P2.30 SPLASH ARTIFACTS IN FSSP MEASUREMENTS – OBSERVATIONS AND FLOW MODELING STUDIES

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## 1. INTRODUCTION

The focus of this study is splash artifacts that contaminate FSSP measurements of cloud droplets. These artifacts can be generated when large cloud particles hit the forward edge of the sample tube on FSSP instruments. Some of the fragments from these collisions can be swept through the laser beam and lead to erroneous measurements of cloud droplets.

Evidence for this kind of contamination has been reported in several earlier papers. The method of using forward scattering to measure the sizes of single transparent spheres is well established, but most conditions in ice clouds are not suitable for FSSP measurements. Furthermore, measurements of water droplets are adversely affected in mixed-phase clouds, as reported by Gardiner and Hallett (1985). They reported that high concentrations of ice can be recognized by a "flat" FSSP size distribution, and they suggested this appearance may be a result of multiple scattering, ice splintering, or ice particle breakup on the laser exit tube.

Gayet et al. (1996) compared data from the FSSP and other instruments. They found that the FSSP measurements are accurate when ice particles are small and spherical, but not if the ice size distribution is broad.

In a recent paper, Field et al. (2003) described studies with a *fast* FSSP to measure the inter-arrival times of particles. The *fast* FSSP records the amplitude and timing of each pulse of scattered light (Brenguier, 1993). Field et al. examined data from airborne measurements in ice clouds and found a bimodal histogram of arrival times at ~$10^{-2}$ and $10^{-4}$ s. They suggested that the $10^{-4}$ s mode may be a result of ice particles hitting the leading edge of the sample tube and breaking into fragments. This burst of fragments passes through the laser beam (10 cm downstream) and appears as a very small region of high concentration. Field et al. also used a modified FSSP that had no sample tube, and it produced bimodal arrival times. Their calculations of particle bounce trajectories suggested that it is possible for these fragments to reach the sample volume section of laser beam.

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This paper describes observational data that demonstrate the occurrence of fragment production in liquid and mixed-phase clouds. It also describes air flow modeling studies that show the velocity field is affected by the presence of the sample tube in the FSSP and suggest that the trajectories of some splash fragments can intercept the laser beam.

## 2. INSTRUMENTATION

During the IDEAS-3 project (Instrumentation Development and Education for Atmospheric Science), two FSSP-100 probes were mounted side-by-side on an under-wing instrumentation pod, as shown in Figure 1. One probe was a standard probe operated by the NCAR Research Aviation Facility (RAF) while the other was from GKSS (Germany).

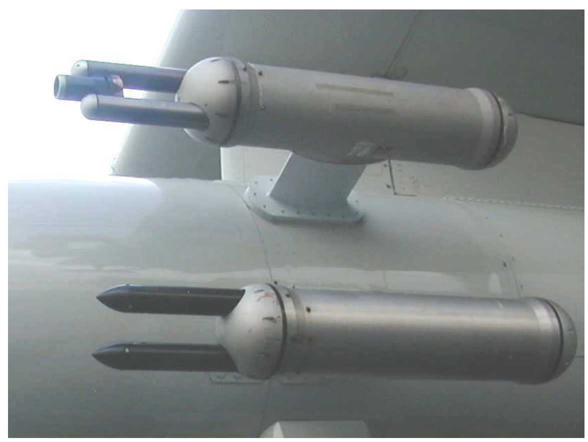

*Figure 1. Standard FSSP (above) and GKSS modified version (below) mounted on NCAR C-130 instrument pod. For scaling, FSSP arm length ~23 cm and diameter 5.1 cm.*

External modifications to the GKSS probe involved removing the sample tube and replacing the standard hemispheric caps on the ends of the arms with bullet-shaped tips. Note the absence of the air sample tube on the GKSS-modified probe. In earlier tests, GKSS found the optical alignment to be sufficiently rigid that the air sample tube was not needed. The goal of this modification was to eliminate the effects of splash artifacts by removing this tube and by changing the tip shapes. Both the RAF and GKSS probes used Signal Processing Package electronic interface upgrades (from Droplet Measurement Technologies, Boulder).

