ALTITUDE EFFECT ON VARIOMETERS

F. G. IRVING

Department of Aeronautics
Imperial College of Science and Technology
London, England

Presented at the 14th OSTIV Congress
Waikerie, Australia 1974

Theory shows that mechanical variometers should indicate something close to the true vertical velocity of the aircraft at all heights (e.g. Refs. 1 and 2). Any errors are due to variations in the viscosity of the air at the internal leak or to temperature differences between the air passing through the leak and the air of the outside atmosphere. These effects could also lead to differing calibrations for climb and descent, since the state of the air flowing in from the atmosphere during a descent is not necessarily the same as that of the air flowing out from the capacity during a climb, other things being equal. However, these effects can be minimized by suitable design and, for all practical purposes, a modern aeroplane rate-of-climb indicator may be assumed to show true vertical velocities in a standard atmosphere. Laboratory calibrations of PZL sailplane variometers also show similar characteristics, although the laboratory conditions do not reproduce the proper atmospheric parameters. For the present purposes, it will be assumed that mechanical variometers do indeed show true vertical velocities assuming, of course, accurate calibration at sea-level.

Consider the case of a pilot regulating his inter-thermal cruising speed by reference to a MacCready ring attached to a mechanical variometer. He rotates the ring until its datum is opposite the figure corresponding to his mean rate of climb - a somewhat elusive quantity in real life - and then flies so that the speed which appears on the ring opposite the variometer pointer corresponds to his ASI. The theory is too well-known to require repetition here. For the present purposes, we will ignore the sundry variations on this simple theme and will assume still air between the thermals.

The usual MacCready construction is correct at any altitude provided that either (a) all speeds, in both the forward and vertical directions are "true" or (b) all speeds are equivalent. As George Burton (Ref.3) has pointed out, errors can occur when flying at altitude because the pilot is presented with two sets of data which, in general, do not satisfy either of the above conditions: the variometer displays "true" vertical speeds whilst the airspeed indicator, subject to various possible errors which we will ignore, displays "equivalent" speeds. The MacCready construction and the consequential variometer ring calibration are usually carried out by reference to a sailplane performance polar expressed in terms of "equivalent" speeds. If Reynolds number effects are neglected, such a polar will be applicable at all heights. That is to say, the forward speed and rate of sink corresponding to a particular point on the polar will be the same at all heights provided "equivalent" speeds are understood. At any particular height, the "true" values can be obtained by dividing the "equivalent" values by $\sqrt{\sigma}$, where σ is the local relative density of the air.

It therefore follows that only under standard sea-level conditions, when true and equivalent speeds are the same, will the variometer and ASI provide compatible sets of information, permitting accurate use of the MacCready ring.

If one wishes to deal in terms of true vertical speeds at any height other than sea-level, the MacCready construction should strictly be carried out in conjunction with a polar plotted in terms of true speeds. Having derived optimum inter-thermal speeds, these should then be converted back into equivalent airspeeds so as to be usable by the pilot. In effect, a series of different ring calibrations are required for different altitudes.

So far, this has not been done and, as George Burton has observed, the use of a "sea-level" MacCready ring leads to excessive inter-thermal speeds if the altitude is appreciable. There are two additive effects:

(a) The pilot sets the ring datum to too high a value - the true rate of climb as opposed to the equivalent rate of climb. This causes the airspeed figure opposite a given sink indication of the variometer to be too high.

(b) When gliding, the variometer indicates true rate of sink and since this is greater than the corresponding equivalent value, there is an additional increment to the "optimum" gliding speed displayed opposite the pointer.

Consider, by way of example, a typical Standard-Class sailplane operating at a mean height of 3000 m (9840 ft). Suppose that the mean true rate of climb is 3 m/s (5.82 knots). The equivalent rate of climb is then 2.58 m/s (5.02 knots), the optimum inter-thermal speed is 143 km/h (77.3 knots) EAS and the corresponding average speed is 87.2 km/h (47.0 knots) EAS.

If the pilot sets the MacCready ring to 3 m/s, effect (a) above is due to his using this value for the datum setting instead of the equivalent value of 2.58 m/s. However the overall speed error is determined by finding the speed at which he must fly in order to cause his ASI reading to coincide with that displayed on the MacCready ring opposite the variometer pointer, remembering that the ring is incorrectly set and the variometer is showing true rate of sink. The calculation is fairly lengthy, but the outcome would be that he flies at 154 km/h (83 knots) EAS. He is, therefore, flying 11 km/h too fast. Further analysis shows that effects (a) and (b) make roughly equal contributions to the overall error. As noted in Ref. 4, trying to assess the effect of an error in inter-thermal speed of this magnitude on the average speed is best done by calculation rather than by construction. Using the expression of Ref. 4, the deficit in average speed is 0.52 km/h (0.28 knots) EAS or 0.61 km/h (0.33 knots) true airspeed.

