Reply to Review by Darrel Baumgardner

Dr. Baumgardner brings out some good points that were not adequately addressed in the manuscript. These point will be addressed in the order in which they appear in his review and a revised manuscript will include all of the responses.

Regarding the Introduction being redundant. A paper on shattering needs to be mostly standalone, with sufficient introduction to present a background for the material presented. The Introduction is actually quite short and provides only a few salient references to previous papers that are germane to the paper. There is some redundancy in presenting the work by Cooper (1978), but since this author was working directly with Dr. Cooper during that period of time, I have some small additional insight into his work that is included in the Introduction. I think it is important to present this brief background, but it can be removed if requested by the editor.

The remainder of the Introduction deals with the historical development of optical array probes. This is presented in factual terms and any claims that are made are backed up by peer-reviewed references. If there are any controversial statements in section, such the statement that the 2D-S measurements are thought to be reliable enough to be used as a baseline for comparison with older technology probes, then this statement can be toned down, or even eliminated.

The reviewer brings out the potential differences between splashing raindrops and shattering ice crystals. Certainly, there will be some differences, and we can modify the text to state that we do not expect ice crystals and raindrops to shatter in exactly the same way, producing quantitatively the same number of fragments with the same trajectories. However, the main point is that both processes produce a burst of small particles that are quasi-spherical and closely spaced, and that some (unknown) percentage of these particles can be identified using their arrival times. To illustrate this claim qualitatively, included in this review we show Fig. 1 (2D-S images of splashing raindrops from Baker et al. 2009) and Fig. 2 (2D-S images of shattered ice particles).

Figure 2 also includes a diagram showing schematically how the arrival time algorithm works. We agree with the reviewer's suggestion that a complete description of the shattering algorithm can be included in the paper. We suggest that a description of how the data were processed and of the shattering algorithm, which includes more than removal of artifacts using arrival times, be included as an Appendix. Figure 2 would comprise a part of this description.

The reviewer suggests that the paper should include a wide range of cloud and particle types in order to provide a statistical analysis and corrective information for older datasets. This is not possible or practical for two reasons: 1) Unfortunately, we do not have a comprehensive dataset of measurements with two 2D-S instruments. We were only able to install both 2D-S probes for a few flights during the SPARTICUS field campaign. Again, unfortunately, we could not find regions where both probes were working properly in clouds without large ice that would produce shattering, and it was necessary to do this to confirm that the probes were responding similarly in regions without shattering. The only flight we could find where the two probes agreed in a region without large ice was in a cumulus cloud with small cloud drops, where shattering was not a factor. This flight (on 23 July) took place after the official close of SPARTICUS and the cumulus cloud was intentionally penetrated, something that was outside the normal SPARTICUS flight profile. Figure 3 shows this comparison and will be added to a revised manuscript, if requested. While we do not have a large statistical dataset, we do have measurements taken approximately one hour previous to the anvil penetration showing that the two probes were in reasonably good agreement measuring high concentrations of cloud drops in a cumulus cloud. 2) The response characteristics of the 2D-S do not apply to older probes. This is apparent from the different shattering results for the 2D-C and CIP compared with the 2D-S results presented in this paper. Thus, shattering results from the 2D-S cannot be applied to datasets collected by older probes.

One of the major objections of the reviewer is that the "…evaluation and conclusions of our study is based on the premise that the 2D-S is superior to all other OAP probes." We would like to point out that nowhere in the manuscript do we state that the 2D-S is "superior" to all other OAP probes. We do, however, state that it uses newer technology components and that the response of the instrument has been evaluated in the laboratory and compared with other OAP probes on (NCAR and NASA) aircraft. The results of these comparisons are supported by references to peer-reviewer literature. We also do not claim that measurements made by the 2D-S are correct and that measurements made by the older OAPs are not. In fact, we point out that uncertainties, both known and unknown, certainly affect the measurements.

This brings out another point of discussion. While I agree with the reviewer that uncertainty analyses are an extremely important component of instrument analysis, I disagree that an uncertainty analysis should be attempted in this paper. An uncertainty analysis is useful only if there is a way to perform the analysis with a reasonable degree of accuracy. Generally, this requires a standard for comparison of the measurements. However, there is no standard to which one can compare cloud particle measurements. Without a standard, a propagation of error approach is only a guess. It is problematical that many papers have published "uncertainties" that are based on crude estimates of bias errors, and that these "error bars" are then used as justification by subsequent authors for comparing with remote retrievals, models, etc. In this case and uncertainty analysis would do more harm than good. We are certainly willing to discuss the types of uncertainties that exist and we do not imply that the 2D-S reduces uncertainties. We are only willing to show comparisons and discuss expected trends, such as in Fig. 1 in the paper, where there is little physical justification for the high concentration of small particles near cloud base (except for shattering), and Fig. 2, where 2D-S measurements support the particle concentration trend expected from physical arguments.