## 3. FIELD STUDIES

Observational data were obtained from two projects: IDEAS-3 (Aug.-Sep. 2003 in Colorado) and RICO (Rain in Cumulus over the Ocean, Dec. 2004 – Jan. 2005 in Antigua). The NCAR C-130 aircraft was used for both of these projects.

### 3.1 Response in mixed-phase clouds

An example of data from the side-by-side FSSP probe is shown in Figure 2, in mixed-phase clouds at -13°C. Concentrations from the two probes showed close correspondence except when large snow particles were present in high concentrations, 21:48:00 to 21:48:20. During that time, concentrations in the RAF standard FSSP were about five times greater than the GKSS probe.

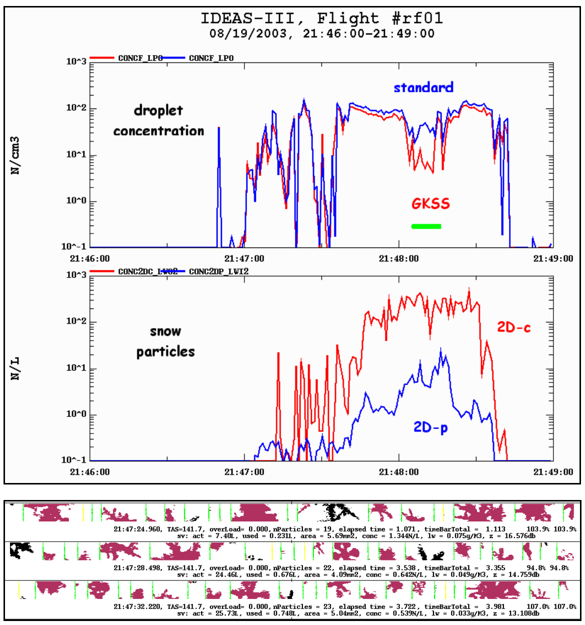


*Figure 2. Three minutes of cloud particle measurements in mixed-phase cloud at -13°C. Concentrations from FSSP (top) and PMS 2D probes (middle). Bottom panel has snow particle images from 2D-c probe; 800 µm row height.*

Particle size distributions are shown in Figure 3 as ten second averages from the FSSPs. Note the large discrepancy in the fourth panel, 21:48:05 to 21:48:15. This corresponds to the time when higher concentrations of large snow particles were present, as indicated by the green bar in Figure 2. We suspect that snow particles hitting the front of the standard FSSP sample tube generated a large number of small fragments, many of which passed through the laser beam and were counted. The GKSS-modified FSSP did not exhibit this feature.

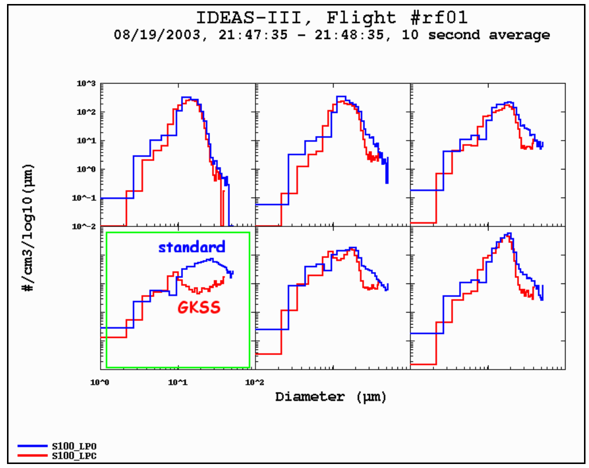


*Figure 3. Size distribution plots for the time period shown by arrow in Figure 2.*

### 3.2 Response in rain

Figures 4 and 5 show data during rain penetrations from IDEAS-3 flights. In rain, the standard FSSP concentration exceeded GKSS when larger rain drops were present.

