

Airflow Issues

Affecting Airborne Instrumentation Accuracy

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Summary

The measurement of atmospheric parameters from an aircraft can be influenced by distortion from the aircraft itself. Movement of air around the aircraft fuselage can impact not only flow speed and direction, but the concentrations of various constituents being measured. In particular, distortion of certain sizes of particles can generate errors that are larger than those inherent in the measurement sensor itself.

Errors can be minimized if flow speed, direction, and particle behavior is known for potential sampling locations in order to site instrumentation intelligently. In the past, airflow and particle trajectories around research aircraft have been modeled by potential flow codes. These codes give reasonably accurate estimates of flow and particle behavior at locations removed from the aircraft boundary layer. However, advances in computational fluid dynamics may permit faster, more accurate representations of airflow around aircraft. This should lead to better placement of research instrumentation and measurements of greater accuracy.

1. Introduction

Atmospheric research aircraft deploy a great variety of sensors for state parameters, atmospheric chemistry, cloud physics, and remote sensing. Instruments used for these measurements have fundamental sources of uncertainty that can often be quantified. In most uncertainty analyses, it is assumed that the air reaching the sampling inlet or sensor is representative of the freestream atmospheric flow. However, movement of air around the aircraft fuselage can impact not only flow speed and direction, but the concentrations of various atmospheric constituents. The additional uncertainty caused by the aircraft itself is a function of location and the type of measurement being made. In some cases, as described later, errors due to sampling location may be larger than errors inherent in the measurement itself. These errors must be understood and minimized, by suitable selection of sampling location, for the most accurate atmospheric measurements.

2. Flow Speed and Direction

Changes in flow speed and direction that occur as an aircraft moves through the atmosphere can affect measurements in a number of ways. Various gases in the atmosphere may react when contacting surfaces. When measuring gases in situ, air must be drawn from outside the aircraft boundary layer. The flow speed at in situ sampling points is usually required to calculate the actual volume of air sampled, which affects species concentration and fluxes (Cooper and Rogers, 1991).

Deviations in flow angle are generally less critical for gas sampling and remote sensing than for particle sampling. Turbulence may occur within inlets that are not aligned with the airflow, resulting in inefficient particle transmission (Huebert et al., 1990). Even if the mean flow angle is known, it may vary during the course of a flight due to changes in aircraft attitude. Flow-straightening shrouds have been developed to minimize this problem (McFarland et al., 1989; Soderman et al., 1991; Ram et al., 1995; Murphy and Schein, 1998; Eisele et al., 1997; Twohy, 1998).

The basic airflow patterns around a moving aircraft are well understood, with slowing ahead of the nose, and acceleration around the fuselage outside the aircraft boundary layer (Fig. 1). Flow speed thus may be either slower or faster than freestream, depending on location, but is generally faster at fuselage mounting locations behind the cockpit. Flow speed at most fuselage locations is not expected to differ by more than 10% from freestream (e.g., Twohy and Rogers, 1993). The direction of the flow is not always parallel to the fuselage axis but may deviate by a few degrees or more, especially at forward or wing locations (Twohy and Rogers, 1993; MacPherson and Baumgardner, 1988). Flow around the aircraft radome has been extensively studied, as this is often the favored location for air motion sensors (Nacass, 1992).

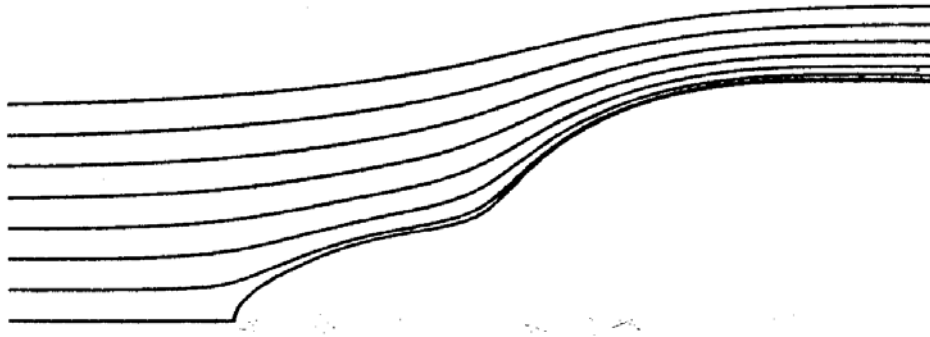


Fig. 1. Streamlines calculated around the simulated shape of a Fokker F-27 aircraft. From King (1984).

Some general airflow rules were formulated by King (1984) based on potential flow simulations for idealized shapes and axisymmetric representations of an F-27 and C-130 aircraft. In particular, he noted that the flow fields are determined primarily by the fuselage radius in regions removed from the aircraft nose and regions of high curvature (cockpit), and that flow parameters can be scaled relative to this radius. Measurements verified these results (King et al., 1984).

