Investigating Airflow Effects on the Accuracy of Cloud Particle Measurements

Olusegun Goyea

Academic Affiliation, Fall 2005: Graduate, City College of New York (CUNY)

SOARS®, Summer 2005

Science Research Mentor: Dave Rogers and Tom Horst
Writing and Communication Mentor: Markus Stobbs

ABSTRACT

Accurate cloud droplet measurements are important for an increased understanding of cloud microphysical processes, especially the nucleation and growth of cloud particles through condensation and coalescence. In addition, cloud droplets play a significant role in the formation of precipitation; therefore, accurate measurements are important for precipitation forecasting. A Forward Scattering Spectrometer Probe (FSSP) is a cloud droplet measuring instrument that uses light scattering intensity in determining size distribution and concentration. A German version of the FSSP was developed, with minor structural changes, in order to reduce inaccuracies associated with cloud droplet measurements.

The goal of the research was to investigate the effects of changes in droplet velocities and trajectories during measurement using the standard and modified FSSP probes. This investigation will help determine a probe configuration with improved measurement capabilities. Two modeling and simulation packages were used; Gambit and Fluent. Gambit was used to generate probe prototype models, 3d computational grids and the computational flow domain. Fluent was used for flow simulations under specified boundary and operating conditions. The analysis examined flow fields at various airspeeds (focusing on 145m/s as a case study), angles of attack and trajectories of 20-50μm sized particles passing through the measurement volume.

The results obtained showed change in particle velocities within the sampling volume for both probes. In addition, both probe simulations showed evidence of particle trajectories approaching the sampling area. This plays an important role in determining the amount of particle passing through the laser beam. Further investigations have to be carried out in order to determine the more suitable probe configuration.

This work was done under the auspices of the Significant Opportunities in Atmospheric Research and Science (SOARS®) program of the University Corporation for Atmospheric Research, with funding from the National Science Foundation, the U.S. Department of Energy, the National Oceanic and Atmospheric Administration, and Goddard Space Flight Center, NASA.
**Introduction**

**Background**

There are uncertainties associated with the measurement of cloud droplet concentrations and particle size determinations using the Forward Scattering Spectrometer Probe (FSSP). Although, these uncertainties are known to exist, they have not been well investigated and understood. Studies are continually been carried out to investigate some of these uncertainties and thus far have presented solutions, however, there are other uncertainties to be fully studied. Some of these uncertainties are caused by airflow effects. A flow analysis of one of the airflow effects found that the FSSP under-predicted cloud-size droplets by 10% for both speed curvature distortions at 0° angle of attack and furthermore, under-predicted by 24% at 4° angle of attack (Norment, 1988).

In addition, there are several other possible airflow effects, one of which is caused by blocking of the flow by the probe. This leads to changes in flow velocity and direction, and these can affect particle sizing, size-sorting, and concentration measurement. Particle sizing error can result if particles preferentially cross the laser beam away from the beam center; size-sorting refers to the cross-streamline movement of high inertia (larger) droplets in regions of flow curvature while the low inertia droplets move along the flow streamlines. The result is a biased measurement of the droplet size distribution.

Another is the shattering effect, which occurs in bigger size particles. These bigger particles break into smaller fragments on colliding with the upstream edge of the sample tube. Some of these fragments may pass through the laser beam and cause errors because they appear as a high concentration of small droplets that are not present in the cloud.
Despite the variety of uncertainties associated with the FSSP, it is generally considered to be most suitable for determination of the size and concentration of cloud drops as compared to its predecessors the Axially Scattering Spectrometer Probe (ASSP) and impactor slides (Cerni, 1983). It should be noted that there are different types of FSSP but they all have similar principles of operation.

**Instrument**

The FSSP is routinely used by the Research Aviation Facility (RAF) during research flights. It is mounted on instrument pods located underneath the wings of the research aircraft, NCAR/NSF’s C-130 (figure 1). The instrument determines concentrations and sizes by the amplitude and intensity of scattered light as the particles travel through its laser beam. Measurements are recorded on particles that pass through the depth of field (DOF) located at the center of the laser beam. The FSSP measures a nominal size range of 0.5\(\mu\)m to 47\(\mu\)m and can detect concentrations greater than 1000cm\(^{-3}\). It is mainly configured to detect spherical water drops with a refractive index of 1.33.
As shown above, the structural configurations of these probes differ. The main difference is the presence of a sample tube in the standard FSSP configuration which has been eliminated by the Germans. Some of the main reasons for the modification are due to airflow effects during research flights.