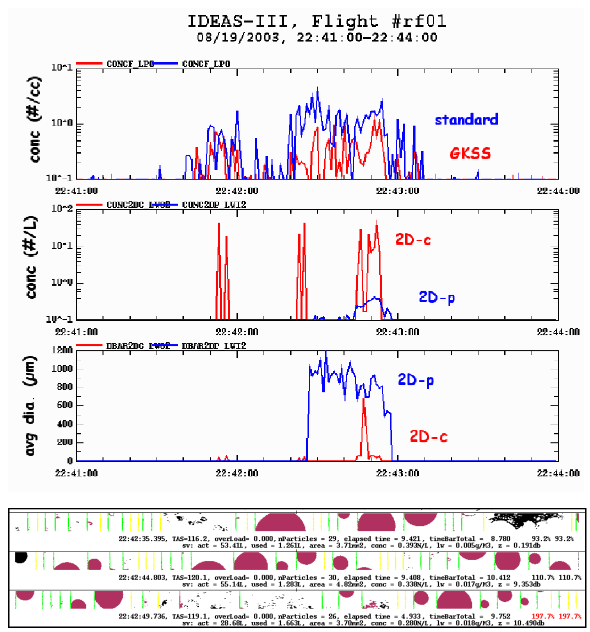


*Figure 4. Three minutes with pass through rain at +14°C. Concentrations from FSSP (top) and PMS 2D probes (middle). Third panel shows average particle diameter from 2D-c probe. (bottom panel) rain images from 2D-c probe; 800 µm row height.*

Size distributions from the FSSPs are shown in Figure 5. Note that the standard FSSP indicates a higher concentration than the GKSS probe. We think this is evidence of splash artifacts that are created by large drops hitting the sample tube and then pass through the laser beam.

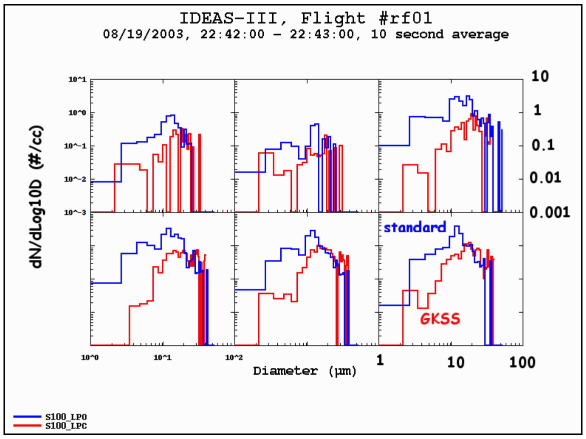


*Figure 5. FSSP size distributions during rain penetration.*

## 4. MODELING FLOW AND PARTICLE PATHS

Flow simulations were done to estimate the air velocities at the front of a standard and a GKSS-modified FSSP. The results shown here are for only the front of a standard FSSP.

### 4.1 Flow Domain

The 3-D geometry of the probes and flow domain was created with Gambit®. The domain is a rectangular box 1.2 m long and 0.9 m wide. Only part of the probe is within the domain, i.e., forward from the canister's hemispheric cap. The probe is aligned with the long axis of the box. The computational mesh has 278,000 cells that are ~0.6 mm at the surface of the probe and get progressively larger, reaching ~37 mm at the edge of the domain.

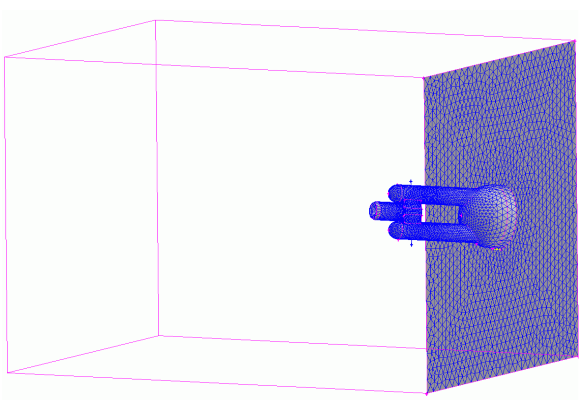

*Figure 6. Domain of flow modeling is a box containing the front end of a standard FSSP. Air flow is left to right.*

FLUENT® was used to simulate airflow and particle trajectories. We used the segregated-implicit solver for incompressible, laminar, steady flow in air at standard sea level pressure and 300 K. The far field velocity was typical for flight speeds of the NCAR C-130 at 100 m $s^{-1}$, and the flow was aligned with the axis of the probe. (We are also exploring off-axis flow conditions, not reported here.)

