The Total Energy Variometer in the Flowfield of Thermals

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Abstract

According to its physical working principle the TE variometer indicates additional signals which are caused by the horizontal components of the flow field of thermals. The interpretation of the readings will support the decision when to initiate a turn or to determine the direction of an appropriate displacement in circling flight.

Notation

E	total energy
g	acceleration due to gravity
H	altitude
m	mass
P_{stat}	static pressure
P_{TE}	total pressure
s	distance
t	time
v	airspeed
V	speed (inertial system)
ρ	air density
$\frac{1}{2}\rho v^2$	dynamic pressure

Subscripts

GPS	global positioning system
TE	total energy

Introduction

The classic variometer exclusively uses pressure variations to indicate the rate of climb and rate of descent of a glider. However this type of variometer also indicates variations of altitude caused by control manoeuvres by the pilot. In order to avoid this effect, the total energy variometer was developed. The idea is to indicate only variations of the total energy, not the exchange of kinetic energy (speed) and potential energy (altitude).

The total energy E of a glider is determined by:

$$E = \frac{1}{2} m V^2 + m g H \qquad (1)$$

Usually the total energy pressure P_{TE} is measured, where

$$P_{TE} = \frac{1}{2} \rho v^2 - P_{stat} \qquad (2)$$

Consequently any variation in the airspeed v, and therefore of the dynamic pressure $\frac{1}{2} \rho v^2$, results in a variation of the TE variometer reading. In the vicinity of a thermal there are horizontal flows which systematically influence the measurement of the airspeed v and therefore also the TE variometer reading.

Horizontal Wind Gusts

Although $v = V$ is used in a number of applications, the airspeed v is generally not identical to the speed V of the glider, which is defined in an inertial system. Air is often not in a homogenous state but can be subjected to forces that accelerate or decelerate it. A non-homogenous wind field caused by wind gusts or, more generally, by sudden variations in the wind field results in sudden variations of the airspeed v, which is determined via the dynamic pressure.

This means that the airspeed indicator and the TE variometer are influenced by gusts that have a component parallel to the flight path (horizontal gusts). Thus, when the glider crosses horizontal gusts, the TE variometer indicates rates of climb or descent that are not true rates and therefore undesirable. Even if a horizontal gust causes an acceleration or deceleration of the glider until it achieves a new equilibrium of forces, such speed variations will occur extremely slowly because the drag of modern gliders is very small. Consequently a glider can be considered as an inertial platform which, as long as there are no control inputs, moves constantly in the direction of the flight path without any speed variation. Thus, for some glider applications an inertial measuring system would be preferable, e.g. GPS based instruments that have high sampling rates.

At the present time, the following approach regarding this problem is taken: since wind gusts are normally short term phenomenon, over a long period their effects will tend to cancel. On the other hand, speed variations of the glider due to control inputs introduce long term effects. Consequently an appropriate damping of the airspeed variation signal would lessen any short term variations. In current TE variometers, however, this causes an undesired attenuation of the altitude variation signal and, thus, a damping of the TE variometer reading. The setting of the amount of damping depends on individual experience and habit. A high attenuation rate is advantageous during straight flight, in particular if there is a lot of turbulence, whereas a low attenuation rate is recommended while thermalling.

The Wind Field Inside and in the Vicinity of a Thermal

A detailed analysis of the flow induced by a thermal can be performed by applying a model which describes the flow of a vortex ring (Woodward[1]). There are also measurements of the flow field of a thermal (e.g. Konovalov[2]). The rate of climb in the centre of a thermal depends on the environmental lapse rate. Generally there is acceleration in the lower region of the convection space, with slight variations in the intermediate region and a deceleration in the upper region. In the lower region of the convection space:

- there is an acceleration of the vertical flow;
- the diameter of the thermal increases thus enabling spiraling;
- the ascending air is replaced by air from lower and surrounding regions;
- there is a flow converging towards the centre of the thermal (inflow).

