An Airborne and Wind Tunnel Evaluation of a Wind Turbulence Measurement System for Aircraft-Based Flux Measurements*

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(Manuscript received 23 March 2005, in final form 4 April 2006)

ABSTRACT

Although the ability to measure vertical eddy fluxes of gases from aircraft platforms represents an important capability to obtain spatially resolved data, accurate and reliable determination of the turbulent vertical velocity presents a great challenge. A nine-hole hemispherical probe known as the “Best Air Turbulence Probe” (often abbreviated as the “BAT Probe”) is frequently used in aircraft-based flux studies to sense the airflow angles and velocity relative to the aircraft. Instruments such as inertial navigation and global positioning systems allow the measured airflow to be converted into the three-dimensional wind velocity relative to the earth’s surface by taking into account the aircraft’s velocity and orientation. Calibration of the aircraft system has previously been performed primarily through in-flight experiments, where calibration coefficients were determined by performing various flight maneuvers. However, a rigorous test of the BAT Probe in a wind tunnel has not been previously undertaken.

The authors summarize the results of a complement of low-speed wind tunnel tests and in-flight calibrations for the aircraft–BAT Probe combination. Two key factors are addressed in this paper: The first is the correction of systematic error arising from airflow measurements with a noncalibrated BAT Probe. The second is the instrumental precision in measuring the vertical component of wind from the integrated aircraft-based wind measurement system. The wind tunnel calibration allows one to ascertain the extent to which the BAT Probe airflow measurements depart from a commonly used theoretical potential flow model and to correct for systematic errors that would be present if only the potential flow model were used. The precision in the determined vertical winds was estimated by propagating the precision of the BAT Probe data (determined from the wind tunnel study) and the inertial measurement precision (determined from in-flight tests). The precision of the vertical wind measurement for spatial scales larger than approximately 2 m is independent of aircraft flight speed over the range of airspeeds studied, and the 1σ precision is approximately 0.03 m s⁻¹.

* Purdue Climate Change Research Center Publication Number 0504.

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1. Introduction

Accurate determination of vertical wind fluctuations is extremely important in measuring the air surface transport of mass and energy, such as carbon compounds, water vapor, and sensible heat fluxes (Delon et al. 2000; Rinne et al. 2000). Large-scale CO\textsubscript{2} flux measurements are needed across representative ecosystem types to enable investigation of Northern Hemisphere carbon sinks (Ciais et al. 1995; Keeling et al. 1996). Vertical wind measurements from flux towers typically rely on sonic anemometry to enable eddy covariance flux measurements. Flux towers are ideal for long-term measurements in specific ecosystems (Schmid et al. 2003), normally with heights ranging from approximately 30 to 100 m, but they cannot easily be relocated. Aircraft-based measurements are complementary to tower-based approaches since the spatial-scale flux information afforded by aircraft measurements enables extension of the temporally resolved long-term flux tower measurements to larger spatial scales (Oechel et al. 1998). However, the aircraft-based approach is inherently more difficult since a relatively small vertical wind component must be extracted from relatively large motion vectors of a translating and rotating platform. Aircraft-based research platforms are being perfected as the optimum method to expand tower flux studies to regional scales.

Biogeochemical fluxes are measured via the eddy covariance method [see Eq. (1)], where \( \overline{w} \) is the deviation of the vertical component of the three-dimensional atmospheric wind from the mean, and \( c' \) is the deviation of the experimental scalar quantity (e.g., mass and energy) from its mean value (Wofsy et al. 1993):

\[
F = \overline{w} c'.
\]

For scalars that cannot be measured at the required high frequencies (\( \sim 10 \) Hz), disjunct eddy accumulation methods have been developed (Rinne et al. 2000). However, to successfully implement them for aircraft the real-time computation of \( \overline{w} \) is essential.

Determination of vertical wind involves measurement of two key sets of quantities. These include the air motion relative to the aircraft (relative wind vector) and the measurement of aircraft motion in relation to the earth (inertial vector). In this work, we address the determination of the accuracy and measurement precision of the relative wind vector by performing wind tunnel calibrations of a commonly used airflow measurement probe known as the “Best Air Turbulence Probe,” or “BAT Probe” (Crawford et al. 1996; Hacker and Crawford 1999), displayed in Figs. 1–4.

In-flight calibrations are typically performed to calibrate the aircraft–probe combination. However, an accurate relationship of actual versus measured airflow angles is difficult to obtain in-flight since the aircraft–probe combination cannot be precisely set at a known value of attack angle or sideslip angle. The BAT Probe is capable of resolving flow angle differences (either attack or sideslip) smaller than a pilot can manually maintain. Thus, a specific known value of flow angle cannot be maintained for a long enough time for statistical significance under the varying conditions encountered in in-flight calibrations. This is essential to determining the precision of measurement of the attack and sideslip angles. Wind tunnels provide an environment in which the BAT Probe (in isolation from aircraft-induced flow distortion and dynamics) can be oriented so that the angle of the oncoming airstream is known and can be compared to the computed airflow angle. The departure of the measured airflow from po-
Potential flow theory at each known value of attack or sideslip angle can also be ascertained. If not determined, such departures from theory would manifest themselves in systematic errors in the final wind computation.

