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# Airdata Measurement and Calibration

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Edward A. Haering, Jr.

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Edward A. Haering, Jr.  
*NASA Dryden Flight Research Center  
Edwards, California*

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Dryden Flight Research Center  
Edwards, California 93523-0273

## **ABSTRACT**

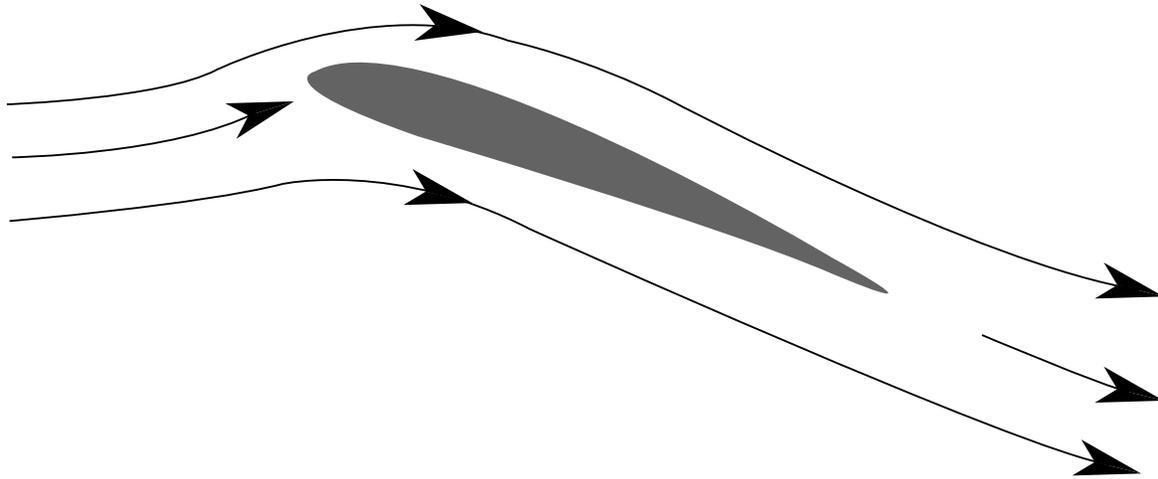
This memorandum provides a brief introduction to airdata measurement and calibration. Readers will learn about typical test objectives, quantities to measure, and flight maneuvers and operations for calibration. The memorandum informs readers about tower-flyby, trailing cone, pacer, radar-tracking, and dynamic airdata calibration maneuvers. Readers will also begin to understand how some data analysis considerations and special airdata cases, including high-angle-of-attack flight, high-speed flight, and nonobtrusive sensors are handled. This memorandum is not intended to be all inclusive; this paper contains extensive reference and bibliography sections.

## **INTRODUCTION**

Airdata are vital to successfully complete an aircraft's mission and are derived from the air surrounding the aircraft. References 1–4 supply pertinent information regarding airdata measurement and calibration. These airdata encompass indicated and true airspeed, pressure altitude, ambient air temperature, angles of attack and sideslip, Mach number, and rate of climb. Typically, pitot and static pressures are sensed and converted (by mechanical means in the instruments themselves) into indications on the altimeter, vertical speed indicator, airspeed indicator, and Machmeter. Similarly, measured local flow angles establish angles of attack and sideslip, and the outside air temperature is measured and indicated in the cockpit. (Instruments that can perform the conversion, such as airspeed indicators, altimeters, and Machmeters, do not correct for errors in the input values.) These measured parameters are commonly input to the airdata computer, which, using appropriate algorithms and correction factors (or calibrations, as discussed later), can provide other parameters, such as true airspeed, required by the aircraft's avionics or flight control system.

The presence of the aircraft in the airstream causes input errors to the measuring instruments — the aircraft disturbs the air that it flies through, thereby also disturbing the airdata measurements. Figure 1 shows the airflow around an airplane wing. The air above the wing has lower pressure than the ambient air, while the pressure below the wing is higher than the ambient air. Compressibility and shock waves also disturb the air and affect the measurements. Compressibility effects become important above approximately Mach number 0.3. As a result, the static pressure around an airplane varies considerably with location. Local flow angles also differ from the free-stream flow direction. In straight-and-level flight, the airflow rises to the wing leading edge and falls below the trailing edge, causing errors in flow direction measurements. To some extent these errors can be studied in wind tunnels, but wind-tunnel measurements cannot replace in-flight measurements.

Accurate airdata are necessary for many purposes and applications. Obviously, the pilot cannot safely fly the aircraft without knowing airspeed and pressure altitude. In civil aviation, the small vertical separation between flight levels assigned by air traffic controllers is based on accurate knowledge of pressure altitude. Numerous systems, such as autoflight controls, engine controls, cockpit and cabin environmental control, weapons delivery, navigation, and air traffic control, depend on accurate airdata. When an unproven airplane undergoes envelope expansion,



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Figure 1. Airflow around an aircraft wing.

careful attention must be paid to flight limits of equivalent airspeed to ensure flight safety. In flight research, most measurands are referenced to airdata quantities, and many parameters are normalized to dynamic pressure. The accuracy needed for a particular application dictates how airdata should be measured and dictates the amount of calibration effort required. References 5 and 6 specify the accuracy levels required of the pitot-static system by civil and military organizations. Flight research activities may require higher accuracies.

## **TEST OBJECTIVES**

If the location of the static ports has not already been identified, then the first objective must be to determine the best location for the static ports, that is, where the smallest or most constant position errors occur. Once this location is established, the calibrations of the total and static pressures, angles of attack and sideslip, and air temperature should be determined to account for the disturbing presence of the aircraft in the flow field. The calibrations must be performed under various flight conditions of airspeeds and altitude as well as aircraft attitudes and configurations (combinations of flaps, gear, and external stores).