Locations under the wing or at wingtips are frequently used for particle measurements. While inboard wing locations under typical conditions are expected to engender relatively small errors (Drummond and MacPherson, 1985), wingtip locations can produce larger errors, especially at high angles of attack (MacPherson and Baumgardner, 1988).

Details of the flow vary with the exact aircraft shape, in particular at forward fuselage locations. For greatest accuracy, flow around each aircraft should be calculated independently. Detailed potential flow calculations were performed by Norment (1985) and Twohy and Rogers (1993) for specific aircraft. However, the influence of the aircraft boundary layer or high-speed flight cannot be simulated using potential flow models, which assume inviscid, incompressible flow. For such problems, computational fluid dynamic simulations may be useful.

3. Particle Trajectories

For studies of aerosol particles and clouds in the atmosphere, a wide range of particle sizes (0.001 to 1000 μm in diameter) must be measured accurately. Particles smaller than about 0.1 μm will approximately follow flow streamlines. Very large particles (drizzle or raindrops) have enough inertia that they are relatively unaffected by airflow distortion and their trajectories remain parallel and straight. Intermediate sized particles (10 to 500 μm) are influenced by changes in airflow, but have sufficient inertia to deviate partially

from the streamlines. As a result, their distribution at various locations around the aircraft varies significantly from freestream conditions (e.g., King, 1984). Locations beneath the fuselage are less affected than overhead fuselage locations, since the curvature effect of the cockpit is eliminated.

The behavior described above results in regions near the aircraft fuselage which are devoid of particles in certain sizes; these are termed “shadow zones”. Above the shadow zone, particle trajectories are compressed, leading to enhancement zones. For most particle sizes, the shadow zone is much deeper than the aircraft boundary layer. The shadow zone for 100 μm particles around an F-27 is evident in the trajectory pattern shown in Fig. 2, which can be compared with the streamlines shown in Fig. 1. King (1984) showed that the maximum shadow zone depth is 15% to 20% of the fuselage radius. Also, this maximum occurs at a particle size that has a modified Stokes parameter S of

$$S = 2a^2 V \rho_w / 9 \eta b \approx 6 ,$$

where a is the particle radius, V is the air velocity, ρ_w is the particle density, η is the air viscosity, and b is the fuselage radius.

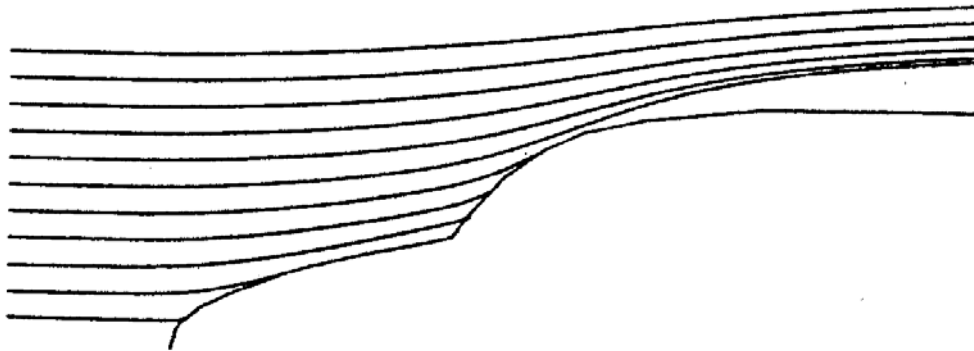


Fig. 2. Trajectories of unit-density 100 μm particles traveling around the F-27 (90 m s^{-1} , air viscosity = $1.75 \times 10^{-5} \text{ kg s}^{-1} \text{ m}^{-1}$). From King, 1984.

The shadow zone depth and degree of enhancement outside the shadow zone varies with distance aft on the fuselage as well as with droplet size. These effects can be severe for some locations, as shown in Fig. 3 for the second overhead position on NCAR’s Electra aircraft. Concentration ratio is the (calculated) ratio of particle concentration at the sampling location to the concentration in the freestream flow. Droplets between about 70 to 900 μm are shadowed at 46 cm from the fuselage. Shadowing is less severe farther from the fuselage, but still significant. Droplets larger than about 50 μm that are not shadowed still have significant concentration ratios, even at 61 cm from the fuselage. Since going farther away from the fuselage usually is not practical, representative sampling of large drops is not possible from this location.

