A Theory of Thermal Soaring

By Betsy Woodward

Glider pilots and meteorologists have for years concerned themselves with vertical currents. Perhaps the most complicated of these, and the least understood, are convection currents. Following the useage of glider pilots these are now generally known as thermals.

Investigations of thermals have been made by both powered aircraft and gliders, and time lapse cameras have photographed cloud development. Aircraft have measured temperature excess, vertical and horizontal velocities, and size but it is difficult to know the position of the aircraft in relation to the thermal, especially in the vertical. These explorations have given valuable qualitative, and in some cases significant quantitative data, but little has been found out about the actual motions in and around the entire thermal. Time lapse cameras have added to the knowledge but the camera is only able to see the outside of the clouds, where mixing with the surrounding air and evaporation is taking place.

In order to discover the field of motion in and around a thermal, one must revert to the laboratory. Experiments on isolated thermals have been conducted at the Dept. of Meteorology, Imperial College, London, and the preliminary results obtained have been reported to OSTIV and published in other journals by Scorer (1). I will attempt here to describe only those laboratory techniques and results that are of special interest to the glider pilot.

It should be noted that the thermals described below are:
(a) rising through neutral surroundings,
(b) no longer attached to the ground.

We shall call these thermals "isolated thermals".

(a) This means that they are rising in air which is neither stable nor unstable, the condition that generally exists on days of good convection below cloud base and above the super-adiabatic layer close to the ground. The same type of motion would be encountered inside cloud (if surrounding air is neutral, i.e. temperatures follow the wet adiabatic).

(b) The thermals in the laboratory were created with a uniform density. Immediately after release they were no longer attached to their source. The manner of release is perhaps the primary difference from the atmosphere, where it is not yet properly understood and is extremely variable. It is felt that a thermal leaving the ground is generally in the form of a "column", i.e. after a short time its vertical dimensions are greater than its horizontal. While attached to the ground, rotation about a vertical axis may occur and this rotation will increase if there is an appreciable super-adiabatic layer. Eventually the column becomes detached from the ground and we may now call it a "sausage". Because mixing with the surrounding air takes place primarily at the top of the "sausage", the tail will rise in relation to the top and eventually we will have an isolated thermal.

In desert regions the rotating column may extend from the ground to several thousand metres and when it finally becomes detached the top may be entering stable surroundings. In countries such as England isolated thermals seem to exist from 200—700 metres above the ground up to the stable layer.

As the isolated thermal rises it mixes with surrounding air, becomes larger, and the temperature excess becomes less. The outside dimensions of the warm air follow a cone with semi-vertical angle approximately 15°. The motion is very like a vortex ring (see Fig. 1). The velocities in the centre of the thermal are greater than the rate of rise of the thermal as a whole; the horizontal velocities also have appreciable values and in a small region are equal to the rate of rise of the thermal as a whole; there is sink at the edge of the thermal.

For actual measurements see Fig. 2. A cross-section of the right hand half of the thermal is shown. We have given a velocity of 1.0 to the cap of the thermal. It can be seen that the vertical velocity in the centre is 2.2 times the vertical velocity of the cap, and that around the edge of the thermal air is descending slightly more than half the speed that the cap is rising. The dashed lines denote horizontal velocities: outflow in the upper part of the thermal, inflow in the lower. The thermal also has an appreciable effect on the surrounding air: the air above is "pushed" up before it becomes engulfed; there is downward motion at the edge of the thermal and some of the air to the rear flows in and up. The area of the thermal is shaded. As the thermal rises its radius will increase, approximately following the cane of half angle 15°.

The vertex of this cone may be regarded as the theoretical point source. Vertical distances are measured from the point source and can be conveniently expressed as multiples of the distance to the thermal cap, as in Fig. 2.

This is the thermal as the meteorologist sees it and is defined as the volume occupied by the original bouyant air (now diluted). As far as the glider pilot is concerned, however, the thermal is the region where he encounters either lift of reduced sink. *His* thermal is, therefore, about three quarters as wide, and its vertical dimensions about 50 % greater than the outline shown in Fig. 1.

