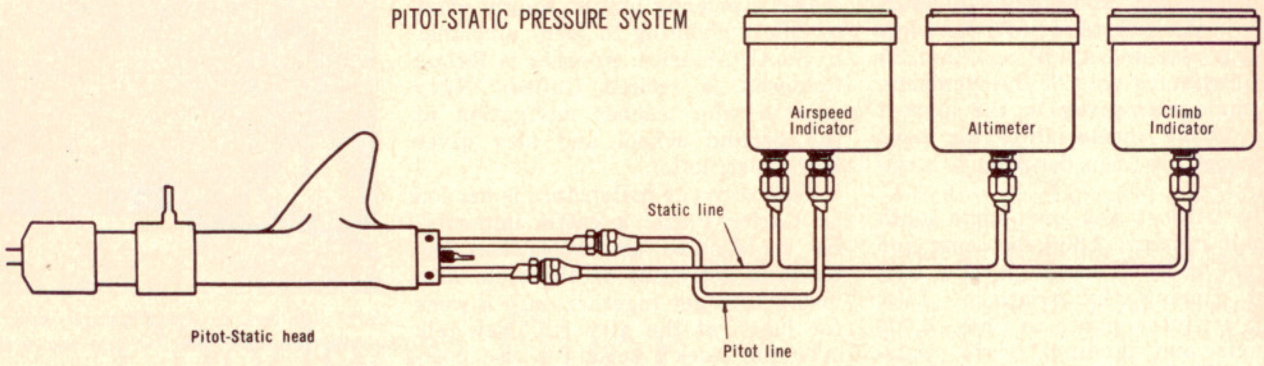


Are You A Pressure-Perplexed

Your altimeter and airspeed indicator—and perhaps your hide—depend upon a properly functioning pitot-static pressure system

"Beechcraft N3567M, Roanoke at one two, six thousand, instrument flight rules, Charleston at four seven, York, over." Just a routine position report, one of hundreds that occur daily on today's airways.

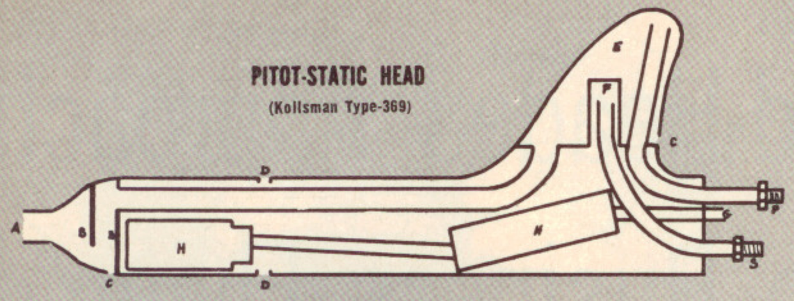
Let's hear the equally routine answer from Roanoke radio: "Roger, 3567M, Roanoke altimeter two nine eight two, over."

Yes, these reports, routine today, were unheard of 50 years ago. The progress of aviation is surely one of the most significant developments of this century. Not only has flying put the world at your doorstep with the swiftest means of going somewhere, but it likewise has developed into one of the safest means of getting there. Nevertheless, it is still a tragedy when an aircraft accident does occur. Among the most tragic accidents are those in which an aircraft strikes terrain or another aircraft for unknown reasons. Here we must speculate whether the pilot actually encountered a mechanical malfunction or whether he just strayed to an unknown position or a different altitude than he intended to attain.

More than one altimeter has been pulled from the wreckage with an erroneous setting which could have caused the accident. This is neither humorous nor entertaining. Neither will this article be humorous or entertaining. However, it will contain some of the fundamentals necessary for the proper use of flight instruments, and it behooves us, the pilots, to know the limitations of these instruments, to know what they actually tell us, and to know how to interpret this information.