For measuring vertical atmospheric winds, four variables are of first-order importance. These include two angular measurements (aircraft pitch angle $\theta$, and attack angle $\alpha$) and two velocity measurements (the aircraft’s true airspeed $U_a$, and vertical velocity $\dot{h}$). Errors in these four variables are directly propagated into the wind computation. At a flight speed of 50 m s$^{-1}$, an error in $\theta$ or $\alpha$ of only 0.1° will correspond to an error of $\sim$0.1 m s$^{-1}$ in the determined vertical wind velocity.

In this study we conducted a set of controlled, low-speed wind tunnel tests to provide a more comprehensive picture of the measurement precision of $\alpha$, $U_a$, and sideslip angle, $\beta$ (where $\alpha$ and $\beta$ are positive if the airflow is coming respectively from below and from the right of the BAT Probe’s longitudinal axis). The wind tunnel calibration was performed at nominal airspeeds of 25 through 40 m s$^{-1}$ (in 5 m s$^{-1}$ increments), and were extrapolated to higher airspeeds (up to 65 m s$^{-1}$). These tests enabled comparison of the flow angles determined from the BAT Probe data under known conditions with the actual angles of the oncoming airflow. The wind tunnel tests determined the accuracy and precision in the measurements of $\alpha$ and $\beta$. The potential flow model is from an unpublished manuscript by J. A. Leise and J. M. Masters (1991), the equations for which have been reprinted in various publications (Eckman et al. 1999; Williams and Marcotte 2000) and are reproduced in appendix A. From the wind tunnel data, a lookup table has been constructed and applied to the computed flow data from the BAT Probe. This lookup table will allow real-time, in-flight computation of the vertical wind, for example, as necessary for disjunct eddy flux methods. Departures of the BAT Probe’s performance from the theoretical flow model are described herein.

Effects of aircraft-induced flow distortion around the body of the aircraft are different for each aircraft platform and can significantly influence the correspondence between measured and free-stream flow variables. In-flight calibrations have been well documented in other publications (Lenschow 1986; Tjernström and Friehe 1991; Williams and Marcotte 2000), but no comprehensive wind tunnel study of the BAT Probe (in isolation from aircraft-induced flow distortion) has been published to date. In this study, the BAT Probe was calibrated in the wind tunnel and the measured airflow variables were corrected with the lookup table. To complete the study, an in-flight calibration experiment was conducted throughout a range of operating airspeeds. The wind tunnel tests of the probe represent an essential complement to the in-flight calibrations of the entire probe–aircraft combination since these two test environments contribute to different aspects of the final calibration of the airflow measurement system.

The aircraft’s orientation and 3D velocity components were obtained during the in-flight calibrations using an inertial navigation and global positioning system (INS/GPS). Postprocessing of the INS/GPS data using a software-based “error model” resulted in the determination of the precision of the angular and velocity measurements of the INS/GPS. By propagating the precision of the flow variables from the BAT Probe with the precision of the inertial quantities from the INS/GPS, the vertical wind measurement precision could be esti-
mated. Knowledge of the vertical wind measurement precision is essential to determining the extent to which reliable flux measurements can be made from aircraft, which can then be compared to ground-based tower data. A glossary of the variables used in this paper is included in appendix B.

2. Description of BAT Probe and sensor calibrations

a. BAT Probe description

The BAT Probe was developed by the late Timothy Crawford of the National Oceanic and Atmospheric Administration (NOAA) and is described in Crawford and Dobosy (1992). The BAT Probe consists of a 0.13-m diameter hemisphere and tapered cone, both of which are mounted on a support shaft. The overall length of the probe is approximately 1 m.

The BAT Probe hemisphere has nine pressure ports (Fig. 2), which are connected to a total of four electronic pressure sensors. Three of these are differential pressure sensors (used to compute flow angles and air-speed) and one is an absolute pressure sensor (to measure static air pressure). The ports at 45° angles from the normal axis (in an “X” pattern in Fig. 2) are connected through a common manifold, which utilizes a separate absolute pressure sensor to measure the static air pressure, $p_s$. The pressure port located in the center of the probe is coincident with the nominal stagnation point of the oncoming airstream and has a diameter of 0.675 cm, which corresponds to approximately 6° of arc on the surface of the hemisphere. This differential pressure sensor (denoted “PX”) measures the difference between the total air pressure and the static air pressure. Thus, the PX output is the difference between port $p_0$ and $p_s$ in Fig. 2 ($PX = p_0 - p_s$). The other eight pressure ports surround the stagnation point of the hemisphere. Each of these is displaced 45° aft of the leading edge of the hemisphere and has a diameter of 0.5 mm. The four ports in a cruciform pattern are used to measure the attack and sideslip angles. These include two vertically opposed pressure ports connected to a differential pressure sensor (denoted “PZ,” so $PZ = p_2 - p_3$), which are used to determine $\alpha$. The two horizontally opposed ports connect to a third differential pressure sensor (denoted “PY,” so that $PY = p_3 - p_1$) and function in the same manner, and are used to determine $\beta$. The data from the four pressure sensors and a temperature measurement are utilized in a potential flow model to compute the airflow angles and true air-speed.

