Reviewer 1 comments and response

We appreciate the reviewers insightful comments and criticisms. We have tried to address them all carefully below in a point-by-point manner and believe the paper has been improved as a result.

Review Comment 1: *There are a number of shortcoming that need to be addressed before this paper can be published. The most significant being the lack of a comprehensive error analysis the documents the source of systematic and random errors and then propagates these into the derived quantities that are being highlighted, i.e., equivalent diameter, particle complexity, density, mass, visibility, SWE, etc. There are many potential sources of uncertainty that were mentioned but no quantitative estimates given. This is unacceptable for an instrumentation paper. One of the uncertainties that is given very short shrift concerns the probability that two more snowflakes will be imaged together, not because they are aggregating when they fall but because one fell one top of the other. A very brief comment is made that under one condition, out of a 1000 images, only 5 were touching. Figure 7 belies that statement since there are many fewer than 1000 particles and I count more than 10 that are touching. Given the long times needed to evaporate ice crystals (see my next enumerated issue), 30-60 seconds, under even modest precipitation rates the probability must be moderately high that as one crystal melts/evaporates, another will fall on top of it. This situation is not addressed but a very simple calculation needs to be made, similar to what is done with other optical spectrometers, to estimate the coincidence probability for different size distributions and precipitation rates.*

Response: We agree with the referee that a comprehensive error analysis is important to address in the paper. For systematic and random error analysis, 45718 snowflakes have been considered, which were collected during an approximate 6 h period during field experiments at Alta Collins on 15 April 2020. During this period, a wide range of precipitation rates ranging from 0.001 to 16 mm hr^{-1}, were observed. Direct measurements made by the DEID consist of: area, temperature, and the evaporation time of snowflakes. The percent error in the area, temperature, and evaporation time for all observations is 1.0%, 0.3%, and 1.0% respectively. The percent error in the calibration constant $(k/d)_{eff}$ is 1.0%. The percent error in derived quantities (using a standard propagation of uncertain analysis) such as equivalent diameter, particle complexity, mass, density, visibility, SWE, and snow height are 0.5%, 2.0%, 3.3%, 4.8%, 3.3%, 5.3%, and 8.1%, respectively.

The probability of subsequent hydrometeors falling on top of one another before complete evaporation of the initial hydrometeor depends mostly on the following parameters: precipitation rate, hotplate temperature, evaporation time, snowflake type, and density. To calculate the coincidence probability, the same data introduced above is considered with a given hotplate temperature of 104° C. With and without overlapping the time series of the area and an average temperature of hydrometeors during complete evaporations is shown in Figure R1a,b below. When compared to a typical evaporation cycle for a single frozen hydrometeor, overlapping is indicated by a significant decrease in temperature and increase in area within a normal cycle of evaporation. By applying these conditions, the probability of coincidence is calculated. A second method takes into account the size distribution, which provides a vertical structure of hydrometeors based on precipitation rate. An overlap is counted if the evaporation time of any hydrometeors is greater than the average time between two consecutive hydrometeor in the vertical direction. Using these two methods, negligible overlaps were observed for a precipitation rate of ~1 mm hr^{-1}, and a maximum of 4.9 % coincidence probability was observed during the highest SWE rate 15.6 mm hr^{-1} and it is given in Figure R2. Note that during instances of overlap, in contrast with optical distrometers, the DEID does not lose measurement of the primary quantity of hydrometeor amount, in this case mass. The DEID provides a combined mass from Eq. 17. Total mass estimation is unaffected although individual particle calculations such as mass, size, and density are.

For data where overlap is identified, these measurements are not considered in the probability and size distributions etc.