We agree to present the complete methodology for processing the 2D-S data in an appendix. However, in the meantime, I would like to address one reviewer comment about data processing. In particular, the review states that "the 2D-S is an optical array probe (OAP), no more and no less. This means that the uncertainties, none of which are discussed in this paper, are the same as in all OAPs. The DOF is uncertain for particles less than about 100 um and highly uncertain for particles less than 50 um." We agree that the 2D-S is an OAP, but the newer technology that supports faster time response and true 10-micron pixel resolution does offer some advantages over older OAP's. Korolev and Isaac (2003) analyzed nearly one-million CPI images of ice and found that images between 20 and 80 microns in the temperature range germane here had 0.9 to 0.6 roundness ratio (defined as a ratio of image projected area to area of a spherical particle). Thus, the large majority of the small images are quasi-spherical. This is also supported by inspection of CPI images in this case. We used the Korolev (2007) size correction of spherical images (i. e., donuts) to correct the size of out-of-focus quasi-spherical 2D-S images. Lawson et al. (2006) show that the true 10-micron pixel resolution of the 2D-S at jet aircraft speeds facilitates re-sizing of out-of-focus images that is not possible with probes with 25-micron pixels and slower response times. Based on this foundation we feel that the data processing methodology, which will be completely described in the appendix of a revised manuscript, provides significant support to our claim that the processed data are credible. Also, to reiterate, even though we do not think it is prudent to present a measurement uncertainty analysis that produces error bars, we will discuss in quantitative terms all uncertainties associated with 2D-S measurements.

The reviewer expresses concerns that the 128-pixels and four arms of the 2D-S may cause more problems with removing shattering than they ameliorate. Certainly, we do not claim to be presenting a comprehensive analysis of shattering, and we do not try to explain all of the reasons why the post-processing software algorithm appears to reduce shattering more than using modified tips. Also, in a revised manuscript we will show photographs and schematics of the two sets of tips used in the experiment and try to place them in the timeline of the Korolev tip evolution.

The review states: "Finally, with respect to the other evidence that is used to show that the modified tips don't work, a single figure (Figure 4) is used to show shattering signatures from two 2D-S probes, one with and one without modified probe tips." No where in the manuscript can I find a statement that says that the modified probe tips don't work. In the Abstract we state: "*Analysis of 2D-S data shows that a particle arrival time algorithm is more effective than probe tips designed to reduce shattering, although application of both techniques ought to be complementary*." And later when describing the results shown in Figs. 4 – 6 we state: "*The measurements shown in **Figs. 5** and **6** suggest that the modified tips reduce the number of small (shattered) particles, but not as effectively as the arrival time algorithm."*

We do agree with the reviewer that the number of 2D-S images that reveal shattered particles Fig. 4) using the post-processing algorithm (with and without the modified tips) should be shown as a function of the number of total particles larger than some specified size, say 500 microns. This is not difficult to do and we will include it in a revised manuscript. However, in the meantime one can get a reasonable estimate of these ratios from looking at Fig. 5, which shows that the number of images > 500 microns seen by both probes is nearly equal, and that there is a large differential in the number of smaller particles.

We do regret that the SPARTICUS experiment did not provide a larger dataset from which we could draw our conclusions. We try to qualify our conclusions based on the fact that this is only one flight, and that it was carefully selected for regions when both 2D-S probes appeared to be functioning as reliably as possible. Otherwise, the comparison would be meaningless.

Finally, I would like to re-emphasize the overarching message that the manuscript is attempting to convey, but first some background and rationale for the submission. The recent *BAMS* paper by Korolev et al. (2010) showed only data collected with 2D-C and CIP probes, and basically concluded that modified probe tips were more effective than post-processing in removing shattered particles. We have no argument with this conclusion, except that 2D-S data were not included in the paper, and we had several discussions with Korolev in an attempt to persuade him to include 2D-S data. As a result of his decision not to include 2D-S data, Dr. Baker and I asked to be removed from the author string, and I decided to submit a paper showing some results from the 2D-S probe. We were not allowed to access the AIIE dataset, so we could only "place" the 2D-S data we received from Dr. Korolev on the plot shown in the Korolev et al. (2010) paper. One of Dr. Korolev's reasons for not including 2D-S data in his publication (in addition to restrictions on page length), is that there were no side-by-side 2D-S instrument comparisons during AIIE. Subsequent to these discussions with Dr. Korolev we were able to collect limited side-by-side 2D-S data on the Learjet, and they are included in this manuscript.