We shall review the operation of two of our most basic instruments, the altimeter and the airspeed indicator, both of which operate from the aircraft's pitot-static system. This system is designed to direct two pressures. One is the static or "still air" pressure resulting from the weight of the atmosphere. The other is the total or impact pressure which is the sum of the static pressure and the additional dynamic pressure caused by the aircraft passing through or shoving against the atmosphere. Airspeed and altitude indications are dependent on accurate measurement of these two pressures. Therefore, the pilot should understand the basic fundamentals of how and why the pitot-static system operates and what are some of its limitations.

Three general types of pitot-static systems are in common use today. The simplest consists of two tubes mounted on the nose, wing or wing struts so that they are parallel to the airstream. One tube has an open end pointed directly into the airstream so that it senses the full impact pressure which is transmitted through the tube to the cockpit. The other tube has a closed end which makes it insensitive to the impact pressure. This second tube has perforations in the side through which the static pressure is exerted on the air in the tube and thus transmitted through the tube to the cockpit. The dispersion of these perforations around the tube partially compensates for small impact pressure effects caused by yawing the airplane or flying it at angles of attack where the tube is not



A. Pitot Orifice
B. Baffles
C. Drain Holes
D. Static Opening
E. Pitot Trap
F. Static Trap
G. Electrical Connector
H. Heaters
P. Pitot Pressure Connector
S. Static Pressure Connector

CAA drawings

AIRSPEED INDICATOR

ALTIMETER

CLIMB INDICATOR

Pilot?

by CAPT. JOHN G. ELLIS, JR., USAF
AOPA 44908

quite parallel to the airstream.

In aircraft intended for instrument flight a more elaborate system, incorporating both impact and static tubes in a single pitot head, is frequently used. Within this single pitot head are two separate chambers, one for static pressure and one for impact pressure. Pressure is admitted to each of these chambers through static holes in the sides of the pitot head and an impact hole is in the front much the same as the openings in the system already described. The impact and static tubes from the cockpit terminate in the pitot head with their openings protruding up into their respective chambers so that no entrapped water will get into the lines. Also, an electric heating element is installed within the pitot head to prevent condensation or freezing of moisture within the pitot head or its two chambers.

In many recent aircraft, the static pressure source has been completely separated from the pitot head. In these systems the static holes usually are located on the side or bottom of the fuselage. Some have a static source on each side with lines from each meeting in a Y-connection from which a single line continues to the cockpit. This dual source permits some compensation for pressure changes caused by yawing or erratic aircraft maneuvers. In these systems the impact pressure is still determined from a pitot head.

A pilot must recognize that his altimeter and airspeed indications can be no better than the pressure measurements he gets from his pitot-static system. Consequently, this system should be a mandatory part of his preflight check, especially before instrument operations. First and foremost, he should see that the pitot cover is removed. Then the pitot head or tubes should be checked for damage or misalignment. If they are no longer parallel to the airstream, then neither the static nor the impact pressure measurements will be correct once the aircraft is in flight. For the same reason, all static and impact holes should be checked to see that

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Pressure-Perplexed

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they are both open and clean. The pitot heater should be turned on long enough to check its operation by feeling the warmth in the pitot head.

Some aircraft are equipped with means for switching from the normal static pressure source to the cockpit itself. If this should ever be necessary the pilot should realize that cockpit pressure is frequently lower than outside air pressure because of suction created by the slipstream around the windows. This lower pressure would cause the altimeter to show a higher altitude than it actually should.

Once the limitations of the pitot-static system are understood, we should know also what the instruments can do with the pressure measurements. The altimeter is perhaps the most important pressure instrument. It is like a barometer in that it measures the static pressure of the surrounding atmosphere with a pressure sensitive element that expands or contracts with pressure changes. The typical mechanism includes a bellows isolated in an airtight compartment. Connected to the inside of the bellows is a static pressure line from the pitot-static system. The motion of the bellows as its expands or contracts is transmitted through a mechanical linkage to a dial calibrated to read altitude in feet.

