Total Energy Errors Due To Air-Data Sampling

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INTRODUCTION

Accurate total energy (T.E.) compensation is important at all levels of soaring activity. It helps the low-time pilot understand the structure of thermals. Achieved rate of climb in often improved by abrupt maneuvering in thermal but this need good T.E. compensation. Finally, sailplane racing performance is critically dependent upon good T.E. information because it is the key to efficient thermal entry and efficient dolphin flying.

It is my experience that most of the total energy systems currently installed do not achieve the performance inherent in the components. This conclusion is independent of what type or brand of equipment is used. Good T.E. compensation is a real technical challenge. We need in-flight, real time measurements of the order of one-percent accuracy. This demands good equipment, good installation, good maintenance and above all—a good source of air-data.

While all of the above elements are important, this paper concentrates on the alternative sources of air-data. The purpose is to derive analytical relationships that will let us use published test data to predict the T.E. performance available with each technique.

The alternatives include:

- Fuselage pitot and static ports.
- Dedicated static pressure probe.
- Venturi T.E. probe (Braunschweig, Nicks, etc.).

USING FUSELAGE PITOT AND STATIC PORTS

Dick Johnson, and Paul Bikle before him, have been measuring and reporting to us the static systems errors in production sailplanes. If inaccurate fuselage static ports are used to derive T.E. compensation, then the T.E. will be wrong. Dick's graphs of airspeed error vs. airspeed contain all of the information we need to predict what T.E. error a pilot might see on his vario during a typical thermal entry maneuver.

A small error in velocity (ΔV) results from a small error in dynamic pressure. Since the plenum pitot measurement commonly used in sailplanes is generally quite good, we assume that all of the dynamic pressure error results from an error in static pressure measurement. The error can be expressed as:

$$(1) \quad \Delta P_S = \rho V(\Delta V)$$

Total energy rate is obtained by a process of subtraction either electronically or pneumatically to give:

$$\text{T.E. rate} = \frac{dh}{dP_S}\left[(2)\text{measured } \frac{dP_S}{dt} \text{ measured } \frac{dP_T}{dt}\right]$$

If we assume that the static pressure is in error as per equation (1), then we can show that

$$(2) \quad \text{T.E. error} = {}^{2}\left[\frac{dh}{dP_S}\right]\left[\frac{d(\Delta P_S)}{dt}\right]$$

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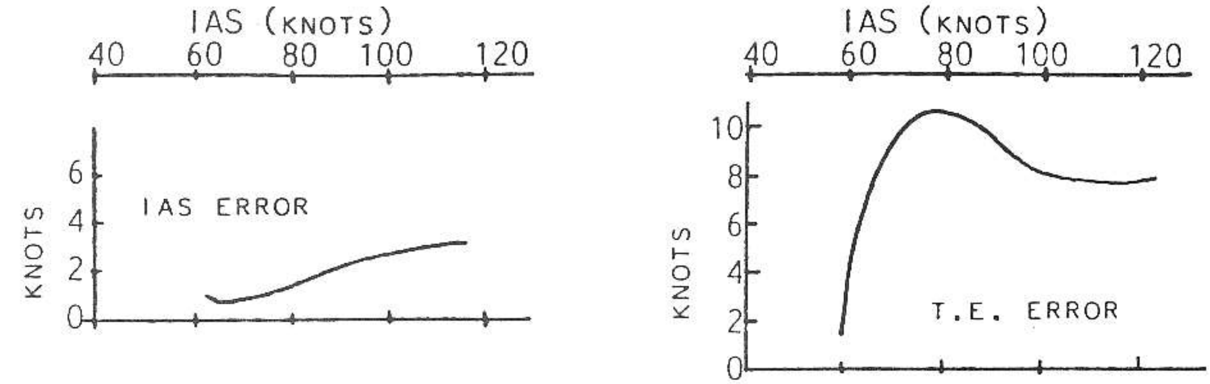

FIG. 1A ASW-20 (-9 DEGREE FLAP)

FIG. 1B PIK-20B (-8 DEGREE FLAP)