On our operational BAT Probes, a fast-response temperature sensor for sensible heat flux measurements is retrofitted below the probe hemisphere (this is shown mounted on our BAT Probe in Fig. 3). The temperature probe’s cylindrical mount has dimensions of 5.1 cm in length, a diameter of 0.6 cm at its end and 1 cm at its base. The potential flow model does not take the presence of this temperature probe into consideration.

b. BAT Probe sensor calibrations

The electronic performance of the BAT Probe was verified and calibrated using a “back to front” strategy. Voltage calibration signals were applied in a laboratory setting to the digitizer inputs on all 16 data channels. Then appropriately scaled test signals were applied forward to each circuit layer until the probe’s electronic performance had been verified for cumulative errors forward to the sensor inputs. A Keithly Instruments Model 236 Source measurement unit was used throughout. This device can supply highly accurate voltage and current stimuli over more than sufficient orders of magnitude for this application. This BAT system output was monitored using a modified version of BAT-Test software. The BAT-Test software was originally developed by the Atmospheric Turbulence and Diffusion Division (ATDD) of the National Oceanic and Atmospheric Administration for a similar purpose. The modified software provided data that presented noise and offset in the lesser significant bits of digital data as a fraction of the full range positive and negative range of the digitizer at full scale limits ($\pm 32$ K counts). With stimulus from the Model 236 unit, the electronic performance of the BAT system was found to be within 1 part in 8000 of the full-scale response. We will describe, below, a method to verify the pressure sensor performance. A corresponding procedure was developed for the temperature sensors, but is not described in detail.

The final step involved the installation of the sensor suite and the evaluation of the overall BAT system’s behavior by exciting each sensor. This configuration simulates the actual operating mode of the BAT Probe. As an example, the PY and PZ pressure sensor pairs were added to the test setup in their proper configuration. We calibrated each of the differential sensor pairs using a water manometer, which was attached to the appropriate sensor port by flexible tubing. The sensor pair calibration was checked by interchanging the excitation port to detect any differences between individual sensors. We observed that the BAT system response was within 0.1% of the ideal (e.g., for PZ it was linear, with $r^2 = 0.998$). For all measurements the actual cali-
3. Experimental methods: Wind tunnel calibrations

The key advantage of wind tunnel tests is that the probe can be tested in a controlled environment, at exact orientation angles, and at known airflow speeds. After each of the differential pressure sensors was independently calibrated using a water manometer (as noted in section 2b), the BAT Probe was mounted in a closed-circuit wind tunnel operated by the Purdue School of Aeronautics and Astronautics. A photograph of the BAT Probe mounted in the wind tunnel is displayed in Fig. 4. This large cross-section tunnel is specifically optimized for low-velocity flows, with wall effects and flow blockage in the test section being negligible. The wind tunnel test section is approximately 1.2 m high \times 1.8 m wide. The BAT Probe was mounted approximately in the center of the test section, oriented along the axis of the flow path. The known values of \( \alpha \) and \( \beta \) were determined by measuring the angular orientation of the BAT Probe’s longitudinal (lengthwise) axis to the known airflow direction inside the wind tunnel. Data were collected with the BAT Probe set at known orientation angles at four different wind tunnel airflow velocities. The data were then used to compute the measured airflow angle values (\( \alpha_{\text{meas}} \) and \( \beta_{\text{meas}} \)) and to compare them to the known values (\( \alpha_{\text{actual}} \) and \( \beta_{\text{actual}} \)).

The BAT Probe was placed in the tunnel on a vertical motion swivel mount controlled by a stepper motor, which allowed the angle of incidence between the probe and the airflow to be changed, and subjected to airspeeds of 25, 30, 35, and 40 m s\(^{-1}\). The accuracy of a hot-wire anemometer velocity sensor in the wind tunnel was checked by comparison to a Campbell Scientific CSAT III sonic anemometer. Data from these two flow velocity instruments showed a difference of less than 2\%. All wind tunnel airflow velocities in this paper are reported as \( U_d \) as determined using the hot-wire anemometer. For each test airspeed, the BAT Probe was subjected to 20 separate trials in various orientations in the wind tunnel. These orientations ranged from 0° to +9° and then from −9° to 0° in increments of 1° (the 0° test was performed twice). For a given airspeed, data were acquired for approximately a one-minute interval at each angle. After the \( \alpha \) data were obtained, the BAT Probe was rotated 90° around its longitudinal axis and was then slewed (i.e., vertically) in the same manner to test \( \beta \). After the tests, a bias of 1.5° was identified in the tunnel’s mechanical mounting mechanism. Thus, the actual orientation angles ranged from −7.5° to +10.5° in increments of 1°.

Wind tunnel operating restrictions limited the tests with the BAT Probe to a maximum airspeed of 40 m s\(^{-1}\). Since the aircraft typically operates at higher airspeeds (normally between 50 and 60 m s\(^{-1}\)), the wind tunnel data were extrapolated up to the flight speeds of the aircraft. Such an extrapolation is appropriate since there is negligible difference in compressibility and viscosity effects between the maximum airspeed obtained in the wind tunnel and the aircraft’s operating regime.