It may be felt that this not very significant: it is, after all, a deficit of only 0.6% and serves to demonstrate that errors in inter-thermal speed have only a second-order effect on the average speed. However, such errors could affect the pilot's placing in a Championship but, even more important, is the fact that the pilot in the non-optimum situation has to work significantly harder than the pilot who pursues the optimum flight plan. With the optimum inter-thermal speed of 143 km/h, the glide angle will be 1 in 23.9; with the incorrect speed of 154 km/h, it will be reduced to 1 in 21.3. This has two effects: the chances of finding the "next" thermal are reduced and the pilot has to spend more time in thermals. In the former case, he would spend 39% of the total flight time in thermals, in the latter case, 44%. Over a 300 km flight under the assumed conditions, the non-optimum pilot would spend an extra 8½ minutes in thermals, gaining an unnecessary 1530 m (5020 ft). So although the effect on average speed is not great, it is clear that the efficiency of the flight is appreciably diminished. As Anthony Edwards (Ref.5) has noted, it pays to glide too slowly rather than too fast. In the case considered here, the same small loss in average speed would occur if the pilot flew at 132 km/h (71 knots) EAS between the thermals (i.e. 11 km/h too slowly) but the glide angle would now be 1 in 27.6. Only 34% of the flight time would be spent climbing and, furthermore, there would be less worry about finding the next thermal.

To summarize: if the pilot, flying at some appreciable mean altitude, follows the indications of a MacCready ring calibrated for sea-level, he will tend to fly too fast. The effect on average speed will be small, but the pilot will have to climb further than is strictly necessary.

As indicated above, one way of avoiding this situation is by having various MacCready ring calibrations for different mean altitudes. This effectively involves expanding the scale relative to the datum mark by a factor $1/\sqrt{\sigma}$, where σ is the relative density appropriate to the height under consideration. That is to say, if the angular distance between the datum mark and a particular speed indication on a sea-level ring is θ^o, the same speed indication will need to be shifted to $\theta/\sqrt{\sigma}$ at altitude. This could be displayed by means of a series of scales engraved on a transparent plastic disc superimposed on the variometer dial and attached to the usual ring, as shown in Fig. 1. Another method is shown in Fig. 2.

A more elegant and less confusing solution would be to have a variometer which displayed equivalent vertical speeds directly. In principle, one could devise a mechanical variometer in which the leak was varied by an altimeter capsule so as to give the correct calibration in a standard atmosphere. No doubt such an instrument would be very expensive and the electric variometer seems to offer better possibilities.

The behaviour of an electric variometer, so far as the effects of altitude are concerned, is quite different from that of a mechanical variometer. A very rough calculation, based on Ref. 6, suggests that a likely relationship at a height where the relative density in a standard atmosphere is σ would be of the form

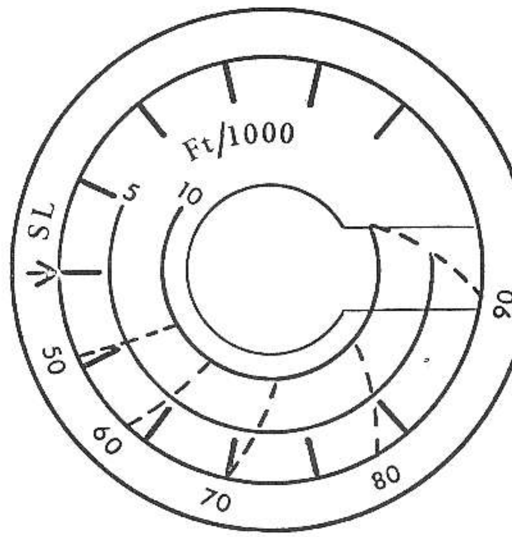

FIGURE 1. A modified MacCready ring calibrated for heights of sea-level, 5,000 ft and 10,000 ft. The markings are on a clear plastic disc attached to the usual verge ring. Variometer details have been omitted for clarity. Speeds are in knots and the calibration applies to the maker's polar for the "Standard Libelle."

FIGURE 2. Perhaps a more practical arrangement. The inner edge of the verge ring is calibrated for sea-level, the outer edge for 10,000 ft. Approximate interpolation for other heights should be good enough. The calibration is for the "Standard Libelle."

$$(dH/dt)_{indicated} = (dH/dt)_{true} \times \sigma^{\eta} \quad (1)$$

where η is of the order 0.8.