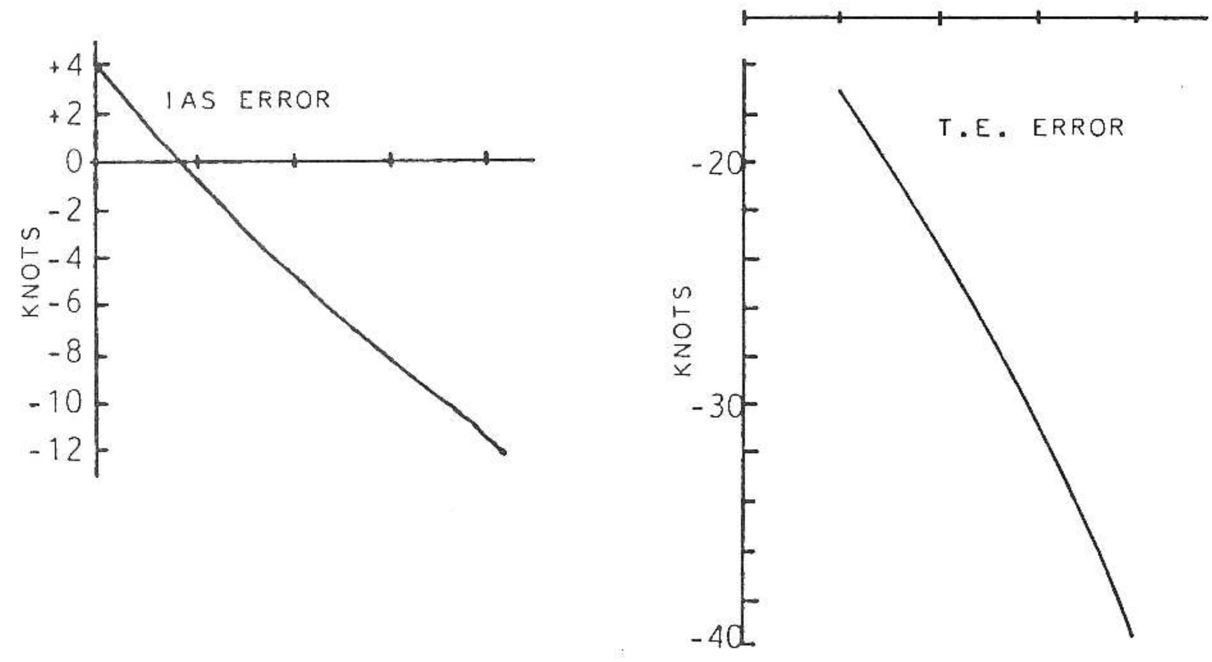

FIG. 1C MOSQUITO (-7.5 DEGREE FLAP)

FIGURE 1

If we differentiate equation (1) and substitute in equation (2) and also note that:

$$\frac{dh}{dP_S} = \frac{-1}{\rho g}$$

then we get

$$\text{T.E. error} = \frac{-2}{g}\left[\frac{dV}{dt}\right]\left[\Delta V + \frac{Vd(\Delta V)}{dV}\right]$$

In order to calculate expected T.E. errors we have to assume some expected rate of pull-up. For example, I use a constant attitude, 45° pull-up from 120 kts to 50 kts. Neglecting drag, this lets me express:

$$\frac{dV}{dt} = -g \sin 45° = -.707g$$

Then the expected error becomes:

$$\text{T.E. error} = 1.41\left[\Delta V + \frac{Vd(\Delta V)}{dV}\right]$$

Now note that: V is the velocity at any instant during the pull-up, ΔV is the error at that velocity as per Dick Johnson's graphs, and $\frac{d(\Delta V)}{dV}$ is the slope of the error curve that can also be lifted from the graph.

SOME EXAMPLES

To illustrate the magnitude of T.E. error that can occur in real sailplanes let's look at three examples. I use the AS-W 20 because it's popular and because I fly one. I use the PIK 20-B because of its well-behaved statics. Finally, the *Mosquito* shows how bad things can get.

Each ship is assumed to be cruising with full negative flaps and doing a 45° pull-up from 120 kts to 50 kts. The left-hand plot of **Figure 1** in each case replicates Johnson's published data and the right-hand curve shows the expected T.E. error.

The AS-W 20 uses a nose pitot and side static ports well behind the wing. The airspeed calibration shows errors up to about 3 kts with cruise flap settings and the maximum slope of the error curve occurs about 80 kts. As the pull-up starts from 120 kts we see an 8 kt negative error in T.E. This is mostly due to the 3 kt velocity error. At 80 kts, the velocity error is much less but its slope dominates to produce over 10 kts of T.E. error. Near the push-over at 60 kts the T.E. error decreases because the velocity is low, the velocity error is small, and the slope is near zero.

The PIK 20-B shows much less T.E. error over the same speed range because both the velocity error and its slope are small.

The *Mosquito* used side statics just behind the cockpit. The proximity of the wing probably contributes to the very large measured velocity errors. The extreme magnitude of these errors, especially at the high-speed end, results in a T.E. error of over 40 kts as the pull-up starts. Such an error would probably saturate any T.E. system to such an extent that it could not recover before the end of the pull-up. The vario would be useless.