**Problem Statement and Objectives**

The goals of this project are to understand the airflow effects associated with the RAF FSSPs and German version, to determine which structural configuration is more suitable, and to reduce inaccuracies related to cloud droplet measurement. The work described in this paper involved using flow modeling and simulation to investigate changes in velocity and particle trajectories. The project was conducted using two commercial flow and modeling simulation software codes, Gambit and Fluent. Gambit is a computer aided design application used for solid modeling. It was used to create the external geometry of solid objects and also generate 3d computational meshes (grids) that
divide the complicated geometry into smaller, more uniform shapes. In addition, Gambit was used to create the computational flow domain containing the solid model.

Fluent is a fluid flow simulation software package that integrates a set of Navier-Stokes equations within every cell of the computational domain to determine parameters such as flow velocity, pressure gradient and so on. It was used to calculate the resulting three dimensional flow fields using specified boundary and operating conditions.

Flow analysis carried out examined:

1. The flow field for the standard and German probes at different airspeeds and angles of attack
2. Particle trajectories using the flow field passing through the measurement volume

The success of this research will help improve our understanding of factors that affect FSSP measurements and may provide possible solutions to the uncertainties associated with the instruments. More accurate measurements are important for an increased understanding of cloud microphysical processes, especially the nucleation and growth of cloud particles through condensation and coalescence.

**Methods**

Airflow analysis has seen extensive use in investigating problems associated with airborne particle measuring instruments. It involves using modeling and simulation packages to reproduce an airflow scenario.

The initial process of the project was creating prototype models of both the standard FSSP and the German-modified FSSP (GKSS) using Gambit. The overall geometry of each probe is symmetrical; therefore, one half of each probe was generated and revolved about an axis (axis of revolution). Each half (face) was generated by joining

SOARS® 2005, Olusegun Goyea, 5
different coordinate points using basic geometry (arcs, lines, etc). The prototype dimensions were generated to scale in Gambit (1 inch = 1 unit). Thereafter, each prototype was placed in the center of a hexahedral volume (200x35x35) and subtracted. The region between the prototype model and the outer boundaries is the flow domain. Afterwards, the flow domain was meshed using a Tetrahedral/Hybrid meshing scheme using T-Grid type meshes. Meshing is a process that breaks down a complicate volume shape into smaller cell units (control volumes) for easy and detailed flow analysis. The T-Grid meshing type uses a combination of tetrahedral and hexahedral cells, as appropriate within the volume.

After the mesh generation, Gambit was used to specify the boundary types associated with each model and flow domain surface, for example, inflow, out-flow, and walls. Subsequently, the operating fluid was specified. The final step in the modeling process was to examine the quality of the grids. Grid quality is a measure of the skew distortion of each cell. It ranges from 0 (best) to 1 (worst). The quality of the grids plays a significant role in the accuracy of variables obtained during simulation. Once suitable grid qualities were achieved, the entity and grids were exported to a mesh file for use by FLUENT.

In FLUENT, simulations were conducted using a coupled solver. The method solves the governing equations simultaneously in each control volume, over the entire flow domain. The governing equations are: continuity equations and momentum equations (x, y and z). A laminar, low – viscosity flow was adopted with steady state and flow conditions. Simulations were carried out using air at an operating pressure of 50kPa, temperature of -20°C, and velocities ranging from 100-200m/s. The base case
used a velocity of 145m/s and angles of attack from 0° to 10°. The angles of attack were assumed to be a measure of the angle of the aircraft during flight.

After the flow field was calculated, water droplets particles ranging in size of 20-50μm were released from a surface located on the inflow plane. The release plane surface area was 1 in², with particles equally spaced over the plane. The flow properties of each particle were observed as they moved throughout the flow domain, focusing on particle trajectories around each probe’s sampling region.
Results and Discussion

Figure 2 & 3 shows the prototype model of both probes generated in Gambit. The probes were created on a scale of 1:1. The total length of each probe was about 42 inches. The laser beam crosses between the arms at about 2/3 distance from the probe body (yellow edge in figure).

Figure 2. Prototype model of the standard FSSP in Gambit

Figure 3. Prototype model of the German in Gambit

SOARS® 2005, Olusegun Goyea, 8
The figure below shows the probe subtracted from the center of the computational flow domain. The domain is 5 times the probe’s length and width (figure 4) so that the domain walls do not interact with the probe to affect the flow. The computational grid consisted of approximately 2 million cells. Figure 5 shows a cross-sectional area of the equiangular skew of the grid quality across the center of the domain. The grid qualities are scaled from 0 to 1 with 0.1 intervals. Each number is assigned a color and this range from blue to red, with blue being ideal cell shape and red represents non-ideal shape. As shown in the figure, there is a mixture of grid quality. With additional time, the grid could be refined in order to improve quality; the existing grid was deemed suitable for preliminary study.