In the intermediate region of the convection space:

- there may be further acceleration of the vertical flow (depending on the temperature gradient);
- there is a further increase in the diameter of the thermal, i.e. there is an increasing amount of ascending air;
- the additional ascending air is delivered by a flow converging towards the centre of the thermal (inflow).

In the upper region of the convection space:

- there may be a further acceleration of the vertical flow under the cloud base and inside the cloud;
- the thermal decelerates upon approaching a stable region;
- the decelerated air diverges horizontally from the centre of the thermal (outflow).

When a glider approaches the centre of a thermal there is tail wind due to inflow conditions at low and intermediate altitudes, and a head wind due to outflow conditions at higher altitudes. Although the speed of the horizontal flow is rather low, it is, more or less, constant. Calculations show that the horizontal flow near the border of a thermal may reach 20% of the speed of the ascending air.

The following calculation shows the influence of such horizontal flows on the TE variometer reading. According to the concept of the TE variometer the sum of kinetic and potential energy is determined by

$$m\,g\,H + \tfrac{1}{2}\,m\,v^2 = \text{constant}$$

that is,

$$g\,dH/dt + v\,dv/dt = 0. \qquad (3)$$

According to this relation an airspeed variation dv/dt causes the indication of an altitude variation dH/dt, such that

$$dH/dt = -1/g\; v\; dv/dt.$$

For example, as shown in Fig. 2, glider in level flight having an airspeed of v = 25 m/s (90 km/h) crosses a wind gust that causes a linear increase in airspeed of dv = 1 m/s over a distance of ds = 100 m, such that the airspeed is v + dv = 26 m/s (93.6 km/h). The airspeed decreases subsequently, again linearly over a distance of 100 m, to the initial value v = 25 m/s.

The time dt related to the distance ds is ds/v = 4 sec. An airspeed input according to Fig. 2 affects a TE variometer reading as shown in Fig. 3.

$$dH/dt = -1/g\; v\; dv/dt = 0.63 \text{ m/s}.$$

If the horizontal gust is crossed at higher speeds, the TE variometer reading increases e.g. dH/dt = 1 m/s at an airspeed v = 113 km/h and dH/dt = 1.5 m/s at an airspeed v = 140 m/s.

Flight Through a Thermal at Low Altitude (Inflow)

The next examples refer to a TE netto variometer, i.e. the glider specific descent rate which is related to the speed of the glider is added to the TE variometer signal. Such a TE netto variometer would, independently of the speed, indicate zero if the air is calm.

During flight through a thermal at low altitude, the inflow conditions cause a reduction in airspeed until the centre of the thermal is reached and an increase in airspeed when the glider departs from the centre of the thermal. According to the example calculation, it is assumed that the horizontal flow at the border of the thermal is 1 m/s. Crossing the thermal with a constant pitch attitude, results in a variation of the airspeed as disclosed in Fig. 4. Figure 5 shows the additional signal of the TE variometer that results from the airspeed variation during the flight through the thermal. The assumed distribution of the vertical flow of the thermal corresponds to the model as given by Woodward[1], see Fig. 6. The curve shows the distribution of vertical flow over a cross section taken through the centre of a thermal. This is the distribution that would be indicated by a fast uncompensated netto variometer. This distribution is compared to that of a TE variometer whose signal also includes the airspeed variation, see Fig. 5. Modern systems provide the possibility of setting the time constant to a desired value in order to damp the signal. Figure 6 also shows an example of a damped signal.

In order to make a proper decision concerning the initiation of a turn and the sense of rotation such that the first circle is as close as possible to the centre of the thermal, the pilot carefully observes the TE variometer reading. As the glider approaches the edge of the thermal, a descent rate is indicated which is greater than the actual descent rate. On the other hand, near the centre of the thermal, a climb rate is indicated that is higher than the actual rate. Near the edge of the thermal there is a rapid increase of the indicated signal. Even if the TE variometer reading is changed by the horizontal flow towards the thermal (inflow), however, the characteristics of the curve remain substantially identical (Fig. 6). Thus, the decision to initiate a turn can directly be based on the TE variometer reading. The well known rules concerning the initiation and the displacement of a turn can thus be successfully applied in the lower and intermediate region of a thermal, i.e. if there are inflow conditions.