## **MEASUREMENT AND CALIBRATION OF AIRDATA QUANTITIES**

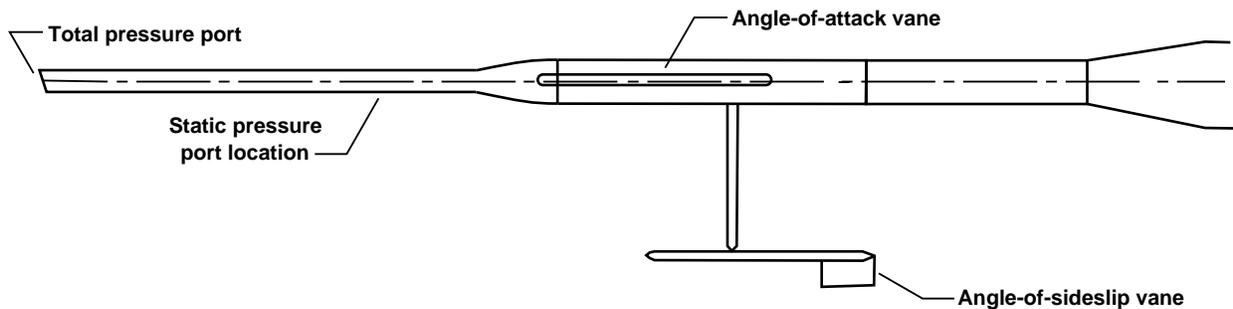
### **Pitot Pressures**

The pitot, or total, pressure is the sum of the static pressure and the pressure rise resulting from stagnation of the airflow (dynamic pressure) in the pitot tube. Total pressure is generally easy to measure accurately; the location is not critical as long as the tube opening is outside the aircraft's boundary layer and is oriented to the incoming flow. For well-sited or aligned probes, the total pressure error is usually negligible. (This assumption can be checked by comparison with a venturi pitot or by flying in formation with a calibrated pacer aircraft.) The shape of the pitot tube opening dictates the flow angles at which the pitot tube works well. For supersonic flight

pitot tubes that are forward of aircraft shocks, such as those on nosebooms (ref. 7), will not have aircraft shock losses (ref. 2). Figure 2 shows a typical flight test noseboom that measures pitot-static pressures as well as local flow angles.

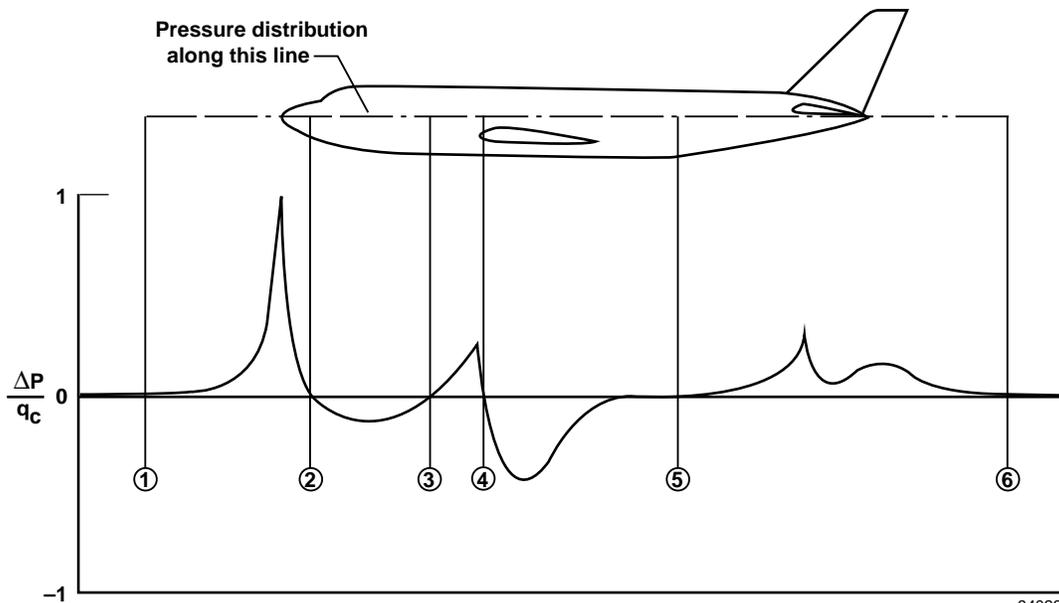
### Static Pressures

Static pressure can be measured with a pitot-static tube or a flush-mounted port on the fuselage. Figure 3 shows a typical subsonic static pressure distribution on an aircraft fuselage (ref. 2). The measured minus true static pressure,  $\Delta P$ , normalized to compressible dynamic pressure,  $q_c$ , is plotted as a function of fuselage position. Zero static pressure error on the fuselage exists at locations 2 through 5. One of these locations is chosen for the static port. To keep pneumatic lag small, the static port is normally located as near the airdata instruments as possible (or the other way around). (To determine this location precisely, several static ports are made in this area. The optimum location is then selected as a result of comparing the various ports



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Figure 2. Noseboom for measuring pitot and flow angles.



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Figure 3. Subsonic static pressure distribution.

with a reference source, such as a trailing cone.) This pressure distribution changes with flight condition, so a calibration over the flight envelope may still be necessary.

Location 1 in figure 3 also has zero static pressure error. A noseboom can be used to place a static-pressure source toward this region. Structural considerations prevent a noseboom from being long enough to have identically zero static pressure error. Some static pressure errors remain and need to be calibrated. Some nosebooms and pitot-static probes have contours designed to compensate the measured static pressure for the position error induced by the specific airplane (or probe for a supersonic noseboom) (ref. 2).