The uninitiated reader of the Korolev et al. (2010) paper could conclude that modified probe tips are more effective than post-processing techniques on all OAP's. As they become available from recent field experiments (e.g., CR-AVE (2005), NAMMA (2006) TC4 (2007), ISDAC (2008), SPARTICUS (2010), MACPEX (2011)), 2D-S datasets are being used in more and more analyses and papers. We felt that it was important to submit a paper showing users of these datasets that both modified tips and post-processing algorithms are effective (also stated in Korolev et al. 2010), and that based on measurements shown in our manuscript, the post-processing algorithm is more effective than modified 2D-S probe tips. We also further emphasize that this is a limited study and that a more comprehensive evaluation of the effectiveness of modified probe tips and post-processing algorithms on all OAP's is needed.

References Not Cited in the Manuscript

Korolev, A.V., G.A. Isaac, 2003: Roundness and aspect ratio of particles in ice clouds. *J. Atmos. Sci.*, **60,** 1795-1808.

Korolev, A. V., 2007: Reconstruction of the sizes of spherical particles from their shadow images. Part 1: Theoretical considerations. *J. Atmos. Oceanic. Technol.,* **24**, 376–389.

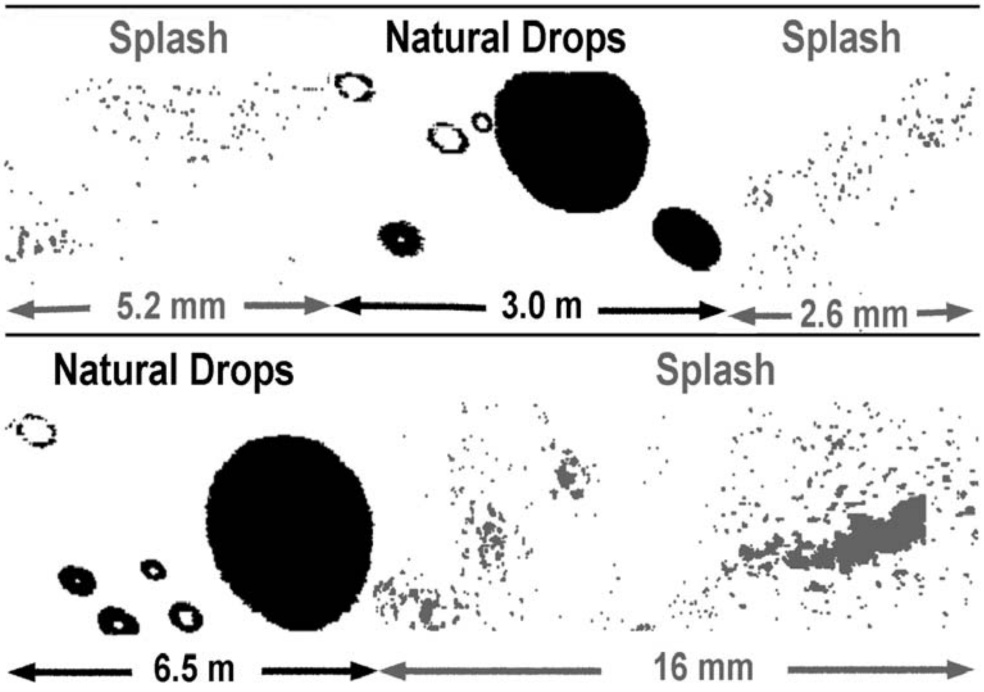

Figure 1. Example of 2D-S images of raindrops and splashing raindrops (from Baker et al. 2009)