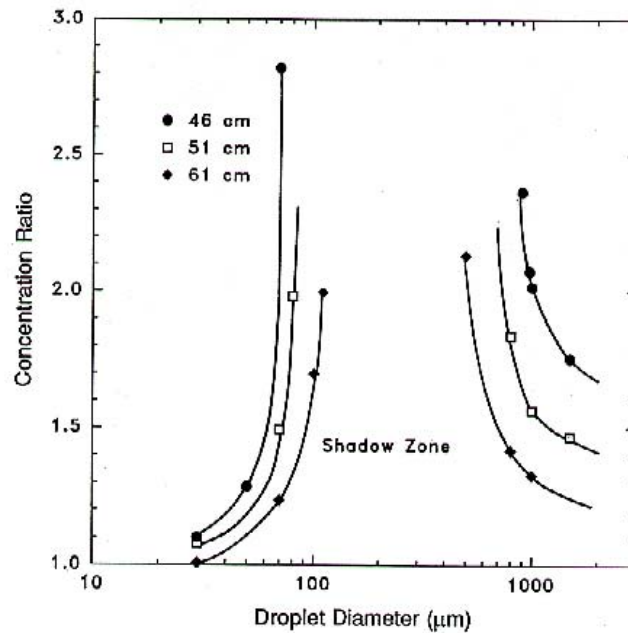


Fig. 3. Calculated concentration ratios as a function of droplet size for an overhead fuselage mounting location on the Electra aircraft (fuselage station 295). From Twohy and Rogers (1993) using a paneled potential flow code after Norment (1985).

Fortunately, only a few types of instruments measure particles larger than 50 μm . These instruments should be located farther forward, underneath the fuselage, or on the wing, where the effect of high curvatures areas on the fuselage is minimized. Wing-mount locations need to be chosen carefully, however, since wingtip vortices can produce large distortions in flow characteristics and particle orientation (e.g., MacPherson and Baumgardner, 1988).

4. Interactions

To operate efficiently and for the greatest scientific gain, research aircraft need to deploy a number of sensors simultaneously. As a result, an aircraft may be riddled with ports, sensors, and inlets. Airflow studies usually focus either on the aircraft airframe itself or on sensors themselves, without considering interactions between the two or between pairs of sensors. However, Norment (1988) found that combined effects of an FSSP instrument housing and aircraft wing were about double the effects of either the instrument or aircraft alone. If sensors are mounted in close proximity, they also may affect measurement accuracy. Figure 4 shows flow speeds measured by two different hot-

wire probes mounted on the NCAR King Air aircraft. Both sensors were located at the same fuselage station, but at different sides of the aircraft centerline. One probe was retractable to measure changes with distance from the fuselage, but was located about 2.75 m behind a cylindrical shaped inlet. Figure 4 shows that both the mean and transient flow speeds were affected by the forward inlet.

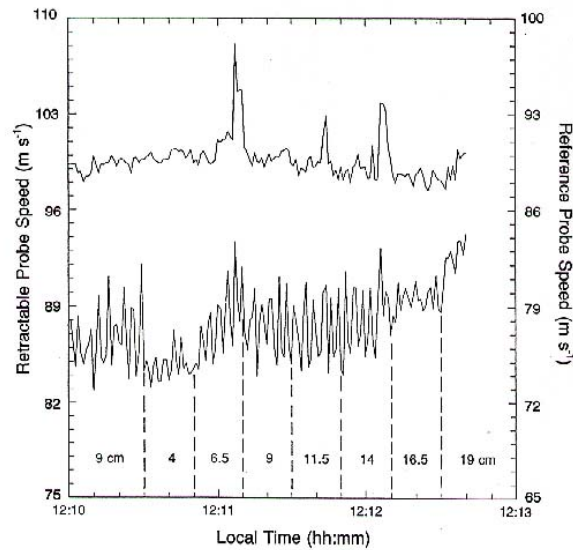


Fig. 4. Time series of flow speed measured by a hot-wire probe with no obstructions (top trace) vs. flow speed measured by the second retractable probe which was in the wake of another sensor (bottom trace). The distances marked at the bottom of the graph represent measurements made at different distances from the fuselage.

Another possibility is that inlets or the aircraft itself can produce spurious particles that can be observed by various instruments (Baumgardner, 1984). Interactions such as these are difficult to assess via computations, and may require actual measurement campaigns.

5. Desired Information

Computational fluid dynamics (CFD) has experienced major advances in recent years, with a multitude of commercial software packages now available. CFD is being used to design and evaluate aircraft sensors (Cruette et al., 2000; Laucks and Twohy, 1998), and many aircraft manufacturers utilize CFD in aircraft design. Results of such simulations for specific aircraft would be extremely valuable to the research community, both in optimal sensor placement and in interpreting results. For example, Cessna has provided airflow and particle trajectory information to the University of North Dakota to

aid in interpretation of measurements made on their Citation II jet. In Europe, CFD is actively being used to optimize measurements on a number of aircraft, as well as on ships (Nacass, 2001).

Specific information desired related to airflow around an aircraft fuselage would be flow speed and angle in 1 inch (2.5 cm) increments up to 24 inch (61 cm) for all potential mounting locations. Concentration ratios for a range of particle sizes are also needed at all potential locations. If this information is not readily available from the aircraft manufacturer, detailed numerical representations of the aircraft shape should be procured from the manufacturer. This would allow CFD to be performed by the research institution itself. While such an effort would be likely to require additional resources, it would permit maximum flexibility for the future.

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