Figure 4. Computational domain with probe at the center.

The result from the 0° angle of attack simulation showed decreasing velocity magnitude as the flow approaches the laser beam (figure 6). There was pronounced decrease in velocity on entry to the sample tube. The velocity changes are due to the presence of sample tube and two supporting cylinders. However, airflow within the sample tube showed increasing velocity. Figure 7 shows a cross-section of flow at the position of the laser beam. It can be seen that flow velocity increased towards the laser beam location. It is defined in layers of concentric circles.
Figure 5. Cross-section showing qualities of the computational grids

Figure 6. Contours of velocity magnitude at 0° angle of attack for standard FSSP, along a vertical plane through the center of the domain.
The result obtained from release of particles from a small source region along the probe axis showed convergence of particles trajectories at the inlet of the sample tube (figure 8). The German probe showed similar characteristics at 0° angle of attack. However, the decrease in velocity at the probe tips is less pronounced than for the standard probe (figure 9).

For both probes, the laser beam cross-section showed increasing velocity in the flow towards the laser beam. The velocity field for the standard FSSP is forced into concentric circles by the sample tube and has a large gradient (figure 7), whereas the flow is more uniform with a weaker gradient for German probe (figure 10).

The result obtained from release of particles through the domain showed convergence of particles trajectories towards the sampling area (figure 11). The convergence was observed vertically (between the two arms of the probe); however, there was also a lateral divergence closer to the laser beam. The reason for the divergence is not understood but will be investigated in further studies. Therefore, at 0° angle of attack, the results are not conclusive.

Figure 7. Cross section through laser beam location for standard FSSP. Location of the laser beam is shown as the central vertical line. Particles are measured if they pass through the optical depth-of-field, the short section in the center of the beam.
Figure 8. Particle trajectories for the standard probe simulation (0°)

Figure 9. Contour of velocity magnitude at 0° angle of attack for German probe along a vertical plane through the center of the domain.
Figure 10. Cross section through laser beam location, similar to figure 7 but for German probe

Figure 11. Particle trajectories for the German probe simulation showing vertical convergence

SOARS® 2005, Olusegun Goyea, 13
The $5^\circ$ angle of attack simulations (figures 12, 13) showed results similar to the standard probe simulations at $0^\circ$ angle of attack. At $5^\circ$ AOA, however, the velocity gradient within the sample tube is not symmetric about the tube’s center, suggesting that there may be a concentration bias (figure 14).

Figure 12. Contour of velocity magnitude at $5^\circ$ angle of attack for standard FSSP

Figure 13. Cross section through laser beam location for standard probe
Figures 14 and 15 show results for the modified probe simulation at 5° angle of attack. The flow features are different from those with the standard probe at 5° AOA. In particular, note that the velocity is fairly uniform through the region of the laser beam (figure 15).

Figure 14. Contour of velocity magnitude at 5° angle of attack for modified probe

Figure 15. Cross section through laser beam location for modified probe
Conclusion

The results from the simulations showed evidence of changes in flow and particle velocities on approach to the laser beam in the FSSP sample volume. This was observed for both probe simulations. At 0° angle of attack, both the standard FSSP and the German probe exhibit favorable flow alignment. However, at increasing angles of attack, the German probe showed a higher potential of obtaining more accurate measurements. The studies reported here are exploratory. Further studies should be conducted for better understanding of the effects of flow alignment on particle velocities and trajectories. The effects of particle shattering on droplet measurements were described, but there was insufficient time to study this particular problem.

Future Work

For future studies, the computational grid should be refined, especially near the sample tube and laser beam, in order improve the accuracy of parameters obtained during simulations. Also, boundary layer grid application should be considered around the probes’ skin-surface, in order to include the effects of viscosity and small scale turbulence. Subsequently, simulations should be carried out employing a k-ε model of turbulence and include changes in kinetic energy, temperature and other parameters not included in a laminar flow model. In addition, the region where tracer particles are released should be increased in order to create a better representation of particle distribution and droplet trajectories.

The results of the simulations showed particles traveling through the laser beam, but, there are not quantitative measures of particles passing through the depth of field (DOF). Additional tasks will include tracking each particle to determine the numbers of particles detected at the DOF, for concentration calculations. The data obtained from the calculations can be compared to actual airborne measurements.

The final stage of a more comprehensive study will include modeling and simulation of drop shattering effects. Data obtained will be analyzed and also compared to airborne measurements.
Acknowledgement

The author will like to acknowledge Dave Rogers, Tom Horst and Markus Stobbs for their immense contributions and guidance during the course of the research. Special thanks to the EOL/RAF system administrators for their software and technical support.
References