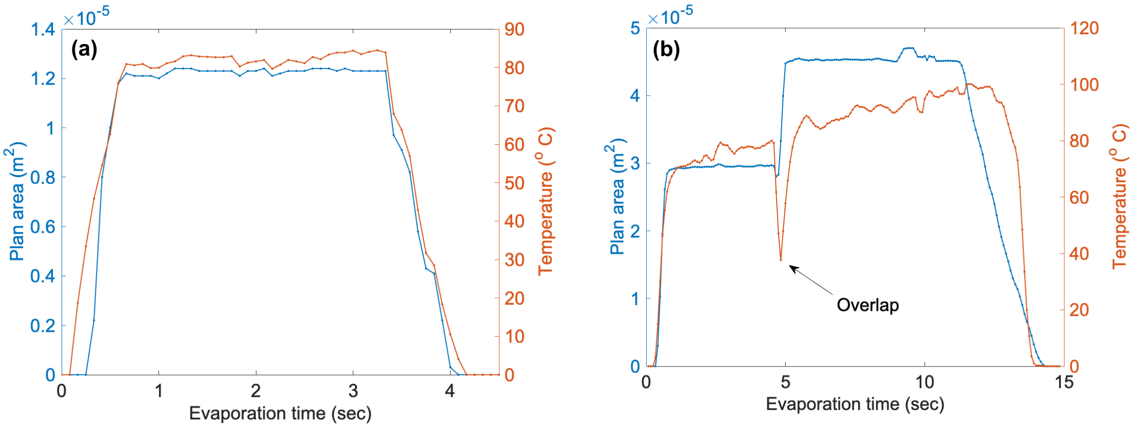

Figure R1. Example time series of individual hydrometeor area and average temperature during complete evaporation for a case (a) without overlap and a case (b) with overlap.

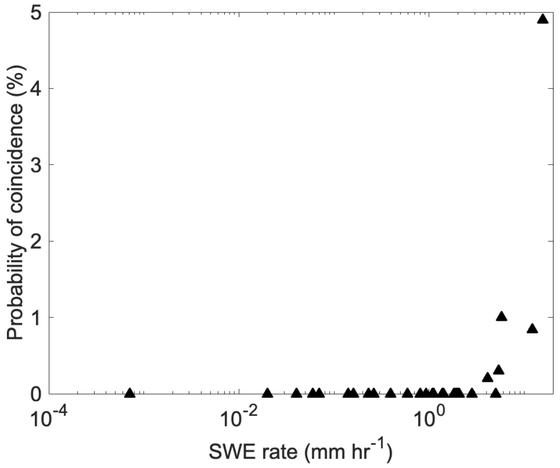

Figure R2. Probability of coincidence as a function of SWE rate.

Reviewer Comment 2: *One of the most critical parameters in all of the equations to predict density and mass, is the time to completely evaporate a crystal; and yet only a single figure (Fig. 5) shows this parameter for a single water droplet. I would like to see some actual Size vs time for ice crystals in field experiments so as to illustrates the variability with size, mass and density. These times also help determine the frame rates and probability of coincidence, so a lot more needs to be discussed about their importance for deriving the parameters that are being advertised as available from this instrument.*

Response: Evaporation time, defined as the time taken for complete evaporation of an individual hydrometeor, depends on the following parameters: the temperature of the hotplate, the roughness of the hotplate, ambient conditions including wind velocity, temperature, and humidity, etc. 45718 snowflakes were considered for plots of evaporation time vs diameter, mass, and density as shown in Figure R3 a,b,c. The plate temperature was set to 104° C and the thermal camera sampled at a frame rate of 12 Hz. The median values with lower and upper quartiles for the evaporation time is 2.41 [1.25, 5] sec. Hence, this range of time scale minimizes uncertainty in measurement for all type of hydrometeors at given hotplate temperature and frame rate.