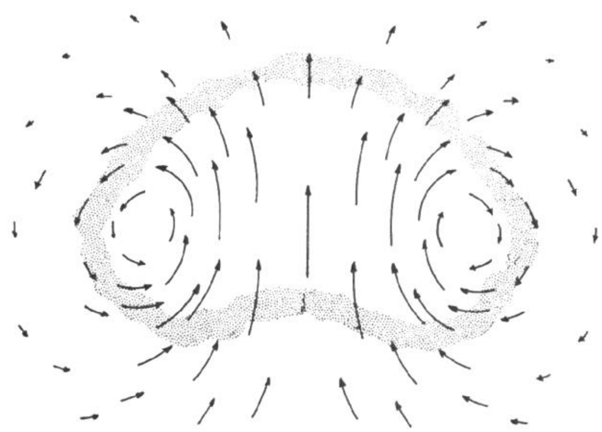

Fig. 1
The motion in and around an isolated thermal. The shaded area outlines the region of buoyant air. The arrows indicate the direction of motion, in relation to the ground, and their length show relative speeds.

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The effect of the inflow and outflow on a circling glider cannot be neglected and as pointed out by Cmdr. H. C. N. Goodhart (see below) these horizontal velocities can add appreciably to the vertical rate of ascent or descent of the glider. If the glider is spiraling concentrically in a field of inflow where the horizontal velocity is 1.0 m/s and is banking at an angle of 45°, this would be the equivalent of 1.0 m/s up; if the angle of bank is 30°, 1.0 m/s inflow equals 0.58 m/s up. Outflow has the same effect but in the opposite direction. Therefore if the glider is spiraling in the lower part of the thermal the inflow adds to his vertical velocity; if spiraling in the upper part, the effect of the outflow must be subtracted from his vertical velocity.

Let us take a sailplane and place it in a thermal. We must first select the sailplane, the height of the thermal cap above the point source, the velocity of the cap and the position of the sailplane in the thermal.

The glider we have selected is similar to an Olympia and its performance in circling flight has been calculated by Welch (2). Its performance is given in Fig. 3. The cap of the thermal is taken to be 600 metres above the point source and its velocity 2.0 m/s. The glider is assumed to enter at 450 metres, or 0.75 times the height of the cap at time, $t = 0$. In Fig. 4b the dotted line shows the vertical velocity of the air in the thermal relative to the ground. The dashed line shows the vertical velocity of the sailplane relative to the ground before the effect of the horizontal velocities has been taken into account. The solid line shows the resultant vertical velocity of the sailplane relative to the ground. At a radius of 53 metres where the angle of bank, Φ, is 40° the inflow, U_r, is 1.0 m/s. Therefore $U_r \tan \Phi$ = vertical velocity, $V_z = 0.84$ m/s. This amount, 0.84 m/s, has been added to the vertical velocity of the sailplane (dashed line), 1.65 m/s at 53 m, bringing the resultant vertical velocity to 2.49 m/s.

We will assume that the sailplane is spiraling at the radius where he is obtaining his maximum vertical velocity. This is 60 metres, his angle of bank is 35°, and his vertical velocity is 2.5 m/s. Since the rate of rise of the thermal cap is only 2.0 m/s, he is rising in relation to the thermal. To find his position and performance at later stages, computations were then made at 10 second intervals. It must be remembered that the thermal as a whole is rising, its radius is increasing and its vertical velocity is decreasing.

From laboratory experiments:

$$\frac{Z_c}{Z_c'} = \frac{V_{zc}'}{V_{zc}}$$

$$R \simeq \frac{Z_c}{4}$$

$$t = k Z_c^2$$

where Z_c is the height of the cap above the point source, V_{zc} is the vertical velocity of the cap and R is the radius of the thermal. In the case selected the constant, k, equals 1/2400.

In Fig. 4 the velocities at 20, 40, 80 and 120 seconds are shown. As the sailplane rises in relation to the thermal the effect of the inflow decreases (at $t = 50$ seconds it is in a region where there are no horizontal velocities). It then enters the region of outflow so that the resultant vertical velocity is less. The glider rises relative to the thermal, in this case to 0.89 times the height of the cap and maintains a vertical velocity of 0.89 times the vertical velocity of the cap.