Flight Through a Thermal at High Altitude (outflow)

During a flight through a thermal near the upper part of the convection region, there is a variation in the airspeed reading as shown in Fig. 7. The increasing airspeed during the approach of the thermal and the decreasing airspeed inside the thermal result from the diverging horizontal flow in the upper part of the thermal (outflow). Figure 8 discloses the signal which corresponds to the airspeed variation shown in Fig. 7 and which is an additional input for the TE variometer. Figure 9 shows the distribution of the vertical flow and its superposition with the additional signal resulting from the outflow (Fig. 8). It is evident that the best point of time to initiate a turn is not very well defined. The TE variometer indicates a positive value before the edge of the thermal has been reached. Near this edge, the signal rapidly decreases, and inside the thermal the TE variometer indicates a value which is lower than the actual climb rate.

Consequently the following aspects should be taken into account in order to properly decide when to initiate a turn:

If the TE variometer indicates low climb rates but no vertical accelerations can be sensed by the pilot, then the edge of the thermal has not yet been reached and the initiation of a turn is not recommended.

Strong horizontal wind gusts may produce a promising TE variometer reading that can mislead the pilot into initiating a turn. In this case, however, the positive reading does not remain and will disappear after less than 90° of rotation. In this case, it is advisable not to continue the initiated turn, but to return to the original flight direction. If the initiated turn is completed, the loss of time and altitude is greater than if the turn is aborted.

Measurements During Flight

Figure 10 displays the measured airspeed of a glider and the TE variometer reading as a function of time. The airspeed curve shows short term variations that are caused by small amounts of turbulence. In addition, there are variations of medium size that do not represent accelerations or decelerations of the glider (a pilot would be able to sense the corresponding forces; moreover there would be notable aerodynamic losses). Obviously, these variations of medium size result from horizontal flows which can be recognized both in the airspeed signal and the TE variometer signal.

Circling Offset From the Centre of a Thermal

After a turn has been initiated to start circling, at least the first circle is usually offset from the centre of the thermal. Thus, the TE variometer reading is used to determine the direction of displacement of the circle in order to approach the centre of the thermal. However, in this case horizontal flows (inflow or outflow) in the vicinity of the thermal also influence the reading of the TE variometer.

Figure 11 shows an example of such a configuration. There is an offset of 100 m between the centre of the thermal and the centre of the circle of the glider. The radius of the circle is about 80 m. A 360° turn takes 20 seconds at a speed of 25 m/s (90 km/h) and a bank angle of 39 degrees.

The reference numbers 0 and 2 (Fig. 11) represent the two points of the circle where the radial horizontal flow of the thermal is at 90° to the local flight direction. Consequently the airspeed signal and the TE variometer signal are not influenced by inflow or outflow at these points.

Inflow

The airspeed indication during circling is shown in Fig. 12. This airspeed variation is caused by the converging flows towards the centre of the thermal (inflow). This airspeed variation affects an additional input for the TE variometer, as shown in Fig. 13. Figure 14 shows the vertical speed of the air over the circle (0-1-2-3) offset from the centre of the thermal. In addition, the corresponding TE variometer reading, which includes the input of the airspeed variation, is shown in Fig. 14. The location of the centre of the thermal corresponds very well with the TE signal. The maximum of the TE curve is near the centre of the thermal (cf. reference sign 2), whereas the minimum of the curve corresponds to the point where the glider is at a maximum distance from the centre of the thermal (cf. reference sign 0). It is therefore appropriate to displace the circle towards said maximum (best heading rule) or away from the minimum (worst heading rule), which is well known to and usually applied by glider pilots. Furthermore, according to Fig. 14 there is also the possibility to react immediately upon a strong and continuous increase of the TE variometer (best gradient rule).