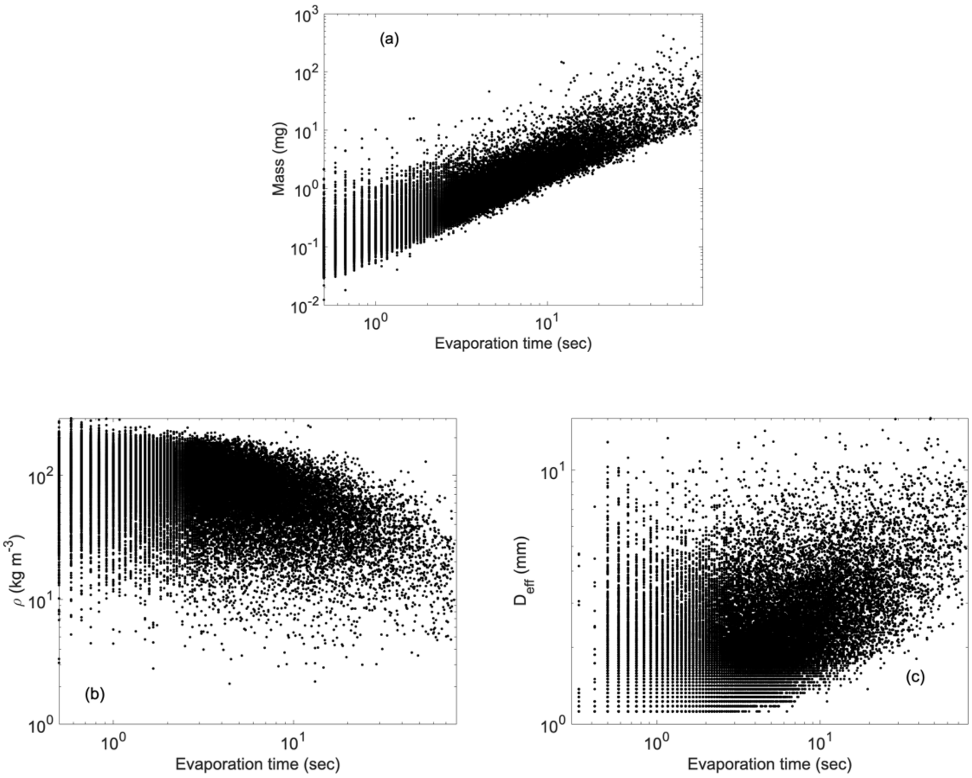

Figure R3. (a) mass, (b) density, and (c) equivalent diameter as a function of evaporation time of water droplets originating from melting snowflakes.

Reviewer Comment 3: *The camera frame rates that are mentioned vary quite a bit, from 5-240. It appears that the higher frame rates were used just to validate certain aspects about detection and melting rates, but operationally much lower rates are used. Why? This raises a very important issue that is not addressed: "What is the processing time?". With 1.2 Mpixels to process from each frame, how long does it take to identify and accept/reject each particle in a frame, what are the filtering criiteria and has fast can all the derived parameters be output? Is this near-realtime or does this require substantial pot-processing time so that the applications can only be for research and not for operational applications?*

Response: Higher frame rates were used to validate aspects of particle detection and the melting rates etc. and a lower rate (12 Hz) was used in field observations. To determine a thermal camera frame rate that would capture the widest possible range of hydrometeor types , an experiment was performed during a snow event at Red-Butte Canyon on 25 March 2020. The thermal camera was operated at a frequency of

60 Hz with the plate temperature set to 104° C. The total mass of hydrometeors was estimated using two different algorithms, from the total mass in each frame, a summation of the mass of each particle. The difference in total mass between the two algorithms can arise due to rejection of hydrometeors with an evaporation time less than three consecutive frames or from incomplete evaporation at the end of sample period. A period with a length of three frames (0.25 sec) was selected as a minimum for performing an accurate mass measurement. The total mass of hydrometeors that fell on the hotplate within half an hour was calculated using sampling frequencies of 1, 2, 3, 6, 10, 12, 15, 20, 30, and 60 Hz and shown in Figure R4. Using the frame-by-frame method the calculated total mass at 12 Hz frequency is 99.82 % of the total mass calculated at 60 Hz, so it is this method that is used for SWE accumulation calculations. Using the particle-by-particle method the calculated total mass at 12 Hz frequency is 94.79 % of the total mass calculated at 60 Hz.

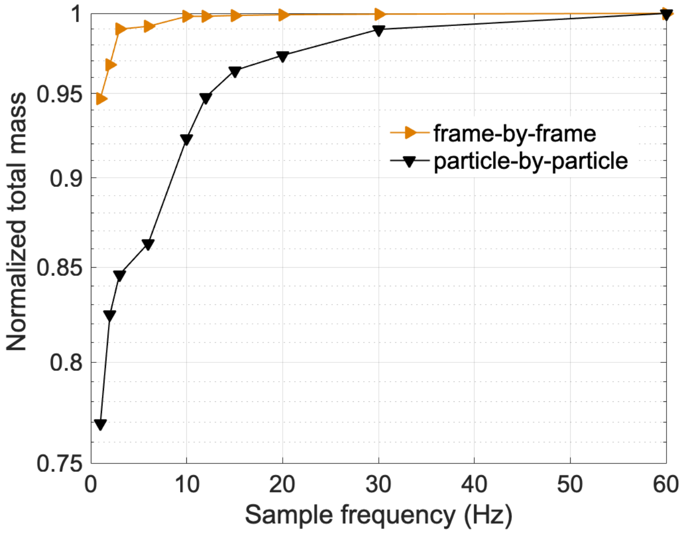

Figure R4. Normalized total mass that is total mass at different frequency divided by total mass at highest frequency is plotted against sample frequency.