It was then decided to find the lowest point at which the glider could enter and still rise relative to the thermal. Fig. 4a shows the vertical velocities at $t = -40$ seconds. At

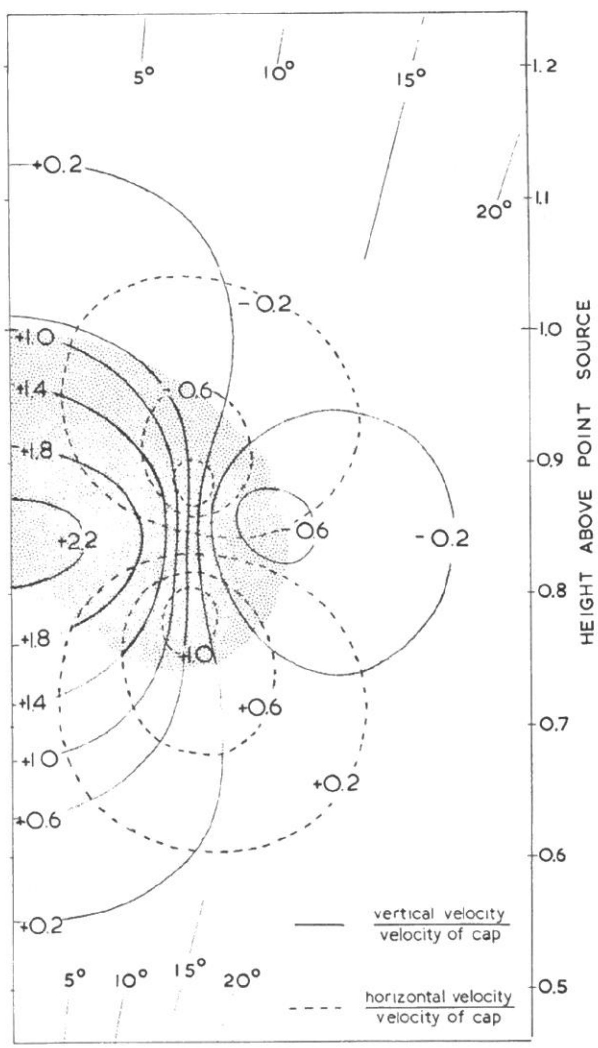

Fig. 2
A cross-section of the right hand half of a thermal showing lines of equal vertical velocities and equal horizontal velocities

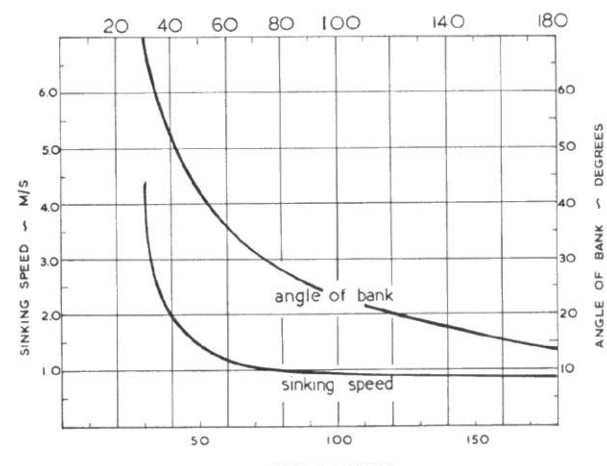

Fig. 3
The performance of a sailplane (similar to an Olympia) in circling flight

$t = -60$ the sailplane must bank at 45° and the vertical velocity obtained from the inflow is equal to that obtained by the updraft. The computations were not carried on beyond this point as it was felt they would have little similarity with that which could actually be achieved. A summary of the information is given in Fig. 5.