Hence, displacement manoeuvres are frequently successful if there are inflow conditions, even at rather low altitude when the diameter of a thermal is small. Moreover, the displacement manoeuvres towards the centre of the thermal are supported by the converging flows.

Outflow

Figure 15 shows the airspeed signal during circling. The airspeed variation is caused by flows diverging from the centre of the thermal (outflow) and causes an additional input for the TE variometer as indicated in Fig. 16.

Again, Fig. 17 shows the vertical speed of the air over the circle (0-1-2-3) offset from the centre of the thermal, the TE variometer reading over this circle including the input of the airspeed variation and the corresponding reading of a lightly damped variometer. A TE variometer signal having the characteristics of Fig. 17 does not produce a unique indication of the centre of the thermal. There is no unique maximum and no unique minimum. The well known procedures to displace the circle towards the maximum (best heading rule) or away from the minimum (worst heading rule) are not appropriate to identify the centre of the thermal. The best way to solve this problem is to take advantage of the rapid increase in the TE signal which is indicated when the glider crosses the edge of the thermal, as indicated by point 1 in Fig. 11. Once having passed point 0 of the circle the glider approaches the centre of the thermal.

According to outflow conditions there is an increasing head wind which causes the TE variometer to indicate an increasing signal already before the glider reaches the ascending air of the thermal. This is the indication that the glider is approaching the centre of the outflow more and more and, thus, the centre of the thermal. When the glider enters the ascending air (cf. reference sign 1) the TE variometer signal further increases. The corresponding vertical acceleration should be perceptible to the pilot.

The head wind reaches its maximum between reference numerals 1 and 2 (see Fig. 15). This maximum corresponds to a first maximum of the TE variometer signal which, however, does not indicate the centre of the thermal (see Fig. 17). Consequently, the following rule is recommended in order to displace a circle towards the centre of a thermal: a rapid increase in the TE variometer signal and the (probably) non-delayed perceptible vertical acceleration announce the approaching of the centre of the thermal. At this point the turn rate of the glider should be immediately reduced. In order to effect a displacement of the circle by approximately half of its diameter, the original turn rate should be recovered after 3-4 seconds.

During the subsequent 360° circle the turn rate is to be kept constant, and the TE variometer reading and the vertical acceleration are observed. Afterwards, the procedure to displace the circle may be repeated upon a further rapid increase of the TE variometer signal. The damping rate of the TE variometer can be set to low.

Concluding Remarks

According to its physical working principle, the TE variometer indicates additional signals that are caused by inflow at lower and intermediate altitudes and outflow in the upper part of a thermal. If there are inflow conditions all known procedures (best heading rule, worst heading rule, best gradient rule) to displace a circle towards the centre of the thermal are supported by the TE variometer reading. However, if there are outflow conditions the maximum and the minimum of the vertical movement of the air is not correctly indicated. In this case both the best heading rule and the worst heading rule are not appropriate, but initiating a displacement of the circle upon a strong and continuous increase of the TE variometer reading (best gradient rule) is the only way to successfully displace a circle towards the centre of the thermal.

References

[1]Woodward, B., "A Theory of Thermal Soaring," *OSTIV Publication IV*, July 1959.

[2]Konovalov, D. A., "On the Structure of Thermals," *OSTIV Publication XI*, 1970.

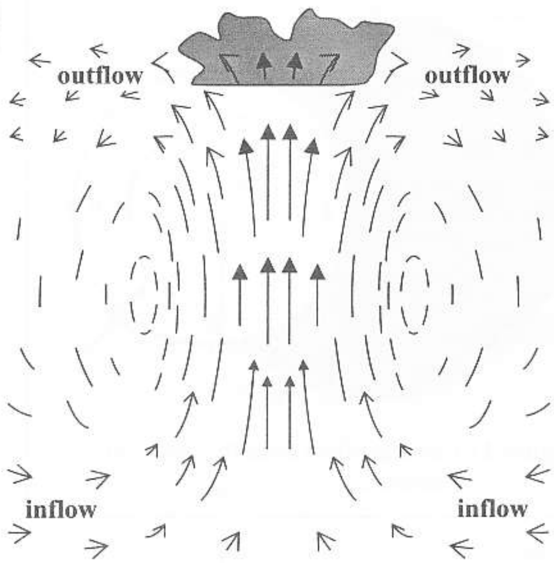

Figure 1 Inflow and outflow in the flow field of a thermal.