Even with the selection of the best static port position, some pressure errors will remain, and these errors must be determined in flight. The difference between the locally measured static pressure and the ambient static pressure, which is dependent upon angle of attack, airspeed, and aircraft configuration, is called *position error*.

Three calibration types are generally used to determine position error: direct comparison, altimetry, and velocimetry. The direct-comparison calibration type involves measuring the true static pressure from a known source. The result is then compared with the static pressure of the airplane being calibrated. Direct comparisons are completed using the trailing cone and pacer methods described in later sections of this memorandum. The altimetry type adds one level of complexity by first determining the true pressure altitude. This altitude is then converted to static pressure. The tower-flyby and radar-tracking methods, also described in later sections of this memorandum, use altimetry. The velocimetry type uses the ground speed of the airplane and windspeed to determine true airspeed. If test maneuvers are conducted in opposite directions, wind errors can be minimized. Temperature errors affect this calibration type. After the pitot and static pressure system is calibrated, the flow angles and temperature may be calibrated.

## Temperature

The undisturbed ambient outside air temperature (OAT) can only be directly measured on board the aircraft at very low speeds. At the low speeds, temperature is typically measured mechanically using a bimetallic strip that moves a needle indicator. At higher speeds the stagnation or total air temperature (TAT) is measured and then corrected to ambient conditions to provide better accuracy of OAT measurement. TAT is the sum of the OAT and the adiabatic temperature rise resulting from the stagnation of the airflow. Because there is not 100 percent stagnation (some airflow past the sensing element is required), a correction, termed the recovery factor, has to be determined. OAT can be readily determined by the methods in reference 1 once the true TAT and Mach number are known.

The location for the TAT is not critical as long as the probe inlet openings are outside the boundary layer and are aligned with the airflow when the aircraft is in its normal flight attitude. A favorable location is on the aircraft nose, in the area where the flow is still attached.

Most modern aircraft use TAT probes with electrical resistance elements, or thermistors (ref. 8), with a mechanical design that prevents liquid, ice, or dirt particles from affecting the sensing element. Most probes also have housings that are electrically heated to prevent icing; the

sensor results must be corrected for this heating. TAT measurements must also be corrected for self-heating (resulting from the electrical excitation of the heating element), radiation, and the previously mentioned recovery factor.

The combination of these errors is often termed the recovery factor, which must be determined from indicated temperature to TAT. The easiest way to determine this factor is to compare the readings with a reference TAT probe that has been calibrated in a wind tunnel. Another method is to compare the indicated temperature readings with those obtained on another aircraft in which the temperature system has been calibrated.

Figure 4 shows a typical temperature calibration for the case in which a reference probe is not available. Plotting total temperature as a function of Mach number squared yields a linear trend. The ordinate intercept is the ambient temperature. The slope and ambient temperature are used to determine the recovery factor (ref. 1). The data for one plot must be gathered in a short time-and-distance interval and at a constant altitude so that the ambient temperature remains constant.

Another method for determining the recovery factor uses a direct measurement of ambient temperature. This temperature is obtained using a thermometer in a tower for low-altitude flight. Still another method uses meteorological data and true Mach number to calculate true total temperature and, thereby, the recovery factor (ref. 1).

### Measurement of Flow Angles

The locations of the flow angle sensors greatly affect their measurement. At subsonic speeds the local angle of attack is affected by flow around the body and wing of the airplane, which is

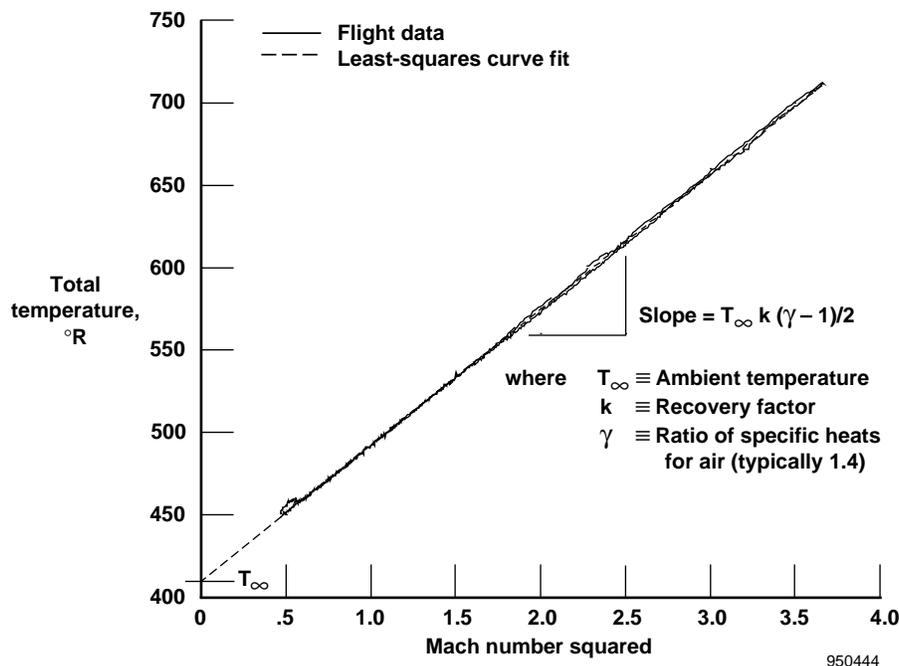


Figure 4. Total temperature calibration.

termed *upwash*. Upwash affects the sensors near a lifting surface much more than it affects sensors on a noseboom. Wingtip-mounted sensors are greatly influenced by upwash and sidewash; thus, they are rarely used. Flow angles are typically measured with one of three sensors: flow vanes, fixed differential pressure probes, and null-seeking servoactuated differential pressure probes (refs. 1 and 2). Flow vanes resemble small weather vanes and are connected to a potentiometer or other angle-measuring transducers. These vanes should be mass-balanced to remove biases and to improve precision in dynamic maneuvers. Flow vanes tend to be more sensitive than the other two sensors, especially at low speeds. On the other hand these vanes are more susceptible to damage than the other sensors are.

