Airspeed

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One of the most important instruments on your panel is the airspeed indicator, or ASI. Do you know how it works? When was the last time you had it calibrated? Have you ever had it calibrated? For given flight conditions, do you get POH book values? If you don't get book values, then your ASI may be incorrect. Alternatively, your manifold pressure gauge, tachometer, and/or fuel flow gauge may be incorrect. All these must be accurate to insure that you get book values. However, let's talk about how the ASI works. In a second article we'll talk about how you can calibrate the ASI using a GPS receiver.

The airspeed indicator is a differential pressure instrument that depends on the pitot-static system. Remember the discussion of the pitot-static system from ground school. You do remember that, don't you? I didn't think so. If I didn't teach it, I probably wouldn't remember it either. The design of the airspeed indicator is based on Bernoulli's equation. There I go again expecting you to remember something from ground school. What's Bernoulli's equation? Well, Bernoulli's equation says that the total energy in an airflow is the sum of the potential energy due to air pressure and the kinetic energy due to motion of the air, or

$$\text{Total energy} = \text{Potential energy} + \text{Kinetic energy}$$

Translated into aircraft terms, we have

$$\text{Total or Pitot pressure} = \text{Static pressure} + \text{Dynamic pressure}$$

Let me write this as an equation

$$P_{\text{Total}} = P_{\text{Static}} + \tfrac{1}{2}\rho V^2 \tag{1}$$

where P_{Total} is the total or pitot pressure, P_{Static} is the static or local atmospheric pressure and $\tfrac{1}{2}\rho V^2$ is the dynamic pressure, with ρ the local density and V the velocity (TAS).

Now how do we get velocity out of this equation? Well, let's solve the equation for the velocity

$$V = \sqrt{\frac{2(P_{\text{Total}} - P_{\text{Static}})}{\rho}} \tag{2}$$

This result says that if we can measure the total (or pitot) pressure along with the static (or local atmospheric) pressure and know the local density, we can find the velocity of the aircraft. How do we do this?

The Bonanza, as do most light general aviation aircraft, uses a pitot-static system, with the pitot and static pressure sources located separately, as shown schematically in Figure 1. The pitot probe (tube) is located outboard on the left wing; whereas the static pressure source is comprised of two small buttons, each with three holes, located on opposite sides of the fuselage just aft of the wing trailing edge. The ASI takes the difference between the total and static pressures, mechanically (or electronically) manipulates it and displays the result as airspeed. Thus, the ASI is really just a calibrated differential pressure gauge.

But what about the density ρ? We can't measure the density directly. Furthermore, the density depends on the local atmospheric pressure and the local temperature. However, we need a value for the density to calibrate the ASI so that it gives you airspeed. In fact, the ASI is
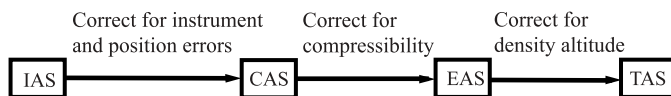
Total Pressure Port, P   **Pitot Probe**

Static Pressure Port, P_{Static}

Airspeed Indicator
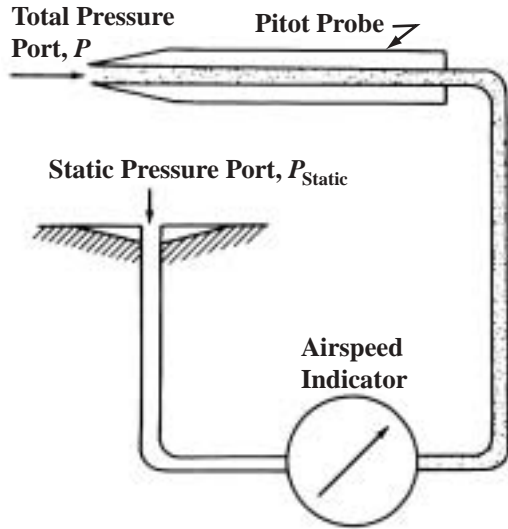
Figure 1.   Schematic of a separate pitot-static source system.

calibrated using the density at sea level on a standard day, i.e. $\rho_{\text{SSL}} = 0.002378$ slugs/cubic foot. Consequently, the ASI seldom, if ever, reads the actual velocity (TAS) of the aircraft. As a result, Equation(2) reduces to

$$V = \text{Constant}\sqrt{P_{\text{Total}} - P_{\text{Static}}} \qquad (3)$$

How do you find TAS? What does the ASI read? Figure 2 illustrates the process of correcting the number read off the ASI, called Indicated AirSpeed (IAS), to give TAS. First, no instrument reads precisely the correct value even with precisely the correct input. The difference between the actual value and the indicated value is called instrument error. In essence this is a mechanical problem. The POH assumes zero instrument error. Consequently, in Figure 2 instrument error is lumped together with position error.

Position error results from incorrect pressure values read by the pitot probe and the static ports. Except at very high angles of attack, the pitot probe is quite accurate. However, the static pressure port can be very *inaccurate*. What we want the static pressure port to measure is the atmospheric pressure well ahead of the aircraft, i.e., in what is called by aeronautical engineers the free stream. Obviously, we cannot do this directly without sticking a long probe out ahead of the airplane. Except on flight test aircraft, that is neither a good nor a practical idea. Instead, aeronautical engineers look for a position on the aircraft that gives the same static pressure reading as that in the free stream. This is not easy to do. No matter where you locate the static pressure port(s), the static pressure reading depends on the aircraft configuration and flight attitude, e.g., clean, gear down, flaps down, gear and flaps down, high angle of attack, slipping or skidding. For late model Bonanzas, the POH shows that in the clean configuration the position error is about

Correct for instrument   Correct for   Correct for
and position errors   compressibility   density altitude

IAS → CAS → EAS → TAS

Figure 2.   Corrections to IAS that yield TAS.