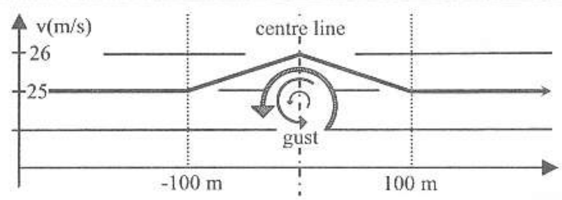

Figure 2 Airspeed changes through a horizontal wind gust.

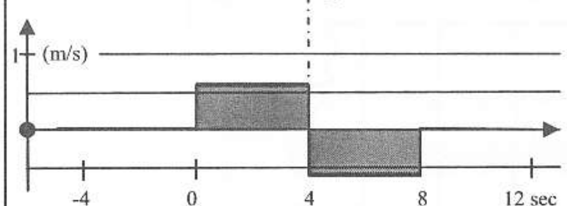

Figure 3 Additional TE variometer signal.

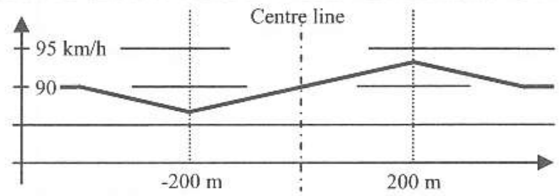

Figure 4 Flight through a thermal, airspeed at inflow (left to right).

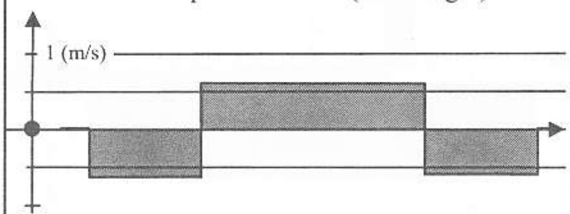

Figure 5 Additional TE vario signal at inflow.

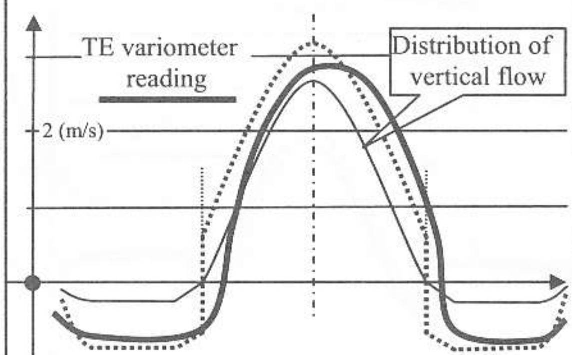

Figure 6 Distribution of the vertical flow and TE variometer reading at inflow.

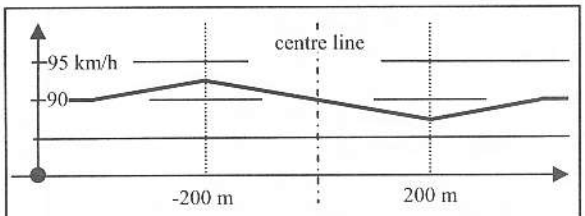

Figure 7 Flight through a thermal, speed at outflow.

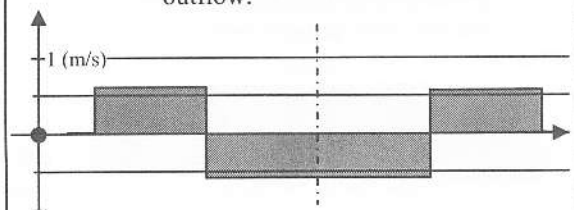

Figure 8 Additional TE variometer signal at outflow.

