped to images with 640×640 pixels applying ROI to get clean images.

In addition, the big raindrops described in the manuscript result from a large diameter estimation due to the overlapping rain streaks in the CCTV image. In order to reduce the overestimation of the raindrop diameter, the central axis coordinates of the rain streaks in the CCTV image were obtained, and the short diameter information was recovered based on the central axis information of the overlapping rain streaks.

(Revised Manuscript, Lines 333-335)

If the rain streaks overlap, the diameter of the raindrops can be estimated large. In this study, in order to reduce the overestimation of raindrop diameter, the main central axis coordinates of rain streaks in images were obtained, and main short diameter information was estimated.

Q4. Fig. 8. Comparing the DSDs retrieved from the camera and PARSIVEL, It appears that the variation of DSDs is not well captured by the camera. In particular, significant overestimation has been found for large raindrops. The contributing factors should be discussed.

Answer:

Since the PARSIVEL data also has an error in the observation data of the in-situ instrument, the variance was reduced by applying the correction factor for each diameter proposed in previous research results (Raupach and Berne, 2015). However, the problem of underestimating the number concentration for raindrops smaller than 0.5 mm with the PARSIVEL disdrometer still existed. In order to reduce the problems of these instruments, we plan to conduct comparative verification with 2DVD (Two-Dimensional Video Disdrometer), which has higher observation accuracy for small rain particles of less than 0.5 mm compared to PARSIVEL.

Large raindrops can be seen as occurring in calculating raindrop diameter based on rain streak information by overlapping rain streaks. The length of the rain streak is highly dependent on the camera's exposure time, and as the exposure time decreases, the length of the rain streak becomes shorter. As a result, the overlapping phenomenon of rain streaks can be reduced. This study focuses on increasing the meteorological usability of existing CCTV image data, not on instruments produced for research. Future research results related to hardware settings, such as exposure time and shutter speed, will be performed to suggest ways to utilize CCTV data for disaster prevention.

*** References**

Raupach, T. H., & Berne, A. (2015). Correction of raindrop size distributions measured by Parsivel disdrometers, using a two-dimensional video disdrometer as a reference. Atmospheric Measurement Techniques, 8(1), 343-365.

Q5. Fig. 9. It appears that fitting a distribution to some extent alleviates the overestimation of large drop concentrations, have you tried to construct the DSD using the fitted distribution? I would expect improved results.

Answer:

As noted by the referee, fitting distributions based on observational DSD can lower the number concentration variance by diameter. Rain rate estimation accuracy can be improved through fitting distribution information, and rainfall spatial distribution accuracy of remote sensing data such as satellites and radars may be improved by using CCTV image data. However, the fitting distribution has a high dependence on the fitting model, which can cause errors by diameter, and the density dependence of small raindrops is also high. By improving the observation data's accuracy, the fitting distribution's accuracy can be expected to be improved. Therefore, this study focuses on the raindrop diameter estimation method observed in video image data. The method for estimating the diameter of raindrops based on the central axis information of rain streaks was improved. The improved results for diameter overestimation due to overlapping rain streaks were additionally described in the manuscript.

(Revised Manuscript, Lines 150-153)

Accordingly, the representative angle of each extracted rain streak was calculated. The border information of each rain streak was obtained, and center axis information of the rain streak was obtained based on the border information to calculate the drop angle. Moreover,

the rain streak was rotated to set the long and short axes of the streak at 0° and 90°, using the angle information.

(Revised Manuscript, Figure 11)

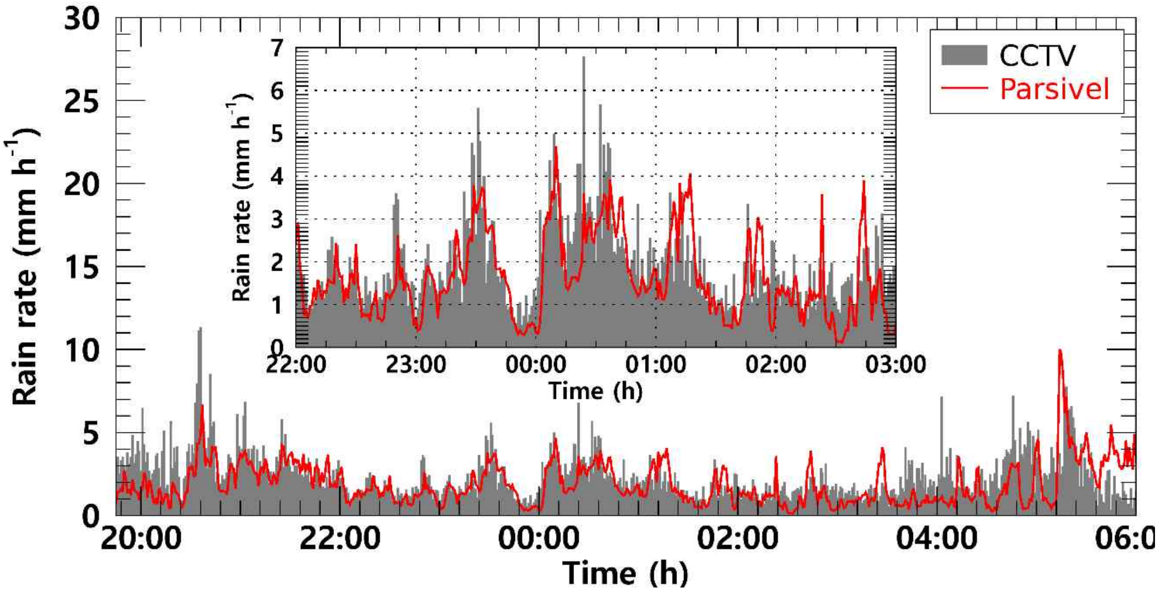

Figure 11: The rain rate time series calculated from the surveillance camera images (gray bar) and PARSIVEL observation data (red line) from 1945 LST on March 25 to 0600 LST on March 26, 2022.

Q6. Given the significant bias found for large raindrops, I believe the evaluation should be made for a heavy rainfall event. Otherwise, the story is incomplete.

Answer:

We agree with the referee's opinion. By adding an analysis case, we tried to increase the reliability of the research results for rain rate and DSD (Drop Size Distribution) estimation based on general CCTV image data, which is the aim of this research.