Fixed differential pressure probes generally are hemispherically or pyramidally headed probes with two pressure ports for measuring the flow angle in each axis. When the two pressures are equal, the probe is aligned with the flow. A nonzero differential pressure can be converted to the angle of the flow to the probe.

The null-seeking probe is similar to the fixed probe, except that a servo rotates the probe to achieve zero differential pressure. The angle to which the probe is rotated measures the local flow direction relative to the aircraft body datum.

### **Angle-of-Attack Calibration**

True angle of attack can be determined during steady flight as the difference between the pitch attitude angle and flightpath climb angle of the airplane (ref. 1). (Measurement methods for these quantities will be discussed in a later paragraph.) This analysis requires minimum effort, but the result may not be valid during unsteady flight.

To obtain true angle of attack for unsteady flight, the winds aloft, airplane ground speed, and true airspeed — for which the position error must be known — are combined. This combination is known as trajectory or state reconstruction (refs. 9–13). Assuming that the vertical winds are zero usually is valid for a nonturbulent atmosphere. Dynamic effects on the sensors must also be considered, including the bending of the airplane structure and the effects on accelerometers and flow vanes from angular rate and acceleration (ref. 12).

Typically, production angle-of-attack sensors are mounted on the side of the fuselage forward of the wing. Upwash caused by wing lift should not affect the sensor in supersonic flow; however, the sensor may be affected by other local shock waves (ref. 12).

### **Angle-of-Sideslip Calibration**

In theory, angle of sideslip can be calibrated in the same manner as angle of attack. In practice, however, wind variability makes steady flight angle-of-sideslip calibration difficult because calculated true angle of sideslip is very sensitive to lateral winds (ref. 1). Obtaining bias errors for angle of sideslip through trajectory reconstruction presents similar difficulties (ref. 12). This problem increases in difficulty as aircraft speed decreases. In a similar way that upwash affects angle of attack, sidewash affects angle of sideslip. Sidewash and shock wave effects can be determined through trajectory reconstruction.

## **PARAMETERS REQUIRED FOR AIRDATA CALIBRATION**

Quantities used to calibrate airdata parameters include velocity, attitude, angular rates, angular and linear accelerations and atmospheric data. During steady-state flight, most of these quantities can be recorded using pencil and paper. For greater accuracy, however, especially during dynamic maneuvers, digital recording is used.

### **Position, Velocity, and Attitude**

Several of the calibration calculations require Earth-relative position or velocity components. These data can be determined by an inertial navigation system (INS); ground-based radar, laser, or optical tracker; or global positioning system (GPS). Euler angles for aircraft attitude (roll, pitch, and yaw) can be measured using INS and some GPS units [11-14].

An INS generally provides a complete Earth-relative data set, self-contained in the airplane, but these data are subject to drift errors. These drift errors are aggravated by maneuvering flight. An INS that uses ring-laser gyroscopes generally has less drift than one that uses mechanical gyroscopes. Altitude from an INS typically uses airdata to stabilize its integration loop. Some INS units have significant transport delays or lags because of filtering, or both, that should be taken into account.

Ground-based radar, laser, or optical trackers can be used to determine aircraft position and velocity. These trackers are not subject to the kinds of drift that INS experience, but they are susceptible to errors, such as atmospheric refraction (ref. 15). Where an INS determines velocity from integrated acceleration, systems using radar, laser, and optical trackers determine velocity from differentiated position. Radars can track aircraft to much greater distances than laser or optical trackers.

A GPS receiver can determine the time, position, and velocity of an airplane without drift errors. Position data from a GPS receiver may be degraded by selective availability when a nonmilitary receiver is used. Velocities are not affected by this problem. Using differential GPS greatly increases position accuracy, but a reference ground receiver is needed. These GPS data are typically received on the order of 1 sample per second. The Euler angles of the airplane can be measured using multiple GPS antennae on the airplane and the carrier phase of the GPS signal.

Another type of inertial reference blends INS and GPS. This reference has all the benefits of an INS with GPS used to remove the drift error associated with INS.

### **Rates and Accelerations**

The angular rates, angular accelerations, and linear accelerations of the airplane are used in the calibration analyses of dynamic maneuvers. Linear accelerometers can also be used in steady flight to measure the pitch and roll attitude of the airplane (ref. 1).

An angular rate may be measured by a rate gyroscope. Angular accelerations can be determined by differentiating the angular rate data. Direct measurement of angular acceleration

data is possible but generally difficult. The location of an angular rate gyroscope is unimportant if the airplane is inflexible and the location is subject to experience only minor vibration.

Linear accelerometers should be located as near the center of gravity as possible. If a significant offset exists between the accelerometer location and the center of gravity, then angular rates and angular accelerations will affect the linear acceleration data. These effects can be subtracted if the moment arm, angular rates, and angular accelerations are known. Linear accelerometers are affected by gravity and may also be affected by aircraft bending (ref. 12).

## **Atmospheric Data**

To convert the Earth-referenced data from such sources as INS or radar into airdata, the state of the atmosphere must be known. Measurements of the atmosphere can be made from ground-based devices, upper-air weather balloons, and satellite data. If direct atmospheric measurements cannot be made — for example, for a vehicle flying in near-space — a first-order approximation can be made using a standard atmosphere (ref. 16).

Weather balloons employ radio tracking for wind measurements by the rawinsonde method. The balloon carries an instrumentation package and telemeters the data to a ground station that also tracks the location of the balloon to determine the wind. The processed data include temperature, humidity, pressure, and windspeed and direction as a function of altitude. These balloons are released from many locations around the world at least twice a day. Data from a single balloon may have significant errors, so an atmospheric analysis may be required (ref. 17).