### 4.2 Results - Velocity Field

The velocity field along a vertical central plane is shown in Figure 7. It shows the air decelerating to ~85 m $s^{-1}$ just ahead of the sample tube, accelerating to ~103 m $s^{-1}$ inside of the tube at the location of the laser beam, and then decelerating as it approaches the hemispheric cap. The velocity profile is flat across the middle ~2 mm of the laser beam where the scattering measurement is made. Note that this simulation does not include the small hollow scarf tube that protects the laser beam window. Measurements of flow inside the air sample tube indicate that this small scarf tube causes an asymmetry of the interior flow (Nagel, personal communication).

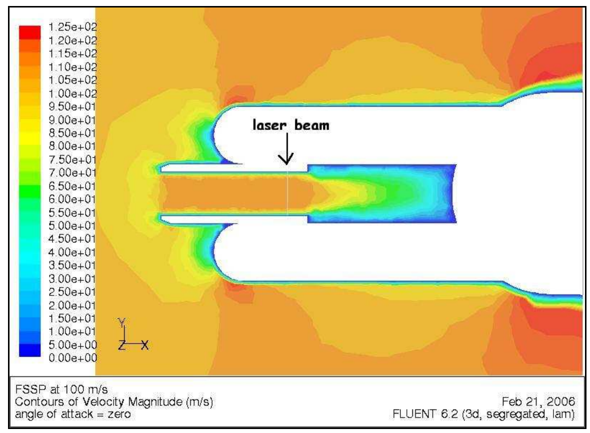


*Figure 7. Velocity contours in a vertical plane along axis of the probe. Note location of the laser beam.*

### 4.3 Results - Particle Trajectories

Particle trajectories were estimated by releasing an array of unit-density spherical particles from a line that is slightly larger than the sample tube and located 35 cm upstream. FLUENT uses a force-balance method to track these particles through the domain. If a drop has enough inertia to impact on a surface of the probe, there are several options for its interaction, as selected by the user. They can "reflect" with an elastic collision, departing along a line complementary to the angle of incidence. They can be "trapped" as if the wall were porous. They can "escape" (leaving the problem domain), or deflect in a "wall jet" in which the exit angle and velocity depend on momentum flux that depends on impingement angle and drop Weber number. Additional options are open for the user to describe droplet-surface interactions. For this study, we used the wall-jet boundary condition.

Figure 8 shows the front end of the standard FSSP and trajectories of 50 µm diameter water drops in flow of 100 m/s. Some of the drops that hit the leading edge of the sample tube are deflected into the laser beam. Although the physics of drop rebound and breakup mechanisms are not adequately represented in this simulation, the process suggests an explanation for the differences between data from the standard and GKSS probes.

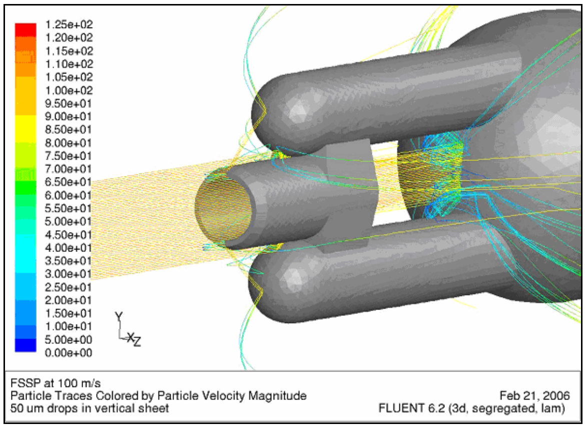


*Figure 8. Front end of standard FSSP with sample tube and trajectories of 50 µm drops in a flow simulation. Drops are released along a vertical line that is slightly larger than the sample tube. Some drops that hit the front edge are deflected into the laser beam.*

## 5. DISCUSSION

Evidence exists from earlier observational studies that cloud ice and water can create splash artifacts when particles impact the upwind surfaces of instruments. The capability to carry two nearly identical FSSPs allows us to investigate the likelihood of contamination by these artifacts. The results show that both liquid and ice particles that hit upstream surfaces may bounce, coalesce into the surface, or break into fragments. Their fate depends on several factors, including energy, surface tension, surface roughness, and the angle of interception. Some of these factors are included in the local Weber number, which has been used successfully for industrial spray design applications.

Using flow modeling, trajectories of particles can be traced, and the fraction of particles that bounce into the laser beam can be estimated. In future studies, we plan to explore questions about the occurrence of artifact production through both observations and modeling.

## 6. ACKNOWLEDGEMENTS

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