Thus, the altimeter actually measures pressure, *not* altitude. Its calibration is based on an average pressure versus altitude relationship that exists under standard atmospheric conditions. Therefore, any deviation from these standard conditions will cause corresponding errors in the altimeter indication. Since these errors can be extremely large under certain circumstances a pilot should understand how they are generated and how to compensate for them. To do this he must understand the fundamentals of the pressure versus altitude relationship.

The atmospheric pressure at any altitude is caused by the weight of the air above that altitude. Standard sea level pressure is 14.72 psi (pounds per square inch) or 29.92 in Hg. (inches of mercury). At higher altitudes there is less air remaining above so the pressure is likewise less. Figure one shows the relationship between pressure, temperature and altitude under standard atmospheric conditions.

The amount of pressure change from one altitude to another depends on air density. Air is denser at low altitudes where it is compressed by higher pressures. Consequently, the air in a 1,000-foot interval will weigh more at these lower levels than it will at the less dense high levels. Therefore, the rate of pressure change from one altitude to another is greater at the lower levels. For example, from sea level to 1,000 feet the pressure change is 1.06 in. Hg., but from 9,000 to 10,000 feet the change is only 0.80 in. Hg.

STANDARD ATMOSPHERE TABLE

Altitude (ft.)	Pressure (in. Hg.)[1]	Temperature (°C.)[2]
0	29.92	15.0
1,000	28.86	13.0
2,000	27.82	11.0
3,000	26.82	9.1
4,000	25.84	7.1
5,000	24.89	5.1
6,000	23.98	3.1
7,000	23.09	1.1
8,000	22.22	−0.9
9,000	21.38	−2.8
10,000	20.57	−4.8
11,000	19.79	−6.8
12,000	19.02	−8.8
13,000	18.29	−10.8
14,000	17.57	−12.7
15,000	16.88	−14.7
20,000	13.74	−24.6
30,000	8.88	−44.4

(1) Inches of mercury
(2) Centigrade

Altimeter errors can be generated by deviations from either standard pressure or standard temperature. In areas where sea level pressure is less than standard, there is actually less air than normal. Consequently, pressures at all altitudes will be reduced accordingly. Conversely, in high pressure areas, pressures will be greater than those used for altimeter calibration.

Temperature affects air density. As shown in the accompanying table, standard sea level temperature is 15° C., and the lapse rate is approximately 2° for each 1,000 feet of altitude. [Temperature lapse rate is the decrease in temperature with altitude.—Ed.] of an air mass is cooler than this standard, it will contract and become more dense, settling closer to the earth. Thus, even though sea level pressure may be standard, a pilot will not have to climb as high to pass through the same amount of air and reach a designated flight-level pressure or indicated altitude. However, if an air mass is warmer than normal, it will expand to higher levels, and the pilot will have to climb higher to reach the same flight-level pressure.

Let's see how these factors affect a pilot who is flying at a constant indicated altitude. Since his altimeter actually measures pressure he will be flying at a constant flight-level pressure. Under standard atmospheric conditions his altimeter will indicate his true altitude above sea level. However, if he flies toward a low pressure area he will have to descend to stay at the same pressure level or indicated altitude. On the other hand, when flying toward a high pressure area, he will be climbing to maintain the same indicated altitude.

If this same pilot flies toward very cold air which has contracted and descended toward the earth, he likewise will have to descend to maintain the same indicated altitude. Conversely, he will be climbing when he flies toward warmer air which has expanded to higher levels. Obviously the most dangerous situation exists when he flies toward a low pressure area which is also cooler than standard.