## **TYPICAL CALIBRATION TECHNIQUES**

This subsection describes typical maneuvers and methods for most airdata calibrations. Tower-flyby, trailing static or trailing cone, pacer aircraft, radar tracking, and dynamic maneuvers are included.

### **Tower Flyby**

The tower-flyby method is the most accurate of the altimetry type of calibrations; however, only subsonic data can be taken. In addition, only a few calibration points can be flown during one flight. Figure 5 illustrates the tower-flyby method (refs. 1, 4, and 12). The airplane is flown at a steady airspeed and altitude near the flyby tower. Passes by the tower are flown at various subsonic Mach numbers. At the same time, the airplane is sighted from the tower through an eyepiece or camera and grid, and the true geometric altitude of the airplane is determined by geometry. Then, the hydrostatic equation is used to adjust the pressure at the tower for the height of the airplane above the tower. This new pressure is the free-stream static pressure at the altitude of the airplane. The total pressure is assumed to be correct.

### **Trailing Static or Trailing Cone**

A direct-comparison type of calibration is the trailing static or trailing cone method (refs. 1, 2, and 18). Location 6 in figure 3 shows a region of nearly zero static pressure error. By trailing a

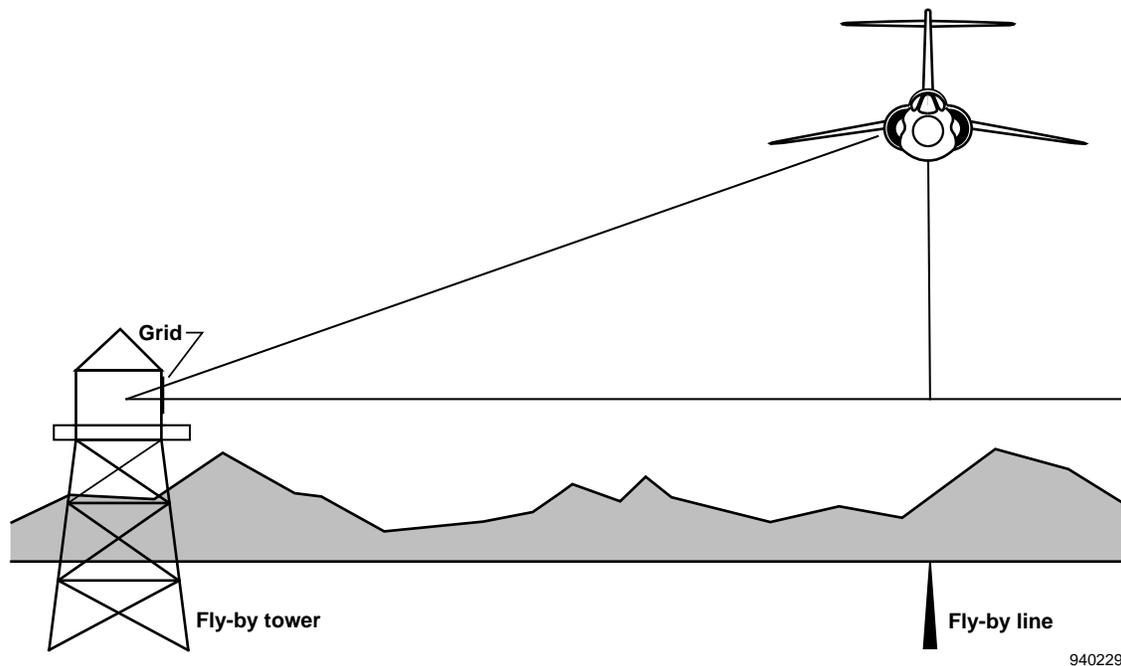


Figure 5. Tower fly-by calibration method.

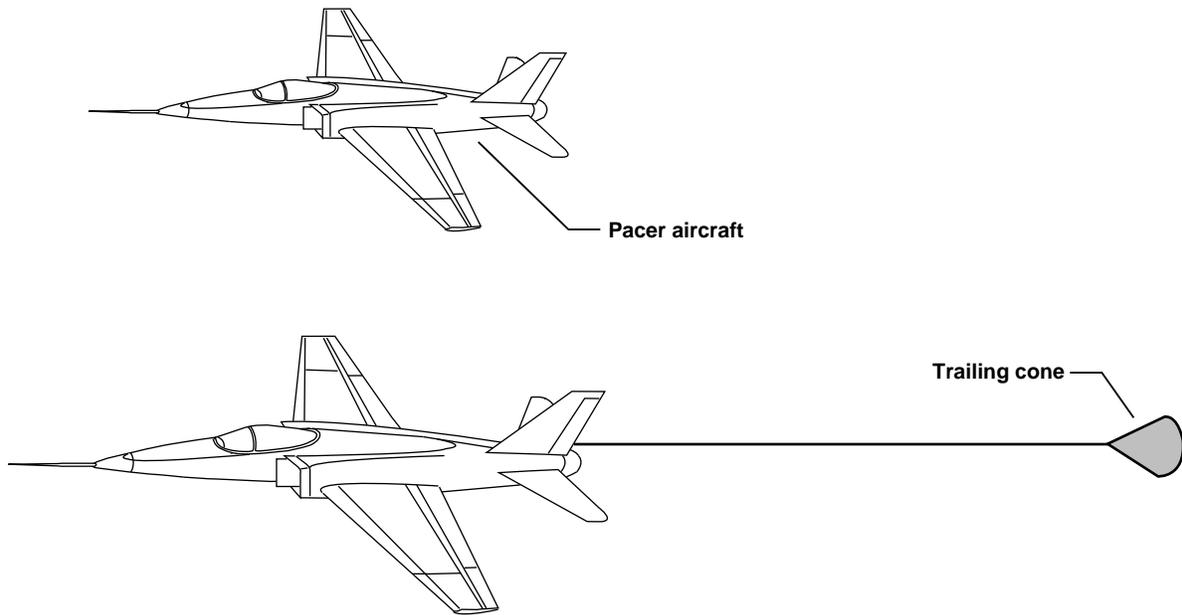
long tube behind the airplane, a nearly free-stream static pressure measurement can be taken (fig. 6). A perforated cone at the end of the tube acts as a drag device to keep the tube stable. Because of the long tube length, only steady level calibration points are possible. A differential pressure measurement between the trailing tube and airdata system static source measures position error directly. Some trailing cones have pressure transducers within them; these do not have pneumatic lag problems.