It should be stressed that the figures presented deal with only one combination of thermal size, height of entry, velocity, and glider performance. It has also been assumed that the glider maintains an angle of bank which gives the maximum vertical velocity, that it is concentric with the centre of the thermal, and that there is no "fumble factor". The thermal structure assumed is that shown in Fig. 2 which is based on the average values obtained in laboratory experiments. In practice there will be a narrow turbulent layer near the cap where the velocities at any instant may be very different from those presented, but the glider never enters this region unless he flies into it from the side or from above. If the size of the thermal is small and the velocities large, care must also be taken as a small change in angle of bank will appreciably affect the resultant vertical velocity obtained.

Fig. 6 shows the vertical velocity distribution in a thermal whose cap is 1000 metres above the point source and rate of rise is 2.0 m/s. The radius of the warm air is 250 metres. The figures give the variometer readings that would be obtained by a sailplane whose circling performance is similar to that given in Fig. 3. The left hand side of the diagram gives the readings that would be obtained from the vertical velocities only; inflow and outflow have not been taken into account. In the right hand side these horizontal velocities have been included. As a result, the bottom portion of the "glider pilot's thermal" is wider because the effect of the inflow has added to the rate of climb; the upper portion is narrower because of the outflow. If we had selected a thermal where the radius of warm air was less, then the widening and narrowing due to horizontal velocities would be greater. It should be pointed out again that it is assumed that the glider is spiraling concentrically in the field of inflow or outflow. If not concentric, which is usually the case in practice, then the effect of the horizontal velocities will not be as great as that shown in Fig. 6. If the glider is not concentric, spiraling in the lower portion of the thermal the inflow will tend to center him; in the upper portion the outflow will tend to "throw him out".

It can be seen that calculating the performance of sailplanes in thermals can be a tedious affair. There are an infinite number of combinations that may be used.

There will undoubtedly be a number of readers who will disagree with the assumptions made here. If so, the author would like to receive comments. She does not attempt to draw similarity between isolated thermals and "dust devils" (or "rotating columns"). The model presented is simple thermal convection, ignoring wind shear, and should only be applied above several hundred metres. While making flights during the past two years this model has been kept in mind and conditions encountered appear to have verified the picture.

The isolated thermal is also one of the few models that can explain two observations reported by glider pilots. One deals with the increase or decrease of airspeed when entering or leaving a thermal. Part of this change of airspeed is momentarily due to the vertical velocity encountered. It is

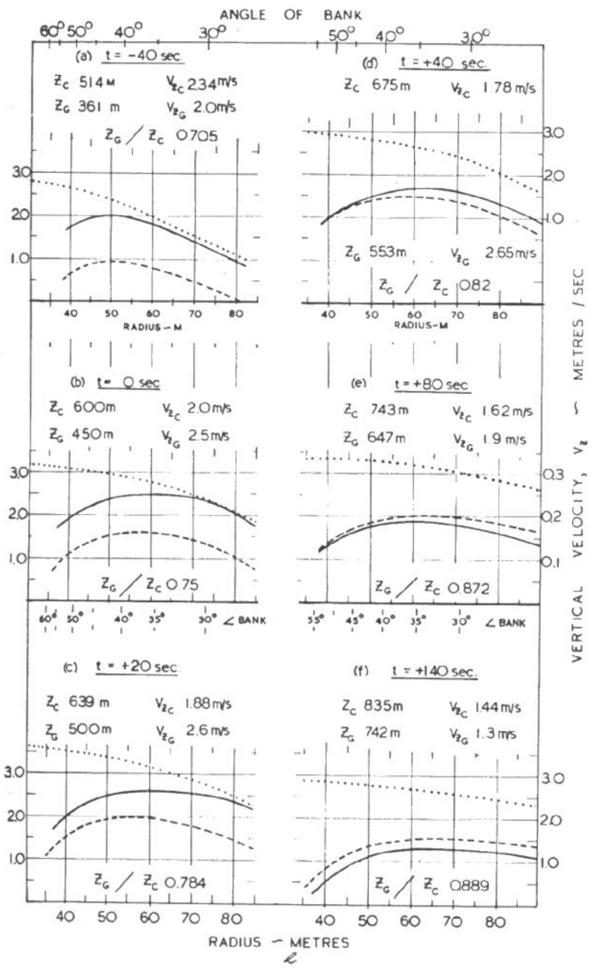

Fig. 4
Vertical velocities of a sailplane as it rises in a thermal (see text)