An altimeter can be compensated for deviations in surface pressure by introducing an altimeter setting. This altimeter setting is a pressure measurement available at all airfields having a weather observation station. It is determined by measuring the actual barometric pressure at the field elevation and correcting this to an equivalent sea level pressure. For example, if the pressure at a field 1,000 feet above sea level is standard (28.86 in. Hg.), then the equivalent sea level pressure, or altimeter setting, is 29.92 in. Hg. However, if the field pressure is higher or lower than standard, then the altimeter setting likewise will be higher or lower than 29.92 in. Hg.

To use this setting the pilot adjusts a knob on his altimeter until the appropriate altimeter setting appears in a small opening on the altimeter face known as the Kollsman window. When altimeter settings other than 29.92 in. Hg. are used, the altimeter calibration is shifted or altered to compensate for nonstandard pressures. For example, in the second paragraph of this article, the pilot reporting over Roanoke received an altimeter setting of 29.82 in. Hg., which indicates that he was flying in a low pressure area.

Use of the correct field altimeter setting insures that a properly operating altimeter will indicate true field elevation when it is at that field. However, it does not insure precise indications at higher levels above that field. It generally improves the accuracy at higher levels, but it does not compensate for air density variations caused by nonstandard temperatures.

Nevertheless, traffic separation procedures are based on indicated altitude. *Indicated altitude is that altitude shown on the altimeter when the correct altimeter setting is used.* Thus, all pilots should fly at indicated altitudes appropriate to their heading or air traffic control instruction and should reset their altimeters to the latest local altimeter setting as their flight progresses. Then vertical separation between aircraft is assured since all aircraft in the same general area will be equally affected by any temperature errors.

Temperature errors are cumulative, for as a pilot climbs higher and higher, errors due to nonstandard temperatures at all the levels below him contribute to his total altimeter error. Conversely, the closer he descends toward the surface the less the temperature error will be. Consequently, if he uses the correct altimeter setting, a pilot can be assured of reasonably accurate altimeter indications during such critical flight phases as an instrument approach.

However, when cruising at higher altitudes, temperature errors can be significant in considering terrain clearance. For example, if the flight-level temperature at an indicated altitude of 10,000 feet is 20° C. less than standard, the pilot's actual altitude above sea level is almost 800 feet less than his indicated altitude. However, at an altitude of 2,000 feet, the same temperature deviation would cause an error of only 150 feet.

If terrain clearance is at all marginal a pilot should compute his temperature error when flying in a cold air mass. This is easily accomplished on any of the various flight computers such as the E6B. It requires rotation of a scaled dial until the observed flight-level temperature is opposite the pressure altitude. Then, true altitude appears opposite a calibrated altitude scale. The pressure altitude needed in this computation is the altitude which would be equivalent to the actual flight-level pressure under standard atmospheric conditions. In essence, it is a pressure measurement which, combined with temperature, will establish actual air density. It can be read directly from the altimeter by momentarily introducing an altimeter setting of 29.92 in. Hg. Of course, the altimeter should be reset to the appropriate local altimeter setting after the pressure altitude is determined.

(For those interested in the finer points, it might be mentioned that even this calculation does not yield an exact temperature correction since it is based on the assumption that the lapse rate below the flight level is normal. However, the error from this assumption is generally small.)

Besides the inherent pressure and temperature errors already discussed, an altimeter is subject to calibration errors caused by scale inaccuracies or failure of the pitot-static to establish the proper static pressure. Calibrated altitude is the indicated altitude corrected for these calibration errors. These errors are usually insignificant. If not, a calibration card giving appropriate corrections should be used. Also, the pilot should check his altimeter immediately before flight by using the latest altimeter setting determined from the tower. If his indicated altitude varies more than seventy-five feet from the actual field elevation, his altimeter is unreliable for operational use.

The following list of terms and their definitions will provide a summary of some of the important elements in this discussion of altitude:

Indicated Altitude — The altitude shown on the altimeter dial when the correct local altimeter setting is used.

Altimeter Setting — Actual surface pressure corrected to equivalent sea level pressure. (Its use is mandatory to avoid large errors in indicated altitude and to insure vertical traffic separation.)