4. Wind tunnel results

The cylindrical temperature probe was mounted on the BAT Probe for both the wind tunnel and in-flight calibrations. The regression between \( \alpha_{\text{meas}} \) and \( \alpha_{\text{actual}} \) indicated a good correlation (\( r^2 = 0.99 \)), but with an unexpected inflection point near \( \alpha_{\text{actual}} \sim 2.5° \). A representation of the data (that optimally depicts the inflection point) is presented in Fig. 5 in which the difference between the measured and actual attack angle (\( \alpha_{\text{meas}} - \alpha_{\text{actual}} \)) is plotted as the dependent variable. Ideally, this value would always be 0°. As shown in Fig. 5, the difference ranges from approximately −0.4° to approximately 1.6° with a very distinct inflection point near +2.5°. The presence of the temperature sensor makes the probe geometry asymmetric about its lateral axis. This factor is not accounted for in the probe’s airflow computation equations. We infer that the temperature probe is the cause of this inflection point. This conclusion is supported by several observations, as discussed below.

In previous work on in-flight calibrations, differences in the \( \alpha_{\text{meas}} \) and \( \alpha_{\text{actual}} \) have been corrected by adjusting a theoretical sensitivity constant (Eckman et al. 1999).
Given the results displayed in Fig. 5, it is clear that use of a constant coefficient would lead to systematic errors that would be attack-angle dependent and larger for positive values of $\alpha$ (i.e., for updrafts). Figure 5 also shows that such a sensitivity coefficient would be dependent on a priori knowledge of both the flow angle and the true airspeed since, at any $\alpha_{\text{actual}}$, $\alpha_{\text{meas}}$ is a small but significant function of true airspeed.

Here $\beta_{\text{meas}}$ versus $\beta_{\text{actual}}$ was obtained by rotating the BAT Probe by 90° and slewing the angle vertically, as for the calibration of attack angle. The results are displayed in Fig. 6 (analogous to the $\alpha$ calibration in Fig. 5). A small bias in $\beta_{\text{meas}}$ was observed, which varied with both airspeed and the value of $\beta_{\text{actual}}$. Since the BAT Probe hemisphere is of a composite layup construction and is not necessarily precision machined, there is a practical limit on the repeatability of manufacturing identical probe hemispheres. Thus, we can reasonably expect that another hemisphere would almost certainly exhibit similar behavior that would differ in minor detail. The slopes of the calibration data displayed in Fig. 6 exhibited dependence on tunnel airspeed, but with the absence of an inflection point. The absence of such an inflection point in the $\beta$ tests also supports the inference that the air temperature probe causes the inflection in Fig. 5.

To ascertain that the inflection in the attack angle calibration plot was real (and not an artifact from a difference between the two differential pressure sensors for $\alpha$ and $\beta$), the pressure lines were temporarily reconnected so that the $\alpha$-sensing ports on the BAT Probe (PZ) were reconnected to the pressure sensors previously used for the $\beta$-sensing ports ($p_1$ and $p_3$), and vice versa. This had the effect of switching the axis on which these two particular pressure sensors made their measurements; thus now $\beta = p_2 - p_4$ and $\beta = p_3 - p_1$. After the connection was switched, an abbreviated version of the wind tunnel calibration was performed (actual flow angles of $-7.5^\circ$ through $+10.5^\circ$, in increments of $3^\circ$). This is equivalent to rotating the location of the temperature probe by 90° with respect to the PY and PZ sensors. The inflection in the attack angle calibration plot was still observed in the abbreviated test with the temporarily switched pressure sensors. The inflection remained with the axis on which the temperature probe was mounted, indicating that this behavior was not dependent on the sensors but dependent on the location of the temperature sensor on the hemisphere.

Since the only macroscopic asymmetrical attribute of the BAT Probe is the temperature probe mount in the $\alpha$-sensing axis, we attribute this departure from theory to the presence of this temperature probe mount. The influence of this temperature probe mount was not accounted for in the potential flow model nor observed prior to this study. Since the relevant potential flow equations assume hemispherical symmetry, they do not account for appendages that break the symmetry of the BAT Probe.

Our wind tunnel data make clear that the departure of the $\alpha_{\text{meas}}$ and $\beta_{\text{meas}}$ data (using the potential flow model) from the values of $\alpha_{\text{actual}}$ and $\beta_{\text{actual}}$ indicate the need for an empirical correction. The correspondence between the measured and actual $\alpha$ and $\beta$ vary with the $U_a$, as displayed in Figs. 5 and 6. Therefore, a lookup

**Fig. 5.** Wind tunnel calibration curve for attack angle, where the $y$ axis is the difference between the calculated attack angle and the probe orientation ($\alpha_{\text{meas}} - \alpha_{\text{actual}}$). For clarity, mean values are shown in lieu of all data points. Inset indicates nominal airspeeds in the wind tunnel.

**Fig. 6.** Wind tunnel calibration curve for sideslip angle, where the $y$ axis is the difference between the calculated sideslip and the probe orientation ($\beta_{\text{meas}} - \beta_{\text{actual}}$). For clarity, mean values are shown in lieu of all data points. Inset indicates nominal airspeeds in the wind tunnel.
The precision for each dataset obtained in the wind tunnel was determined (for each value of $\alpha_{\text{actual}}$ at each value of $U_a$) from the 1σ scatter in the attack angle data. In Fig. 7, the precision of $\alpha_{\text{meas}}$ as a function of $\alpha_{\text{actual}}$ is shown and is expressed as the variable $\sigma_\alpha$ (the 1σ data scatter of attack angle). The corresponding plot of the precision in the sideslip angle is of similar magnitude and shape. The precision in the $\alpha_{\text{meas}}$ and $\beta_{\text{meas}}$ is highly correlated with the measured respective flow angle quantity. Fitting a second-order polynomial to the angular precision data produces an estimate of the precision in the measured flow angle as a function of actual flow angle. This precision is propagated through the wind computation equations and is utilized to estimate the overall precision in the determined vertical wind. From this second-order polynomial ($r^2 = 0.99$), the precision of the measured attack angle can be estimated as $\sigma_\alpha = 0.0004(\alpha_{\text{meas}})^2 - 0.0006(\alpha_{\text{meas}}) + 0.0119$, with a comparable fit being applicable for the estimation of the precision of the sideslip angle, $\sigma_\beta$ (the sideslip precision data are not shown).