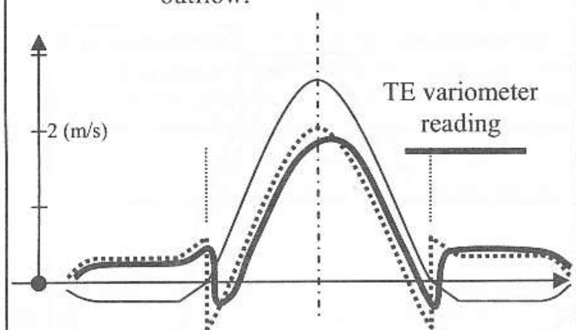

Figure 9 Distribution of the vertical flow and TE variometer reading at outflow.

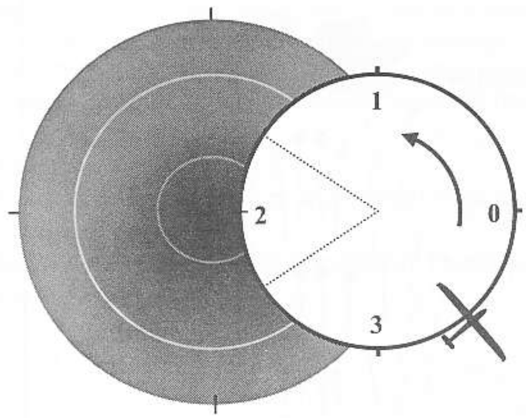

Figure 11 Circling offset from the centre of a thermal.

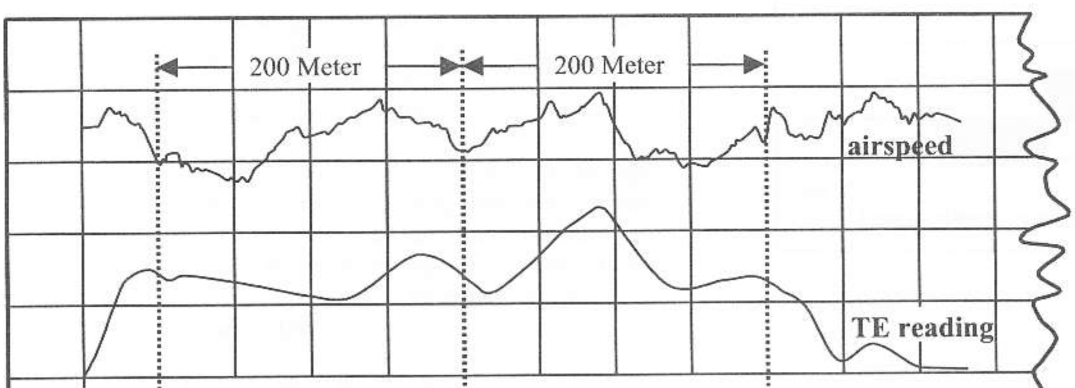

Figure 10 Measurements during flight, airspeed and TE variometer signal.

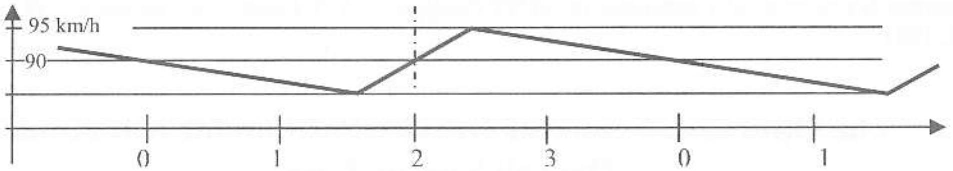

Figure 12 Circling offset from the centre of a thermal, speed at inflow.