Calibrated Altitude—Indicated altitude corrected for calibration errors within the altimeter or the pitot-static system.

Pressure Altitude — The altitude which would be equivalent to actual flight-level pressure under standard atmospheric conditions. (It is determined by using an altimeter setting of 29.92 in. Hg.)

True Altitude—Actual altitude above mean sea level. (It is determined by correcting calibrated altitude for density errors caused by temperature variations.)

The airspeed indicator is the second basic instrument which utilizes the pitot-static system. Instead of measuring a single pressure, the airspeed indicator is a device which measures a pressure difference. It consists of a flexible, hollow diaphragm mounted inside an airtight case. The case itself is connected to a static pressure line from the pitot-static system. An impact pressure line goes through the case to the inside of the diaphragm. Thus, the diaphragm will swell or contract according to the difference between impact and static pressures. As mentioned earlier this difference is the dynamic pressure which increases as the speed of the aircraft increases. The motion of the diaphragm which measures this pressure difference is translated through a mechanical linkage to a pointer which moves on a dial calibrated in miles per hour or knots.

However, the dynamic pressure measured by the airspeed indicator varies both with airspeed and with air density. Consequently, the airspeed indicator can be calibrated to read correctly at only one air density. The density selected is that which exists at standard sea level pressure and temperature. Therefore, the airspeed indicator is correct only when flying at standard sea level conditions.

When an airplane is flown at higher altitudes where the air is less dense, the dynamic pressure is also less. Therefore, the indicated airspeed may be substantially less than the true airspeed. At altitudes up to 10,000 feet, true airspeed normally exceeds indicated airspeed by approximately two percent for each thousand feet above sea level. A precise correction for the error due to density can be accomplished easily with any of the navigation computers by using outside air temperature and the pressure altitude in a procedure similar to that already described for altitude corrections.

This airspeed correction is important in determining the true airspeed for navigation computations. However, this is not true insofar as the control characteristics of an airplane are concerned. The lift derived by the wing passing through the air varies with dynamic pressure in much the same manner as the airspeed indication. The net result of this is that the airplane will stall at approximately the same indicated airspeed regardless of changes in altitude or air density. Likewise, the indicated airspeeds for best glide or best climb under various load conditions will remain approximately constant. Thus, for these various performance criteria, it is the true airspeeds that will vary according to altitude or air density.

Other errors in the airspeed indicator include those due to calibration or to compressibility effects. Calibration errors are caused by inaccuracies in the dial or the pitot-static system. If these are significant, appropriate corrections should be used to convert from indicated airspeed to calibrated airspeed. Equivalent airspeed is calibrated airspeed corrected for compressibility error. This error is insignificant except at high speeds. Consequently, it can be neglected in most piston engine aircraft operating at lower altitudes. True airspeed is determined by correcting equivalent airspeed for the density error already discussed. However, in most normal applications, it is sufficient to apply this density correction directly to indicated airspeed.

In summary, both the altimeter and the airspeed indicator are pressure measuring instruments. Consequently, their biggest errors are caused by variations in atmospheric conditions or by malfunctions in the pitot-static system which samples the pressures. Therefore, in order to navigate accurately and to assure safe terrain clearance and traffic separation, we, the pilots, must understand these errors and know how to compensate for them. Don't accept short-cuts which could cost you your life. END

THE AUTHOR

"Are You a Pressure-Perplexed Pilot?" is the third of a series of articles appearing in The AOPA PILOT *by Capt. John G. Ellis, Jr., an AOPA'er, designed to help you become a more proficient pilot. Ellis saw service in the Korean War as an F-86 Sabrejet pilot before he went to the Massachusetts Institute of Technology to study inertial navigation, instrumentation and control systems. At the present he is stationed at Patrick Air Force Base, Fla., where he is engaged in the missile test program. Other articles by Ellis will appear in* The PILOT *from time to time.*