Laboratory calibrations of Crossfell and Burton instruments (Refs. 7 and 8) have presented some difficulty and have given values of n between 1.0 and 1.3. In these particular tests, no attempt was made to simulate the pressure/temperature characteristics of the atmosphere and it is, therefore, not clear to what extent, in practice, the effects of altitude are related to density and air temperature respectively. Moreover, these effects may differ from one type of instrument to another. Clearly, further experiments are required both in the laboratory and in flight. The latter would be expensive in the U.K., due to the high tows required to produce reliable results.

At all events, it appears that the index n in the above expression exceeds 0.5 and hence, at altitude, the electric variometer gives an indication which is less than the equivalent vertical velocity. Compared with the mechanical variometer, the converse situation will now prevail if the pilot uses an electric variometer in conjunction with a MacCready ring calibrated for sea-level: he will tend to fly too slowly between thermals. This, as demonstrated above, is not likely to have a large effect on average speed and the pilot has a rather less wearisome flight than those following the indications of a mechanical variometer. However, it would be pleasant to be presented with the proper data if possible.

We would like the variometer to display

$$(dH/dt)_{equiv} = (dH/dt)_{true} \times \sigma^{\frac{1}{2}} . \quad (2)$$

This could be obtained by scaling the output of the sensing unit by a factor $\sigma^{(0.5-\eta)}$. Approximately, in the Standard Atmosphere,

$$T/T_o = \sigma^{0.24}, \quad (3)$$

so the above factor may also be written

$$(T/T_o)^{(0.5-\eta)/0.24} \text{ or,}$$

in round figures,

$$(T/T_o)^{(2-4\eta)} .$$

If $\eta = 1$, this becomes $(T_o/T)^2$.

A possible arrangement, therefore, consists of sensing the air temperature by means of a thermistor. The output from the temperature sensor is then applied to a device interfaced between the variometer sensor and the indicator so as to introduce the above factor. Such a device would only apply an accurate correction on a "standard" day, but it would not be difficult to provide an approximate adjustment for non-standard conditions. An attempt (Ref. 8) has been made to construct such a device but it is still in a very preliminary state of development.

CONCLUSIONS

1. Subject to minor corrections, a mechanical variometer displays true vertical speeds whilst an airspeed indicator displays equivalent forward speeds. There is, therefore, a mis-match at any height other than sea-level such that the use of the MacCready ring causes the pilot to fly too fast between the thermals.

2. At likely operating heights, the effect on the average speed is small but there may be a significant effect on the pilot's work load.

3. The problem could be avoided by causing the variometer to display equivalent vertical speeds. Alternatively, a MacCready ring display can be devised which is scaled appropriately for various operating heights.

4. Electric variometers tend to display a value less than the equivalent vertical speed and,

therefore, cause the pilot using a "sea-level" MacCready ring to fly too slowly between the thermals at any height other than sea-level.

5. Again, the effect on average speed is small and in practice may be slightly advantageous in reducing the pilot's work load.

6. It seems likely that, by sensing the atmospheric temperature, an approximate correction can be applied to electric variometers, causing them to indicate something close to equivalent vertical speeds.

7. Finally, although no mention has been made above relating to down-draughts between thermals, total energy, etc., all the usual considerations apply. We simply wish to scale the variometer indications by a suitable factor.

SYMBOLS

H: Height

n: index in equation (1)

t: time

T: absolute atmospheric temperature

T_o: standard sea-level value of T

σ: atmospheric relative density

θ: angular distance between the datum and a particular speed marking on a MacCready ring.

REFERENCES

Johnson, D. P. "Aircraft Rate-of-Climb Indicators". NACA Report No. 666, 1939.

Coulthard, W. H. "Aircraft Instrument Design". Pitman, London, 1952.

Burton, G. "Are we flying too fast?" Sailplane and Gliding, Feb. 1972.

Irving, F. G. "Are we flying too fast?" Sailplane and Gliding, Aug. 1972. (See also Irving, F. G. "The Effect of Errors in Inter-Thermal Speed on the Average Cross-Country Speed", OSTIV, 1974).

Edwards, A. "A Stochastic Cross-Country or Festina Lente". Sailplane and Gliding, Feb. 1963.

Davey, P. G. "The Electric Variometer". OSTIV Publication VI.

Salisbury, M. P. "Response of Glider Variometer Systems". Student project report, Imperial College, 1972.

Johnson, D. G. "Variometer System for Gliders". Student project report, Imperial College, 1973.

ACKNOWLEDGMENT. The scheme for calibrating the MacCready ring is largely based on a proposal by Mr. C. J. S. Chapman of Aston University.