TUNING A TOTAL ENERGY SYSTEM

There are some things we can do do to accommodate poor statics. The rather large errors shown in Figure 1 can be reduced by changing the instrument's response to total pressure relative to its response to static pressure. In the mechanical systems this is done by changing bottle size or trimming a coil of tubing to change volume on one side of the system. In the electronic instruments this is more conveniently accomplished by changing the gain of one of the amplifiers with a control potentiometer mounted on the front panel.

However it is accomplished, the result is a linear correction term that subtracts from the error an amount directly proportional to airspeed. **Figure 2** shows a "best-eyeball-fit" correction overlayed on the three error curves of Figure 1. This correction is subtracted from the error to give the best correction shown in **Figure 3**.

Tuning the T.E. in this way really changes the picture. The *Mosquito*, that had by far the greatest basic error, can be corrected (at least theoretically) to display the least error. This happens because the uncorrected error was almost linear, so a linear correction just happens to do a very good job. Looking at the other corrected error graphs of Figure 3, the PIK still looks good with a maximum error of 1.8 kts at the start of the pull-up. The AS-W 20 displays the worst max error of 4 kts midway through the pull-up. So we see that static induced errors can, in theory, be corrected—at least on some ships.

USING A DEDICATED STATIC PROBE

Instead of using the fuselage static ports, one can install a static pressure probe and dedicate it to the variometers. The static probe has to be located in the free air stream just like a venturi probe. Good mounting locations are in front of the fin, well above the fuselage between wing and tail, or in front on the nose.

Static probes have been used for years and their design is well established. Probe errors are typically proportional to dynamic pressure and a good system can be accurate to 1% at zero yaw angle.

If we assume a small error in static pressure measurement (ΔPs), we can derive the resulting error in T.E. rate. The T.E. display will show:

$$\text{measured T.E. rate} = \frac{dh}{dP_S}\left[\frac{2\,d(P_S + \Delta P_S)}{dt} - \frac{dP_T}{dt}\right]$$

Since $P_T = P_S + P_q$, this becomes:

$$\text{measured T.E. rate} = \frac{dh}{dP_S}\left[\frac{dP_S}{dt} - \frac{dPq}{dt} + \frac{2d(\Delta P_S)}{dt}\right]$$

The correct T.E. rate is simply the first two of the three terms in the brackets. The third term represents the error:

$$\text{T.E. error} = 2\,\frac{dh}{dP_S}\cdot\frac{d(\Delta P_S)}{dt}$$

Since ΔPs is proportional to dynamic pressure we can write:

$$\Delta P = \frac{R}{100}\,\frac{1}{2}\left[\rho V^2\right]$$

where R = percent error in the static probe.

Also, in the atmosphere, $\frac{dh}{dP_S} = \frac{-1}{\rho g}$ so the expected error is:

$$\text{T.E. error} = \frac{-2R}{100g}\cdot V\cdot\frac{dV}{dt}$$

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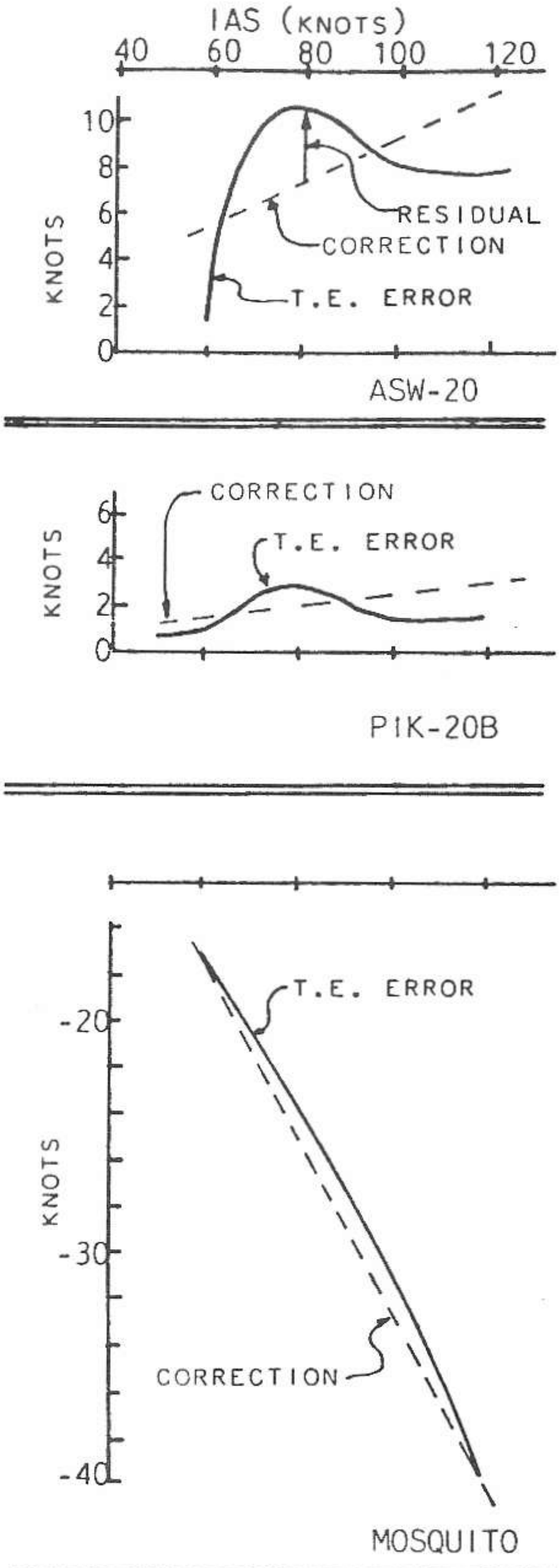