1%. However, with flaps extended the error jumps to about 3.5%. In each case the calibrated airspeed (CAS) is lower than the indicated airspeed (IAS). To give some idea of the importance of the static pressure port, at 100 mph it takes an error in the static pressure reading of only 0.0036 pounds per square inch to yield an error of one mph in the IAS! Incidentally, Part 23 of the FARs requires that the error, including position error, in the ASI be less than 3%, or 5 knots throughout the normal operating range.

If the airspeed is a significant fraction of the speed of sound, then compressibility effects induce an error in the pressure seen by the pitot probe. Unless you are lucky enough to fly a turbine Bonanza in the flight levels, compressibility effects are negligible. Consequently, given the Bonanza's small position error in the clean configuration, and assuming zero instrument error, it is generally safe to assume that indicated airspeed is equal to equivalent airspeed (EAS) in cruise flight. This brings us to the all important density altitude correction to get true airspeed from the equivalent airspeed.

Using Equation (2) with the actual density, ρ, gives us true airspeed (TAS), whereas using Equation (2) with the value for standard sea level density gives equivalent airspeed (EAS). Dividing Equation (2) for TAS by Equation (2) for EAS gives

$$\frac{V_{\mathrm{TAS}}}{V_{\mathrm{EAS}}} = \frac{TAS}{EAS} = \frac{\sqrt{\dfrac{2(P_{\mathrm{Total}} - P_{\mathrm{Static}})}{\rho}}}{\sqrt{\dfrac{2(P_{\mathrm{Total}} - P_{\mathrm{Static}})}{\rho_{\mathrm{SSL}}}}} = \sqrt{\frac{\rho_{\mathrm{SSL}}}{\rho}} = \sqrt{\frac{1}{\sigma}}$$

where $\sigma = \rho/\rho_{\mathrm{SSL}}$ is the ratio of the actual density to that at sea level on a standard day. Alternatively, we write this equation as

$$TAS = EAS\sqrt{\frac{\rho_{\mathrm{SSL}}}{\rho}} = \frac{EAS}{\sqrt{\sigma}} \tag{4}$$

This equation says that the TAS depends on the density, i.e., the altitude; but we already knew that, so what was the point. How do we find the actual density? I'm glad you asked. We find it indirectly. There is a relation between the pressure, the temperature and the density, called the perfect gas equation. It is

$$P = \rho\, \mathrm{R}\, T \tag{5}$$

where here R is the so called universal gas constant and T is the absolute temperature which we get by adding 460 to the temperature in degrees Fahrenheit. Now, if we rearrange this equation we can find the density, provided we know the pressure and temperature. Here we go,

$$\rho = \frac{P}{\mathrm{R}\, T} \tag{6}$$

Here, P the pressure is obtained by setting 29.92 in the Kohlsman window of the altimeter and looking the value up in a table of pressure versus altitude in the standard atmosphere (see Table 1). The absolute temperature, T, is obtained by reading the OAT gauge and adding 460 to the reading. Once we have the actual density we can find σ and hence the TAS from the EAS.

Alternatively, we substitute Equation (6) into Equation (4) and rewrite the TAS in terms of the EAS, the pressure and the temperature

$$\mathrm{TAS} = 2\,\mathrm{EAS}\,\sqrt{\frac{t + 460}{P}} \tag{7}$$

where t is the temperature in degrees Fahrenheit and P is the pressure in pounds per square foot at a given pressure altitude (see Table 1). The E-6B solves Equation (6) when used to determine the true airspeed from the equivalent airspeed.

| | Table 1 |
| Altitude | Pressure |
feet	psf
0	2116.2
500	2078.3
1,000	2040.9
2,000	1967.7
3,000	1896.7
4,000	1827.7
5,000	1760.9
6,000	1696.0
7,000	1633.1
8,000	1572.1
9,000	1512.9
10,000	1455.6
11,000	1400.0
12,000	1346.2

Now that we have all these equations, let's use them to explain a classic ASI phenomenon. We have all read the advice that if the pitot tube is blocked the ASI behaves like an altimeter. That's always seemed like the hard way to explain it. Let's use Equation (3) to explain what happens in this case.

If the pitot tube is blocked, then the pitot pressure, P_{Total}, does not change. Looking at Equation (3) if the static pressure, P_{Static}, changes, then the indicated airspeed changes. So, if the altitude increases the static pressure *decreases*, the difference between the total and static pressure *increases* and the airspeed *increases*. Conversely, if the altitude decreases the static pressure *increases*, the difference between the total and static pressure *decreases* and the airspeed *decreases*. As a practical matter, if the airspeed and the altimeter are both increasing or decreasing, then you may have a blocked pitot tube, e.g., from ice in the clouds. If this happens, use the attitude indicator to level the aircraft, confirm that the aircraft is in level flight using the altimeter and rate-of-climb indicator and turn on the pitot heat to clear the blockage.