From the data obtained at each value of $\alpha_{\text{actual}}$ and $\beta_{\text{actual}}$, the lookup table was constructed by computing linear regression lines for each value of known flow angle. Figure 8 displays the regression plots for the attack angle as a function of the measured true airspeed $U_{a,\text{meas}}$. The value of $U_{a,\text{meas}}$ varied with the attack and sideslip angles since at large flow angles the stagnation point moves off the $p_0$ port of the BAT Probe. This behavior is a drawback in using the BAT Probe at extreme attack and sideslip angles. The value of $U_{a,\text{meas}}$ was then calibrated to the value of true airspeed from the hot-wire anemometer. In addition to allowing conversion from measured to actual $\alpha$ and $\beta$ as a function of $U_{a,\text{meas}}$, the regressions allowed extrapolation of the wind tunnel results to the higher airspeeds that the aircraft will encounter in flight. The range of the regression shown in Fig. 8 was from 25 to 65 m s$^{-1}$ since the in-flight experiment included true airspeeds of up to 62 m s$^{-1}$.

Each regression line in Fig. 8 was computed using the aggregate of all $\alpha_{\text{meas}}$ and $U_{a,\text{meas}}$ data points for the four tunnel airspeeds at each value of $\alpha_{\text{actual}}$ (approximately 17 000 data points for each regression line). The number of data points used to compute the regression for the $\alpha_{\text{actual}} = 1.5^\circ$ test was roughly twice that for the other tests since this test was repeated (this was intended as the test for $\alpha_{\text{actual}} = 0^\circ$ before discovery of the mounting bias). The standard deviation in the slope, $\sigma_m$, and intercept, $\sigma_b$, in each regression line was computed. From these values we can calculate a propagated uncertainty in the extrapolated attack angles, for a given value of $U_{a,\text{meas}}$. The extrapolation precision is derived from the propagated sum of the variances in the slopes and intercepts for each line. As an example, for the extrapolation of the $\alpha_{\text{actual}} = 3.5^\circ$ calibration to an airspeed of 55 m s$^{-1}$, we calculate an estimated precision of $0.0026^\circ$, which is less than the $0.01^\circ$ that can be
resolved with the BAT system as described in section 2b. The 1σ confidence interval was computed for the data in each regression and found to be invariant with airspeed to four significant digits within the extrapolation range. For attack angles encountered in-flight the extrapolation precision is small enough to be disregarded.

The values of $U_{a,\text{meas}}$ were approximately 6% higher than the actual true airspeed $U_a$ in the wind tunnel (as determined with the tunnel’s hot-wire anemometer and checked with the sonic anemometer). This systematic error can easily be corrected via the wind tunnel calibration data. The anomaly in nominal 40 m s$^{-1}$ wind tunnel tests near $\alpha_{\text{meas}}$ values of $-4^\circ$ in Fig. 8 is from a documented short-term decrease in the actual flow velocity in the wind tunnel.

5. Experimental methods: In-flight

The in-flight test served two purposes. The first was to ascertain the effect of including the lookup table on the computation of attack angle when compared to a reference variable (the pitch angle of the aircraft during steady, level, unaccelerated flight). The second purpose was to gather data with the INS/GPS to which a software-based error model could be applied. This model allowed an estimation of the measurement precision of the inertial variables to be performed.

The in-flight experiment portion consisted of straight-and-level flight at various headings and airspeeds and was conducted with the twin-engine Airborne Laboratory for Atmospheric Research (ALAR), a modified Beechcraft Duchess research aircraft. The BAT Probe was mounted on the nose of the aircraft, extending approximately 0.7 m in front of the nose cone and 2 m in front of the counterrotating propellers on the aircraft centerline. The propellers are located 1.85 m to each side of the centerline. The longitudinal axis of the BAT Probe has approximately the same orientation as the thrust lines of the engines and is displaced approximately 0.2 m below the propeller shafts.

The data gathered during these maneuvers allowed a comparison of measured flow angles with the aircraft orientation angles as functions of $U_a$. The aircraft orientation and velocity were determined using an integrated INS/GPS manufactured by the NovAtel Corporation, also known by its trade name as the “NovAtel Black Diamond System.” This system integrates measurements made by ring laser gyros and accelerometers with position measurements relative to GPS satellites to compute the aircraft orientation and three-dimensional velocity.