FIGURE 2
T.E. ERROR CORRECTION

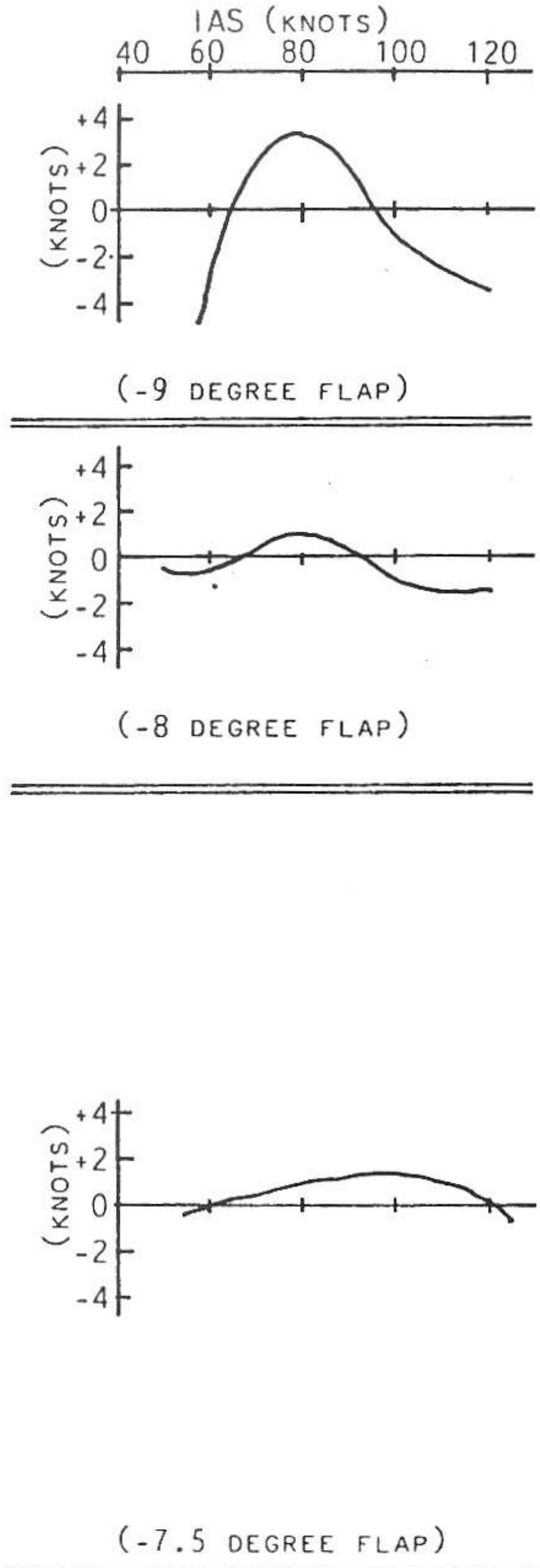


FIGURE 3
RESIDUAL T.E. ERROR

If we again use the constant angle pull-up the error will be:

$$\text{T.E. error} = \frac{2R}{100} \cdot V \cdot \sin\theta$$

Since R is typically 1% with a good probe system, the best we can expect for T.E. error during a 45° pull-up from 120 kts is:

$$\text{T.E. error} = 1.7 \text{ kts}$$

The error will be greatest at high speed (beginning of the pull-up) and will diminish toward zero at low velocities. Since the unexpected T.E. error is proportional to velocity, the tuning techniques that introduce a correction proportional to velocity should work quite well.