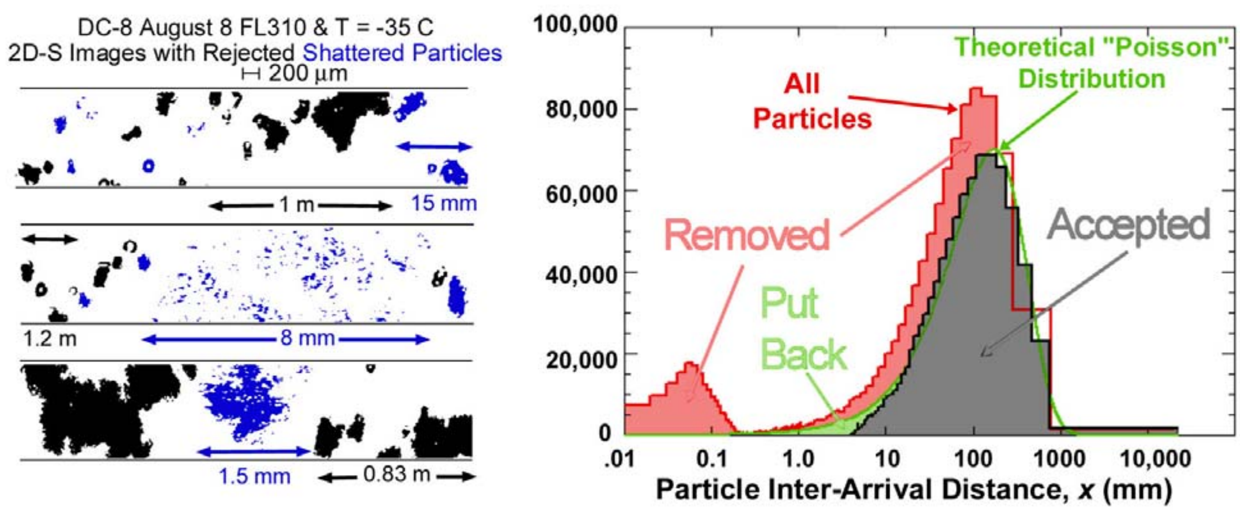

Figure 2. Example of (left) 2D-S images of ice particles and shattered ice particles, and (right) schematic diagram showing number of particles versus particle inter-arrival distance for an ice cloud penetration where shattering was occurring. The distribution shown in red are particles that have been removed due to being too closely spaced (i.e., short inter-arrival distance), or other criteria used in the artifact rejection algorithm. Distribution shown in green includes particles that are "put back" due to statistics based on theoretical Poisson distribution; i.e., real particles that would have been "shielded" (assuming Poisson statistics) by the burst of shattered particles.

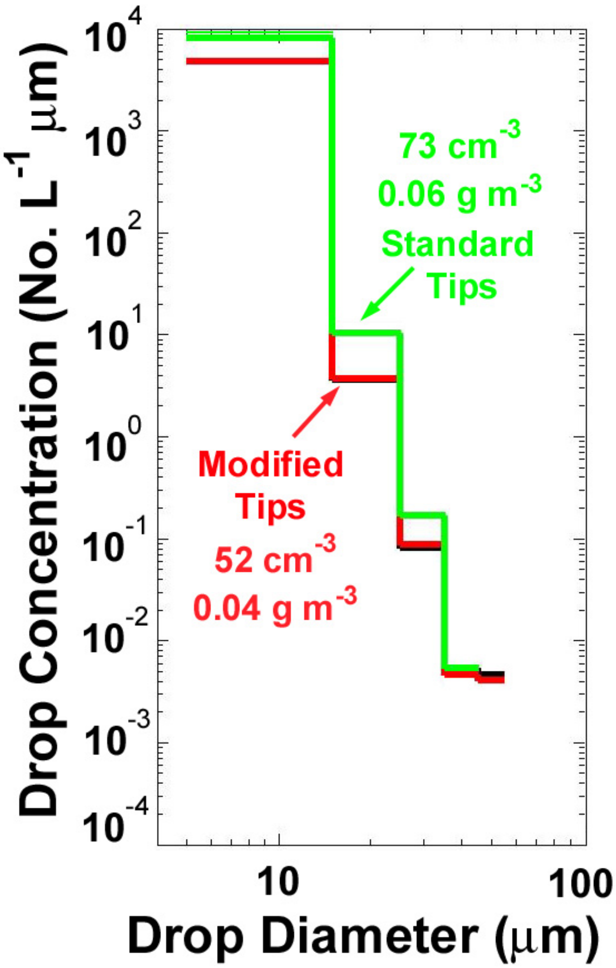

Figure 3. 2D-S drop size distributions from penetration of a small cumulus containing only water drops. The light green trace is from the probe with standard tips and includes shattered particles. A dark green trace is from the probe with standard tips after applying the shattering algorithm, but is not visible behind the light green trace. The red trace is from the probe with modified tips and includes shattered particles. A blue trace is from the probe with modified tips after applying the shattering algorithm is barely visible near the red trace.