The INS/GPS was located inside the nose of the aircraft. The GPS antenna was positioned approximately 0.1 m away from the INS sensor suite, on the outer skin of the aircraft’s nose. The 1σ measurement precision for the aircraft’s three attitude angles (pitch, roll, and heading) and 3D velocity components (east, north, and up) were calculated after each of the flights during post-processing of the INS/GPS data. This was done using a proprietary postprocessing program supplied with the INS/GPS by the NovAtel Corporation. This software applied standard error models for inertial navigation systems and global positioning systems to estimate a 1σ precision for the orientation angles and velocities. These modeled inertial precision data were then used in the calculation of the uncertainty of the vertical wind measurement. Of particular interest is the precision of the two inertial variables that propagate directly into the vertical wind computation—pitch angle and aircraft vertical velocity.

The in-flight attack angle calibration data were obtained through the range of airspeeds encountered in a typical research flight. This enabled simultaneous evaluations of the relationships of $\theta$ versus $\alpha_{\text{cal}}$, and $\theta$ versus $\alpha_{\text{meas}}$. The effect of the wind tunnel calibration of the BAT Probe will be evident in the difference between the relationships that $\alpha_{\text{cal}}$ and $\alpha_{\text{meas}}$ exhibit versus $\theta$. Departures from a 1:1 relationship between the attack angles and $\theta$ can be caused by airflow distortion around the airplane behind the probe. For any object immersed in a subsonic airstream, pressure disturbances from the flow around the object will propagate forward. Therefore, airflow around the aircraft body can distort the airflow at the BAT Probe location.

The flight experiment was conducted west of the Pellston Regional Airport, Pellston Michigan (45°34’N, 84°47’W), at a pressure altitude of approximately 1070 m at four different airspeeds. As is customary, the in-flight data were taken above the atmospheric boundary layer in order to avoid turbulence. For the attack angle calibration, the aircraft was stabilized at a true airspeed of approximately 62 m s$^{-1}$ with a 10° flap setting (since a 10° flap setting is the intended standard configuration for the flux experiments). The single-axis (heading) autopilot was then engaged, and flow angle, airspeed, aircraft orientation, and aircraft velocity data were recorded for a period of approximately 1 min. Airflow angle data from the BAT Probe and inertial data from the INS/GPS were recorded at a 50-Hz data rate. The same procedure was repeated for different headings at 60° intervals (0°, 60°, 120°, 180°, 240°, and 300°) with respect to north.

After data were collected on these six heading legs, the airspeed was changed to 57, 51, and 46 m s$^{-1}$ re-
respectively, for a total of 24 separate heading–airspeed runs. The precision to which the indicated airspeed could be consistently held was approximately 0.5 m s\(^{-1}\), and the altitude was held to within ±30 m of the nominal pressure altitude. The measured true airspeed from the BAT Probe was corrected using the comparison between \(U_{a,\text{mean}}\) and \(U_a\) from the wind tunnel tests.

### 6. In-flight experiment results

The in-flight BAT Probe data was compared with two computed sets of variables [potential flow model only versus corrected flow model (with lookup table from extrapolated wind tunnel data)]. These two sets of results will be hereafter referred to respectively as the data from the “noncalibrated” BAT Probe and the “calibrated” BAT Probe. The only difference is the implementation of the lookup table from the wind tunnel data for the “calibrated” BAT Probe.

For the aircraft to maintain constant altitude at a lower airspeed, the attack angle at which the wing is operating must be increased to keep the aircraft’s net lift equal to the aircraft’s weight. If the aircraft’s vertical velocity is zero, the pitch angle can be utilized as an estimate of the free-stream attack angle, \(\alpha_{\text{meas}}\). Use of \(\theta\) is preferred as an indicator of \(\alpha_{\text{meas}}\) since the ambient vertical wind is zero (Crawford et al. 1996). If the BAT Probe had been calibrated (with lookup table and data that would have been collected with a noncalibrated BAT Probe (no lookup table). Neglecting lift-induced upwash, ideally the correspondence between the attack and pitch angle data should be 1:1, which is much closer to the case for the \(\alpha_{\text{cal}}\) plot. The slope for \(\alpha_{\text{cal}}\) data is closer to unity than the slope for \(\alpha_{\text{meas}}\).

The inflection point noted above in Fig. 5 is not evident in the in-flight experiment since the attack angle at which the probe was operating was always ±3°. The BAT Probe is often mounted at arbitrary incidence angles on various aircraft due to structural constraints (Crawford et al. 1996). If the BAT Probe had been mounted at a higher incidence angle relative to the aircraft’s longitudinal axis, the \(\alpha_{\text{meas}}\) would have been correspondingly higher (thus encountering values of \(\alpha_{\text{meas}}\) at or past the inflection point of +2.5° in Fig. 5). This is clear evidence that independent testing of aircraft turbulence probes in a controlled environment (i.e., wind tunnel) is important and that adding appendages near the hemisphere can lead to errors.