Although in principle a trailing cone may be used throughout the envelope of an airplane, its trailing tube may have some regions of dynamic instability. A method to extend and retract the tube is preferred to prevent damage of the apparatus during takeoff and landing and to adjust the length and thereby ensure stability of the tube. The optimum extension length varies with aircraft and speed but may typically be two wingspans.

### **Pacer Aircraft**

Another direct-comparison calibration method involves a second airplane, known as a pacer airplane (refs. 1 and 4). An accurately calibrated airdata system aboard the pacer is used to calibrate the test airplane. Both aircraft fly at nearly the same altitude, so the calibrated static pressure, or pressure altitude, from a pacer airplane is the free-stream static pressure, or pressure altitude, for a test airplane (fig. 6). In this way, a direct-comparison calibration is done. If some altitude difference exists between the two aircraft, an altimetry calibration can be performed using optical measurements of the altitude difference.

Although it is desirable for a pacer airplane to have performance similar to a test airplane, test aircraft can perform flybys in the same fashion as tower flybys. Position error is determined by



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Figure 6. Trailing cone and pacer aircraft.

the difference in static pressure, or pressure altitude, between the two aircraft. The accuracy of the resulting calibration cannot be better than the accuracy of the airdata system of the pacer airplane.

## Radar Tracking

Figure 7 shows the radar-tracking method. As in the tower-flyby method, free-stream static pressure is calculated for the airplane (refs. 1, 4, and 12). For a calibration run, the airplane flies with wings level, on a constant heading, and at a constant geometric altitude. The airplane begins the run at a low airspeed and accelerates at a slow rate to its peak speed. The pilot then begins to decelerate slowly back to the original airspeed. The entire maneuver is completed at radar elevation angles above 10 degrees to minimize radar refraction errors and below 80 degrees to avoid high radar antennae slew rates. Time-coded radar data are processed to give geometric altitude. Weather data from balloons and other sources are analyzed to determine the true static pressure as a function of altitude and lateral distance. These data are combined to give the true static pressure at the airplane during the entire maneuver.

This radar-tracking method is of the altimetry type and has the advantage of being able to handle large amounts of data at all speeds. This method is less accurate than the tower-flyby method because meteorological and radar errors propagate into the analysis.

## Dynamic Maneuvers

An extension of the radar-tracking method uses radar, or another Earth-relative data source, during dynamic maneuvers to perform a trajectory reconstruction. Typical flight maneuvers

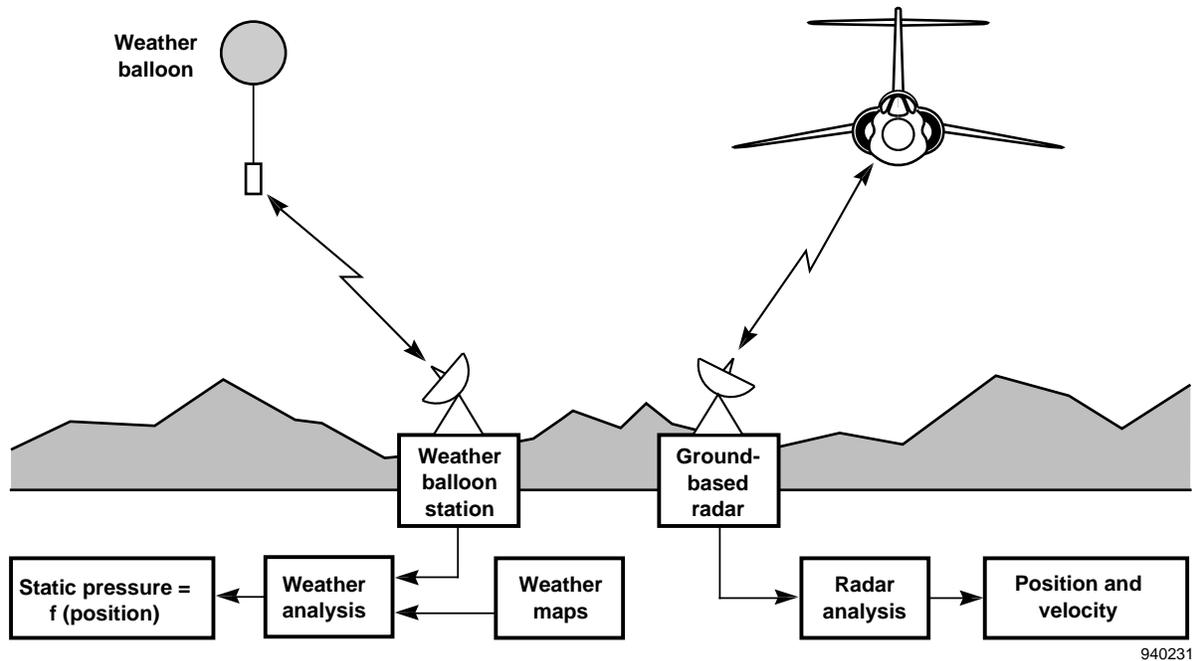


Figure 7. Radar-tracked calibration method.

include windup turns, climbs, descents, roller coasters, pushover-pullups, and rudder sweeps (refs. 1 and 12). Windup turns can be used to get data at elevated normal force or angles of attack. Roller coaster and pushover-pullup maneuvers are used for angle-of-attack calibration. Rudder sweeps are used for angle-of-sideslip calibration. One benefit of dynamic maneuver analysis is that any maneuver done with sufficient data collection can be analyzed for airdata calibration. Note, however, that keeping the varying quantities to a minimum number is desirable because it simplifies interpretation of the results.