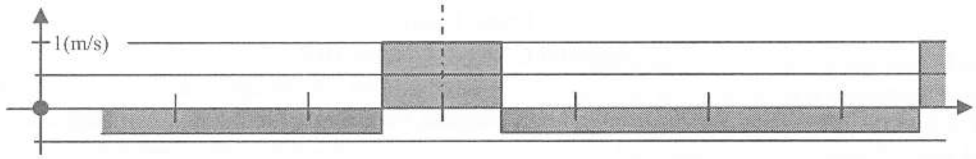

Figure 13 Additional TE variometer signal at inflow.

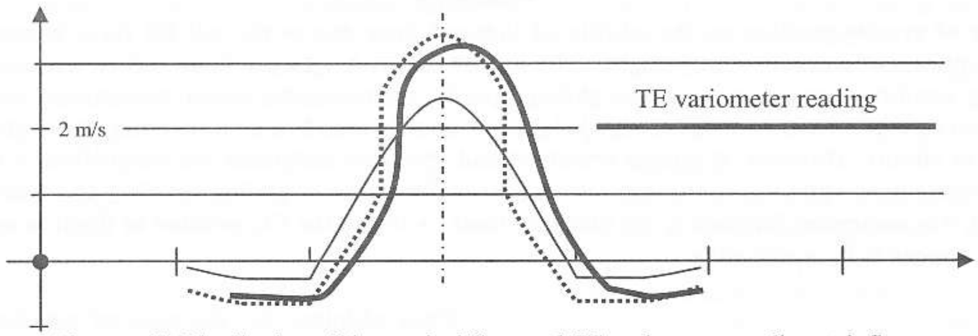

Figure 14 Distribution of the vertical flow and TE variometer reading at inflow.

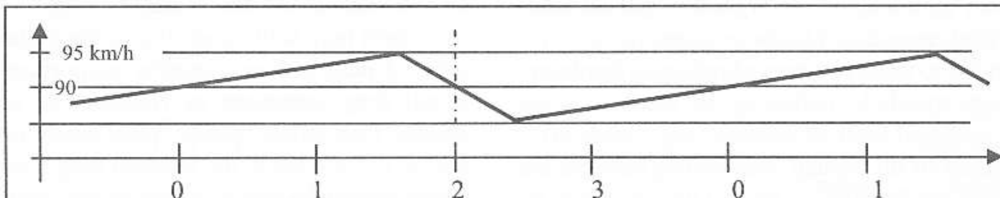

Figure 15 Circling offset from the centre of a thermal, speed at outflow.

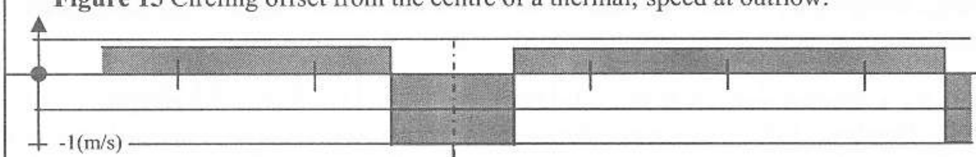

Figure 16 Additional TE variometer signal at outflow.

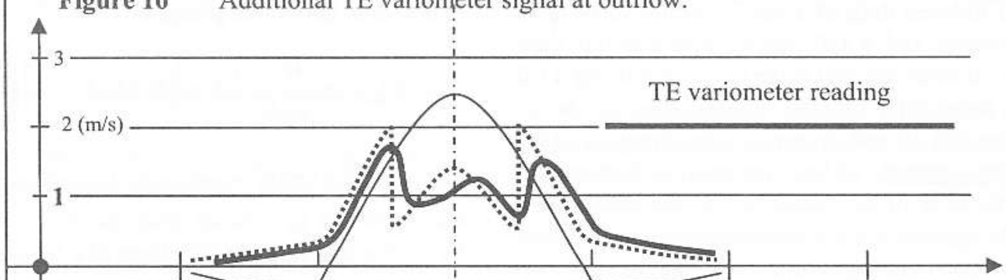

Figure 17 Distribution of the vertical flow and TE variometer reading at outflow.