USING A VENTURI TOTAL ENERGY PROBE

A venturi probe (Althaus, Braunschweig, Nicks etc.) positioned to see free air flow can also provide very good T.E. compensation. These probes are designed to provide a pressure coefficient of -1.00, i.e.:

$$(1) \quad C_P = \frac{P_P - P_S}{Pq} = -1.00$$

From this we can write the probe pressure:

$$(2) \quad P_P = C_P Pq + P_S$$

If one of these probes is connected to a standard vario it will display:

$$(3) \text{ measured T.E.} = \frac{dh}{dP_S} \cdot \frac{dP_P}{dt}$$

Differentiating equation (2) and substituting into (3) we get:

$$\text{measured T.E.} = \frac{dh}{dP_S} \left[\frac{C_P dPq}{dt} + \frac{dP_S}{dt} \right]$$

Since we know that the true T.E. can be written:

$$(4) \quad \text{true T.E.} = \frac{dh}{dP_S} \left[\frac{dP_S}{dt} - \frac{dPq}{dt} \right]$$

We can subtract equation (4) from equation (3) to get:

$$\text{T.E. error} = \frac{dh}{dP_S} \frac{(C_P + 1)dPq}{dt}$$

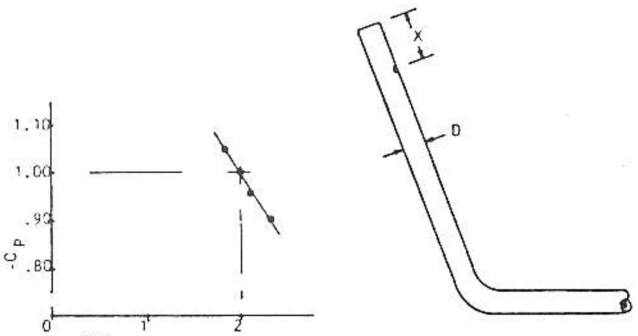
but $Pq = \frac{1}{2}\rho V^2$ and $\frac{dh}{dP_S} = \frac{-1}{\rho g}$ so

$$\text{T.E. error} = \frac{-V}{g} \cdot \frac{dV}{dt} (C_P + 1)$$

If we again assume a 45° thermal entry climb, the error is:

$$\text{T.E. error} = 0.707 \, V(C_P + 1)$$

Note that if Cp is truly -1.00, then T.E. error to zero. If C_P is constant, then the T.E. error is proportional to velocity.



NICKS TUBE CONSTRUCTION SENSITIVITY

FIG 4

From "A Simple T.E. Sensor" by Oran Nicks, *Technical Soaring* Volume IV, No. 3, we have wind tunnel data on the accuracy of a Nicks probe. He found that the most critical parameter is the location of the aft-facing hole relative to the probe tip. **Figure 4** shows how C_P varies with hole position. From this data we can derive a sensitivity to hole position:

$$(6) \ \Delta C_P = 0.27 \Delta \left[\frac{X}{D} \right]$$

Using equations (5) and (6), we can show that hole location must be accurate to within plus or minus 0.017 inch to maintain T.E. error within 1% of velocity or 1.2 kts during our 45° pull-up. (Note: some more recent work by Bill Wells, *Soaring* Nov. '77, indicates that tip chamfer may be as critical as hole position. More data is needed to evaluate this relationship.)

CONCLUSIONS

We have examined the alternative sources of air data available for T.E. compensation. Using published aerodynamic test data, the following conclusions can be drawn:

1. Fuselage statics range from poor to terrible for T.E. compensation.
   - Tuning corrections are generally needed but are not always adequate.
   - Phase errors between pitot and static circuits must be eliminated.
2. A static probe should give acceptable T.E. compensation.
   - Errors are much smaller than fuselage statics.
   - Errors are proportional to velocity so tuning should work well.
   - Phase errors must still be eliminated.
3. It appears from available data that a Nicks probe should give acceptable T.E. compensation.
   - The required manufacturing accuracy is reasonable.
   - There is no possibility of phase errors.
   - A less expensive variometer is required.
   - A gust filter should be used with any venturi probe.
   - If tuning is required it is more difficult than with the pitot/static compensators.
4. Final glide calculators require good pitot and static pressure measurements. A venturi is not sufficient so you have to solve the static problem. A dedicated static probe is probably the most practical solution.