This phenomenon is clearly important to the objective of producing flux (or winds) data with the smallest possible uncertainty. The matter is more complicated than simply subtracting the additional incidence angle from the value of \(\alpha_{\text{meas}}\) since the lookup table requires both \(U_a\) and \(\alpha_{\text{meas}}\) as inputs. Thus, without the wind

### Table 1. Estimates of instrument precision from the wind tunnel tests and INS/GPS model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll angle</td>
<td>(\sigma_\phi)</td>
<td>0.010°</td>
</tr>
<tr>
<td>Pitch angle</td>
<td>(\sigma_\theta)</td>
<td>0.015°</td>
</tr>
<tr>
<td>Heading angle</td>
<td>(\sigma_\psi)</td>
<td>0.050°</td>
</tr>
<tr>
<td>Easting velocity</td>
<td>(\sigma_{\text{vel}})</td>
<td>0.06 m s(^{-1})</td>
</tr>
<tr>
<td>Northing velocity</td>
<td>(\sigma_{\text{vel}})</td>
<td>0.06 m s(^{-1})</td>
</tr>
<tr>
<td>Vertical velocity</td>
<td>(\sigma_h)</td>
<td>0.02 m s(^{-1})</td>
</tr>
<tr>
<td>True airspeed</td>
<td>(U_a)</td>
<td>2%</td>
</tr>
<tr>
<td>Attack angle</td>
<td>(\alpha)</td>
<td>(0.0004(\alpha_{\text{meas}})^2 - 0.0006(\alpha_{\text{meas}}) + 0.0119)</td>
</tr>
<tr>
<td>Sideslip angle</td>
<td>(\beta)</td>
<td>(0.0004(\beta_{\text{meas}})^2 - 0.0006(\beta_{\text{meas}}) + 0.0119)</td>
</tr>
</tbody>
</table>
tunnel calibration information, a given BAT Probe would likely exhibit different relationships between \( \alpha_{\text{meas}} \) versus \( \theta \) depending on the mounting incidence and flight speed. This would result in a systematic error in the in-flight calibration and, thus, a difference in the measured data.

### 7. Uncertainty analysis

Postprocessing of the INS/GPS data during the pitch versus attack angle calibration flight yielded modeled 1σ precision of approximately 0.015°, 0.010°, and 0.050° for the aircraft’s pitch, roll, and heading angles, respectively (as shown in Table 1). The modeled precision in the pitch angle (\( \sigma_\theta \)) is of prime interest for flux calculations since the errors in the roll and heading angles do not significantly propagate into uncertainty in the calculated vertical wind.

An analysis of the sensitivity of the vertical wind computation to the relevant variables is given in the appendix of Enriquez and Friehe (1995). Using a small angle approximation, the partial derivative of vertical wind with respect to attack angle (\( \partial w / \partial \alpha \)) scales with the value of \( U_v \). The same term for precision in the pitch angle (\( \partial w / \partial \theta \)) scales with the negative of true airspeed, \(-U_a\) (the negative sign results from how the pitch angle is defined in the aircraft coordinate frame). The contribution of aircraft vertical velocity scales by a factor of unity into the vertical wind computation, \((\partial w / \partial \theta) \approx 1\). Propagation of the contributions from each sensitivity term can give a good estimate of the overall uncertainty in computing the vertical wind. Given the simplifying assumptions of straight-and-level, unaccelerated flight with a negligible pitch angle (i.e., within small angle approximation), the 1σ uncertainty in the vertical wind due to the precision of the attack angle can be approximated by

\[
\sigma_{w,\alpha} \approx \sigma_\alpha U_v.
\]  

where \( \sigma_\alpha \) is the attack angle 1σ measurement precision (in units of radians). For example, an attack angle of 5° corresponds to a 1σ precision of measurement of approximately 0.02°. If this attack angle is present when the \( U_v \) is 50 m s\(^{-1}\), the value of \( \sigma_{w,\alpha} \) is approximately 0.017 m s\(^{-1}\).

The 1σ uncertainty in vertical wind due to an uncertainty in pitch angle is approximated by

\[
\sigma_{w,\theta} \approx -\sigma_\theta U_w.
\]  

Using the modeled precision in pitch angle of approximately 0.015°, the value of \( \sigma_{w,\theta} \) will be approximately 0.013 m s\(^{-1}\) at a true airspeed of 50 m s\(^{-1}\).

Since the 1σ precision in aircraft vertical velocity, \( \sigma_{\dot{h}} \), scales by a factor of unity into the vertical wind computation (Enriquez and Friehe 1995), the value of the resultant uncertainty component will simply be

\[
\sigma_{w,\dot{h}} \approx \sigma_{\dot{h}}.
\]  

The modeled precision in the northward, eastward, and vertical velocities of the aircraft were calculated as approximately 0.06, 0.06, and 0.02 m s\(^{-1}\) respectively. Therefore, a \( \sigma_{\dot{h}} \) of 0.02 m s\(^{-1}\) will propagate directly into an equivalent uncertainty in the computed vertical wind. Equations (2), (3), and (4) can be combined to compute the absolute uncertainty in the vertical wind due to the modeled precision in pitch angle, aircraft vertical velocity, and the precision in measuring the attack angle:

\[
\sigma_w = \sqrt{\sigma_{w,\alpha}^2 + \sigma_{w,\theta}^2 + \sigma_{w,\dot{h}}^2}.
\]

The contributions of each of the individual measurement precisions are plotted in Fig. 10. The propagated sum of the individual sources of uncertainty [computed through Eq. (5)] is displayed as the thick black line in Fig. 10. This represents the propagated uncertainty in the computation of \( w \) due to attack angle precision and INS/GPS modeled precision.

The spatial scales that are measurable with the BAT Probe are described in Crawford and Dobosy (1992). The Nyquist criterion dictates that at our sampling rate of 50 Hz and airspeeds in the range of 50 to 60 m s\(^{-1}\) the smallest measurable eddies will be on a scale of 2 m and larger. Since eddies of 1 m and larger will not be significantly distorted by the passage of the hemisphere, the scales of interest (>2 m) will not be affected by this.