Sampling at 60 Hz could also be done, but it is less practical operationally. For a ~ 1.2 Mpixels camera resolution, the processing time for each frame is approximately 0.015 sec. The average size of the data for a one-hour period is 1.3 Gb and the associated processing time is approximately 11 minutes. Selecting a frame rate of 12 Hz, in part, assures that the DEID can operate as a real-time instrument. Hence, the 12 Hz represents a cost benefit balance between accuracy of the measurement and time and storage costs.

Reviewer Comment 4: *How do you avoid measuring snow lifted from nearby surfaces, i.e. how do you know that you are measuring freefalling snowflakes?*

Response: At the Alta Collins site location, the DEID is collocated alongside instrumentation deployed at the long-running Collins Snow Study Plot (CLN), which is a well-protected snow study site located at the upper terminus of Little Cottonwood Canyon, averaging 1300 cm of snowfall annually and 17.4 days with at least 25 cm of snow per winter. The full record from CLN spans 41 years (January 1980–April 2021), and the last 21 seasons include a complete record of automated hourly precipitation observations (Alcott and Steenburgh 2010).

This site was chosen in part to avoid the additional measurement of windblown snow that would typically be lifted from exposed terrain features. However, we did not do anything to specifically avoid measuring lifted snow other than using this well-sheltered area along with keeping the plate surface elevated ~1.25 m above the ground surface. Blowing snow is likely to have a distinct signature by way of particle clustering and size. In the current state, no distinction has been made between the characteristics of freefalling and lifted snow. If there is a flux of precipitation falling downwards onto the plate it will be measured whatever its origins.

Reviewer Comment 5: *Can you measure graupel or snow pellets that bounce?*

Response: This is an excellent question. Snow particles bouncing from the heated plate are a function of the following two-time scales: (a) the contact time between plate and snow particle and (b) the melting time of the initial contacting layer of the snow particle. There is a competition between the contact time and melting time. Contact time decreases with increasing density of a snow particle, and melting time increases with increasing density of snow particles. For a given density of snow particle (74 kg m^{-3}), the contact time is O (10^{-1} sec), and the melting time of a 100 μm thick layer is O (10^{-3} sec). When a snow particle melts, the normal reaction force of the surface to the snow particle is weakened. A roughened plate surface and the surface tension between plate and initial melted water layer of the snow particle helps to hold the snow particle in place after impacting the heated plate.

From experimental observations between November 2019 and April 2021, there were no observed incidents of bouncing from the heated plate. The maximum observed density of snow particles was estimated to be 632 kg m^{-3}. There is the possibility for bouncing for higher particle densities, plausibly hail, but these were not observed. As another point of evidence the total SWE accumulation was compared with manual measurements from the Alta-Collins snow-study plot. A windshield was implemented around the manual bucket to increase catchment efficiency. The correlation between DEID and the manual SWE measurement is 0.997 for 10 snow events.

Reviewer Comment 6: *Snowflakes form on aerosols and scavenge them, as well. These will remain as residue after the crystal melts. What is the impact on the measurements and how does this issue get addressed? How about issues of condensation on optical surface/components of the camera? Turbulent flow around the camera will likely deposit blowing snow on camera surface.*

Response: Indeed, due to its location east of the Great Basin, Salt Lake City and surroundings is particularly prone to dust storms. Nonetheless, based on observations from the Alta study plot and Red Butte Canyon from winter 2019 to spring 2021, aerosol residue was noted only following a couple of dust storms. Dust storms left static residue on the hotplate that was recognized by the thermal camera as a brighter signature than the usual dark metal background. To restore accurate measurement the dust residue was cleaned from the hotplate surface by

(1) Manually rubbing the plate with fresh snow and a clean cloth.

(2) Self-cleaning during snow events – the hotplate is briefly turned off remotely during the beginning of a storm and turned on after an accumulation of ~ 2 mm of fresh snow on the plate.

It is common for a very small (~ 0.001%) area of the hotplate to exhibit residue visible in the thermal imagery that remains. Typically, these bright spots can be removed computationally. Using the frame-by-frame method, total mass due to the residues was subtracted in each frame and the total area of all residues was subtracted from the hotplate area. Using the particle-by-particle method, all hydrometeors must complete the cycle of evaporation where the area of hydrometeor must be zero at the beginning and end of the evaporation. Given residues do not evaporate, residues are not counted and the hotplate sampling area is reduced by subtracting the total area of the residues.

Condensation or accumulation on the thermal camera was reported during the entirety of observations only once. During an extreme snowfall event the thermal camera was blocked by blowing snow for one hour and 20 minutes during a single storm that had produced ~ 216 cm after three days of snow accumulation by this point in time.