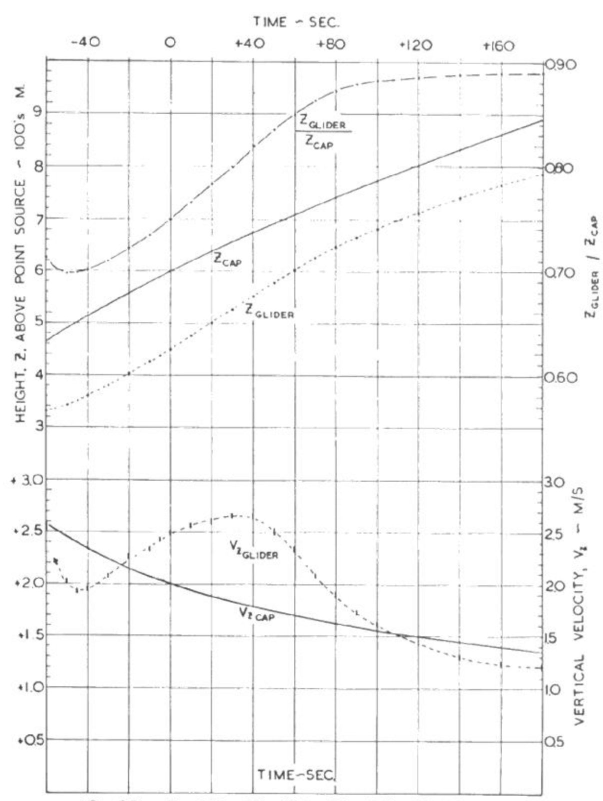

Fig. 5
Summary of information presented in fig. 4

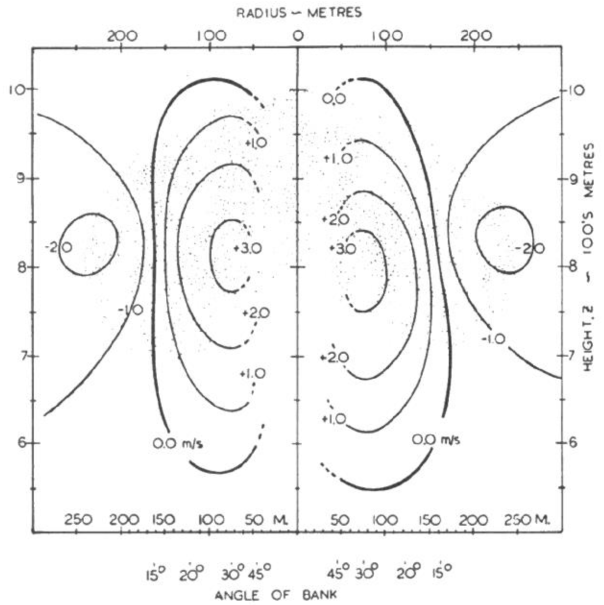

Fig. 6
Variometer readings that would be obtained in a thermal with a radius of 250 metres and vertical velocity of cap of 2.0 m/s. Horizontal velocities have not been taken into account in the left hand side of the diagram; they have in the right hand

felt by many people however that the change in airspeed cannot be fully accounted for by the vertical velocities alone. The horizontal velocities encountered in isolated thermals can help to explain part of this discrepancy.

Secondly, there have been numerous reports by glider pilots that, when flying at and just above cloud base, the cloud often appeared to be "hollow" in the centre, i.e. the base of the centre of the cloud could be a hundred metres or so above the base on the edges. In the case of the isolated thermal, the centre of the cloud *will be* hollow if the surrounding air has a low relative humidity. Mixing with the outside air takes place not only at the cap but, because of the inflow, outside air is brought into the thermal at the rear.

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References:

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(2) *Welch A.* and *L.* and *Irving F.*, 1955: "The Soaring Pilot." John Murry, London.