### 8. Conclusions

When the symmetry of a hemispherical turbulence probe is disturbed (e.g., due to the presence of the tem-
perature probe), computed attack angles will result that are not predicted by the potential flow theoretical model. Manufacturing imperfections and/or addition of auxiliary sensors will cause airspeed-dependent departures from the theoretical BAT Probe performance, as shown by our results. Thus, a controlled calibration of any individual turbulence probe will represent a significant improvement in real-world performance.

Precision of the measured attack and sideslip angles are strongly correlated to the flow angles, and these uncertainties propagate through the computations of $U_a$. This allows uncertainty bounds to be assigned as a function of the attack and sideslip angles themselves.

The in-flight experiment demonstrates the improvements possible if wind tunnel calibrations are applied to the calculated airflow angles. Otherwise, an erroneous sensitivity coefficient would be applied to correct the BAT Probe measurements. In addition, altitude-dependent errors would exist if in-flight calibrations were performed at a different air density than those encountered during experiment flights. This would result in a systematic error in the in-flight calibration and, thus, deviations in measurement performance in various flight regimes.

As shown in Fig. 10, the propagated overall 1σ precision in our determined vertical wind is almost invariant with $U_a$, at $\sim 3$ cm s$^{-1}$, well within the requirements for flux measurements. Operational flux flights have often been conducted toward the slow end of the research aircraft’s operating range because at a given data acquisition rate the spatial resolution coarsens at higher airspeeds (Crawford and Dobosy 1992). In theory, vertical wind precision is better at slower airspeeds since contribution of the precision in attack angles and pitch angles scale directly with $U_a$ (Enriquez and Frieh 1995). However, this benefit will be lessened since the measurement precision of the BAT Probe will be of lower quality when operating at a higher value of $\alpha_{\text{meas}}$ (Fig. 7). Thus, the contribution of the BAT Probe’s attack angle measurement precision varies as a function of both $\alpha_{\text{meas}}$ and $U_a$, and at slower speeds the attack angle will increase. The value of $\sigma_\beta$ does not vary with airspeed but will increase if the aircraft is subjected to dynamic motion. Thus, the value of $\sigma_\beta$ is likely to increase if the aircraft is subject to turbulent buffeting if operating in the boundary layer.

Acknowledgments. The National Science Foundation Grant 0119995-ATM made this work possible. We thank the Department of Aviation Technology at Purdue University for the support provided to the Airborne Laboratory for Atmospheric Research (ALAR). Staff from the Jonathan Amy Facility for Chemical Instrumentation provided countless hours of assistance, including staff members Bob Fagan, Randy Replogle, and the late Greg Hawkins. We thank Professor John Sullivan for providing access to the Boeing Wind Tunnel, and the assistance of graduate student Leon Walter. Collaborators involved in the Network of Airborne Environmental Research Scientists were indispensable to the development of this project, including Jorg Hacker of Airborne Research Australia, Jeff French and Ron Dobosy of the National Oceanic and Atmospheric Administration, and Ed Dumas of Oak Ridge Associated Universities. We dedicate this paper to the late Timothy Crawford of the National Oceanic and Atmospheric Administration, who helped inspire this work.

APPENDIX A

Potential Flow Equations

The potential flow equations for computing the values of $\alpha_{\text{meas}}$ and $\beta_{\text{meas}}$ have been extracted from Eckman et al. (1999) and Williams and Marcotte (2000), having been originally present in an unpublished manuscript (1991) by J. A. Leise and J. M. Masters.

The potential flow equations start with defining the intermediate variables $H_a$ and $H_b$. These intermediate variables represent the proportion between the flow angle-sensing ports (PZ and PY) and the total pressure port (PX), both multiplied by a theoretically derived coefficient. Since the PX and PZ ports on the ALAR BAT Probe are 45° aft of the PX port, the value of the sensitivity coefficient will be 2/9:

$$H_a = \frac{2 \text{ PZ}}{9 \text{ PX}}, \quad \text{(A1)}$$
$H_\beta = \frac{2 \ PY}{9 \ PX}.$  \hspace{1cm} (A2)

These two intermediate variables are then employed in calculating the tangents of $\alpha_{\text{meas}}$ and $\beta_{\text{meas}}$ through Eqs. (A3) and (A4):

$$\tan \alpha_{\text{meas}} = 2H_\alpha [1 + \left[ 1 + 5(H_\alpha^2 + H_\beta^2)^{0.5} \right]^{-1}]^{-1},$$  \hspace{1cm} (A3)

$$\tan \beta_{\text{meas}} = 2H_\beta [1 + \left[ 1 + 5(H_\alpha^2 + H_\beta^2)^{0.5} \right]^{-1}]^{-1}.$$  \hspace{1cm} (A4)

### APPENDIX B

<table>
<thead>
<tr>
<th>Glossary</th>
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<tbody>
<tr>
<td><strong>Terminology, abbreviations, and list of variables</strong></td>
</tr>
<tr>
<td>$\alpha$</td>
</tr>
<tr>
<td>$\alpha_\alpha$</td>
</tr>
<tr>
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<tr>
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</tr>
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### REFERENCES