## DATA PROCESSING AND ANALYSIS

Items of concern for airdata calibrations include data tares, atmospheric references, trajectory reconstruction, and pneumatic lag and attenuation.

### Data Tares

The use of data tares, or zeros, greatly improves the quality of a calibration. These readings should be taken while the airplane is stationary, and no personnel are climbing around it. Readings of all the instruments and transducers are taken before and after the flight. The resulting data can be used to determine if the transducers have drifted and to adjust the flight data if a change has occurred. Some designs of differential pressure transducers can measure tares while in flight and then be returned to a data-gathering mode for the test maneuver. This capability can give highly accurate readings of small differential pressures.

Collecting data during stabilized flight before and after a dynamic maneuver is also a form of a tare. For trajectory reconstruction efforts where accurate wind data are needed, the airplane can

perform slow stabilized turns. Ground speed, true airspeed, and heading are used to measure the winds in flight. Often an airplane will perform calibration maneuvers along a track in opposite directions. A wind tare can be gathered while putting the airplane on a reciprocal heading on the original track.

An airdata calibration can be no more accurate than the sensors used to measure airdata and other calibration parameters. End-to-end calibration of all transducers is highly desirable. This procedure involves calibrating the sensor, signal conditioning, analog-to-digital conversion, data telemetry, and recording systems as a whole unit. Some transducers need accurate placement or alignment, such as accelerometers, INS units, nosebooms, and flow vanes. On flexible aircraft with nosebooms or bendable flow vanes, the alignment should be checked periodically.

### **Atmospheric References**

Climatological data must sometimes be used instead of measured weather data. Common examples include situations in which the airplane is flown great distances from any weather station or at altitudes above those in which measurements are taken. Using monthly climatological data instead of collocated measurements will degrade the quality of the calibration, but that is preferable to simply using the standard atmosphere or other annual reference statistics.

Atmospheric data may be needed for a calibration, but data from a single weather balloon may have significant errors. See the section entitled Atmospheric Data. An atmospheric reference analysis may be required (ref. 17). For this analysis data from multiple balloons are collected at different locations and times. Then, these data are merged with satellite and weather map data. The resulting data are checked for consistency and are interpolated to the flight time and location of the airplane.

### **Trajectory Reconstruction**

The simplest way to reconstruct a trajectory is to use one measurement of each needed input parameter. A more complicated method that increases accuracy is to combine all available data sources and then blend them. This method assumes that each data source has some random error, and these errors cancel each other out when blended with similar data from an independent source (refs. 9–12).

Blending multiple data sources can be accomplished with a multiple-state linear Kalman filter. This filter blends data from multiple sources to estimate the minimum variance of the trajectory of the airplane. The observations and dynamics equations are selectively weighted using a matrix determined by physical intuition about the system. The linear Kalman-filter algorithm consists of prediction and correction steps. The prediction step extrapolates the measured data to the next time point using the dynamics equations. The correction step adjusts the extrapolated state using measured data at that point to give the minimum variance estimate (ref. 12).

By necessity or for a lack of resources, some aircraft have no airdata sensors. In these cases, trajectories must be reconstructed for every data flight. Such reconstruction provides a basis for inferring the airdata parameters of the airplane (ref. 13).

## **Pneumatic Lag and Attenuation**

During unsteady flight, pneumatic lag and attenuation may affect pressure measurements. Pressure variations propagate as waves through the pneumatic tubing to the pressure transducer. The wave propagation is damped by frictional attenuation along the walls of the tubing and fluid viscosity. This damping produces a magnitude attenuation and a phase lag. After the wave reaches the transducer, it is reflected back up the tube. Depending upon frequency distribution of the incoming wave energy and tubing length, the reflected wave may cancel or reinforce incoming pressure wave. If the waves cancel each other out, further spectral attenuation occurs. If the waves reinforce each other, the power of the incoming wave is amplified and resonance occurs.

The response of a pneumatic system can be approximated by a second-order model whose time response lag and natural frequency are functions of tube length, tube diameter, entrapped volume, local pressure, and local temperature (refs. 19–23). The classic treatment of pneumatic lag assumes a first-order model as well as a very large entrapped volume (refs. 1, 24, and 25). These assumptions are only valid for step pressure inputs in an overdamped system. Then, the classical lag calculations agree with the second-order calculations.

Lag and attenuation can be estimated or measured experimentally. Criteria can be set for how quickly pressure can change in the pneumatic system without affecting the airdata. Such calibration methods as the trailing cone may have very large pneumatic lags and may have to be used in steady flight.

## **SPECIAL CASES**

Airdata measurement and calibration for three special cases are discussed next. These cases are high-angle-of-attack flight, high-speed flight, and nonobtrusive sensors. The measurements and calibration techniques previously described were developed for aircraft flying at low angles of attack and low-to-moderate speeds. As aircraft envelopes expand into previously unknown regions, some of the initial assumptions made for the typical methods are no longer valid.

### **High Angle of Attack**

High-angle-of-attack flight, which is arguably above 30-degrees angle of attack, complicates the measurement and calibration of airdata (ref. 26). The typical assumption about total pressure being measured correctly without calibration may not hold. Some total pressure sensors are more suited for high-angle-of-attack flight, such as Kiel or self-aligning probes (refs. 27 and 28). Typical total temperature sensors also suffer because of the high angularity of the flow.

The characteristics of the nose of an airplane become very important at high angles of attack, and flight characteristics can be adversely affected by use of a noseboom. Wingtip-mounted booms suffer from a great deal of upwash and sidewash. A flush airdata sensing (FADS) system can be used over a large range of flow angles without disturbing the flow about the nose of an airplane. FADS systems will be discussed in more detail in a following section entitled Nonobtrusive Sensors.

At high angles of attack or in any extreme of the flight envelope, the equations being used should apply to that flight regime. Many aerodynamic equations may have simplifications that assume small angles. As a result such equations are inappropriate to high-angle-of-attack flight.

## **High Speed**

Sensor location in relation to shock waves becomes important during high-speed flight. A pitot tube located behind an airplane shock results in a total pressure measurement that is too low. Flow angle measurements can be affected by nonsymmetrical nosebooms (ref. 12). Because high-speed aircraft also tend to fly at high altitudes, where the absolute pressure is much lower than at sea level, static pressure measurements are particularly sensitive to pneumatic lag and attenuation. See an earlier section entitled Pneumatic Lag and Attenuation. The higher pressures help total pressure lag and attenuation. Particular techniques for calibrating high-speed aircraft have been previously reported (refs. 29–31).

In relation to slower aircraft, high-speed aircraft use more airspace or have shorter test times for a given airspace. These larger airspaces may present a problem when tracking with radar or other sensors with limited range. Trackers may be used in series as the airplane flies from region to region. Large test regions also require increased atmospheric analysis. For very high Mach-number flight, aerodynamic heating becomes a problem on airdata sensors. For Mach numbers greater than 10, variable gas constant and other real gas effects must be considered.

## **Nonobtrusive Sensors**

Typically, a probe sticking out of the airplane is used to measure airdata parameters. For hypersonic, stealth, and some research aircraft, having nonobtrusive airdata sensors is desirable. This requirement can be met by using a FADS system (refs. 23, and 32–35). In the future, an optical airdata system may be used.

A FADS system consists of multiple flush pressure ports. These ports are usually located on the nose of an airplane. Figure 8 shows a schematic of FADS hardware (ref. 34). These pressures can be analyzed to give such airdata parameters as Mach number, altitude, and angles of attack and sideslip. This analysis can be done by using the equations for potential flow around a sphere and by adjusting for nonpotential and nonspherical flow with calibration coefficients. One benefit of a FADS system is that it is an overdetermined system; that is, it measures more pressures than are minimally needed for the airdata state. Inaccurate pressure readings can be excluded from the calculation, thereby improving its robustness. In addition, the effect of the remaining small pressure errors on the airdata state can be minimized. Some FADS algorithms are time-recursive and iterative, further increasing robustness. Other FADS systems have been calibrated to high-angle-of-attack and to low supersonic speeds.

Another class of nonintrusive sensors in the developmental stage includes optical airdata sensors. These sensors use lasers to measure the speed, flow angles, and temperature of the air. These lasers can be shone through a flush window in the airplane.

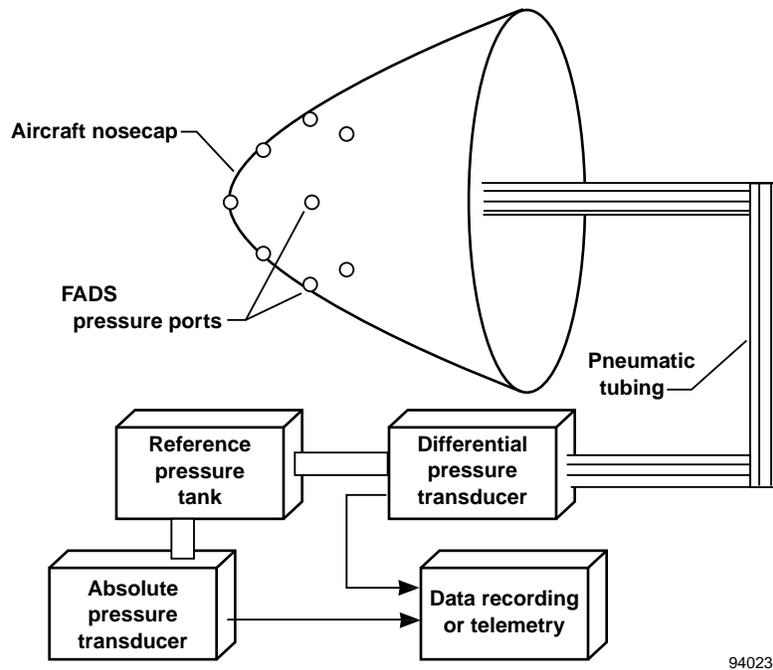


Figure 8. Flush airdata sensor hardware.

## CONCLUDING REMARKS

Airdata quantities are needed for a multitude of tasks, including flight safety, control, navigation, weapons delivery, flight test, and flight research. These quantities generally need to be measured and then calibrated to remove errors. The techniques and procedures have been only briefly described here; numerous references should be studied if airdata values are to be measured and calibrated.

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<b>13. ABSTRACT (Maximum 200 words)</b>  This memorandum provides a brief introduction to airdata measurement and calibration. Readers will learn about typical test objectives, quantities to measure, and flight maneuvers and operations for calibration. The memorandum informs readers about tower-flyby, trailing cone, pacer, radar-tracking, and dynamic airdata calibration maneuvers. Readers will also begin to understand how some data analysis considerations and special airdata cases, including high-angle-of-attack flight, high-speed flight, and nonobtrusive sensors are handled. This memorandum is not intended to be all inclusive; this paper contains extensive reference and bibliography sections.			
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