The art and physics of soaring

With the advent of modern molded composite materials, the performance of sailplanes has improved dramatically and sparked a renaissance in the sport.

Lloyd Hunter

Modern materials technology, combined with three-quarters of a century of experience in glider design, has given us sailplanes capable of superb performance. In the hands of a pilot who understands the basic physics of soaring and has mastered the art of maneuvering his craft, the sailplane of today offers a truly exhilarating sport, whether one's interest is in recreation or competition.

Typically, a modern-day flight proceeds as follows: The pilot and his sailplane are towed by an airplane to about 2000 feet and released. The pilot finds a local thermal and climbs by circling within the thermal until he reaches the top of the convection layer, say at 8000 feet. He then sets a course at a cruising speed of perhaps 80 mph. When his above-ground altitude on this straight run has fallen to between 2000 and 3000 feet (after traveling a ground distance of perhaps 50 miles), he begins searching for another thermal. He then climbs to the top of the second thermal and again sets out on course.

The records held by sailplanes give a good feeling for how far the limits of performance have been pushed to date. The present world-record distance made by soaring in thermals is 908 miles. The altitude record is 46 000 feet; the goal and return distance, 1022 miles; speed around a 300-mile triangle, 94 mph.

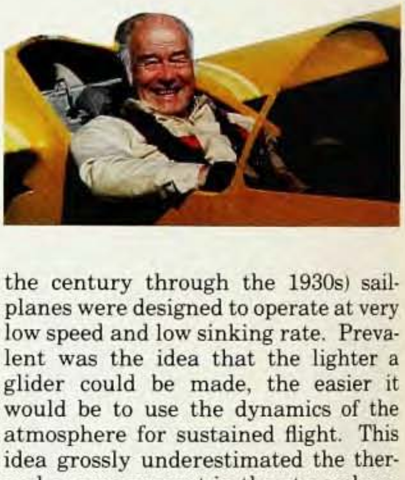
In this article we will review advances in sailplane design and the basic principles of physics and knowledge of atmospheric conditions that even the fledgling sailplane pilot must understand; we will then consider briefly the more advanced skills that underlie the records cited above, which often involve using types of atmospheric lift other than local thermals.

Lloyd Hunter is professor emeritus in the Department of Electrical Engineering at the University of Rochester, Rochester, New York.

History of soaring

If we define soaring as gaining altitude by the use of air currents and without applying self-contained power, then birds have engaged in soaring flight long before man. Most common among those who soar are hawks, vultures, seagulls and swallows. Hawks and vultures in particular are rarely observed flapping their wings. These birds are usually seen with fixed wings, wheeling in graceful circles at considerable height and slowly receding from view as they rise to ever greater heights. They are circling in rising bubbles (really toroidal vortices) of warm air we call thermals, which are the normal mode of atmospheric convection on a sunny day. In the temperate zone of a continent, the convection layer in summer is anywhere from 4000 feet to 10 000 feet thick shortly after midday. In high desert areas, the convection layer may be up to 20 000 feet thick.

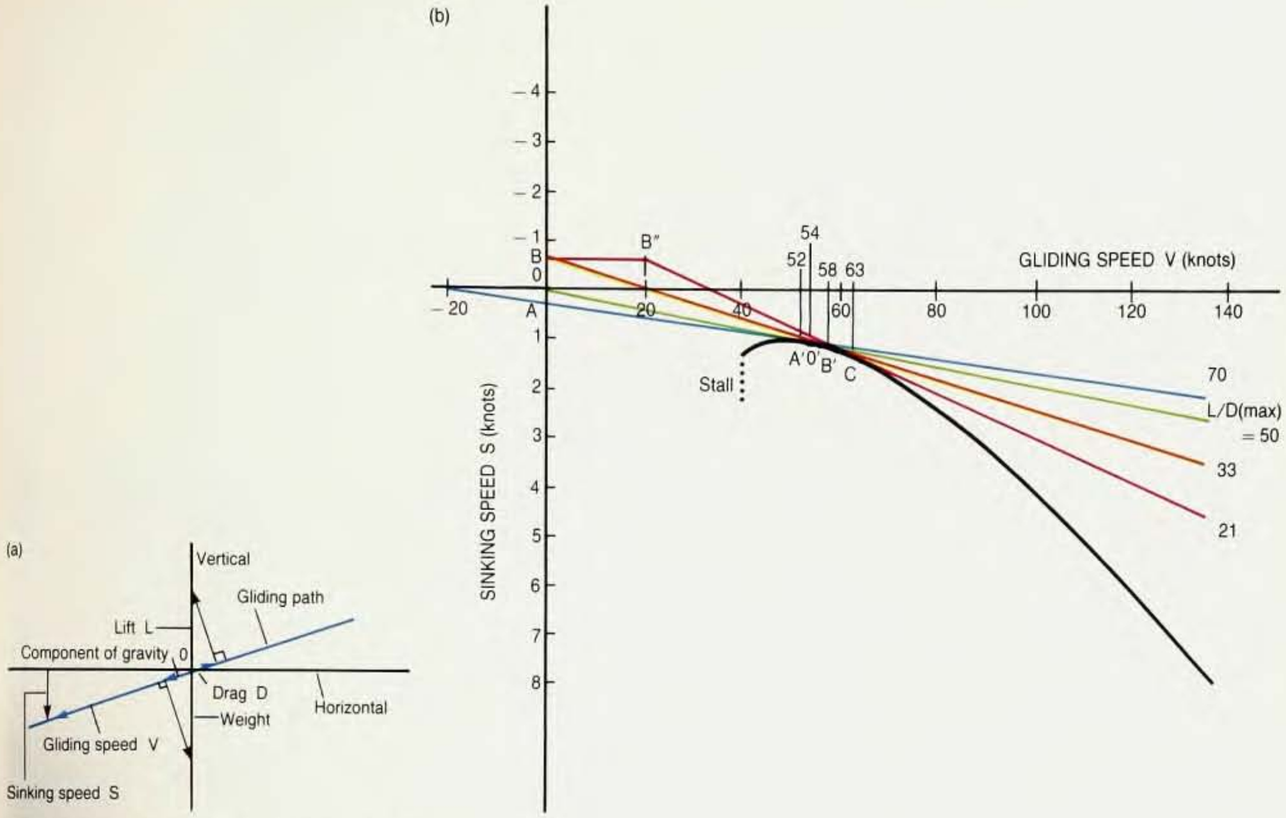
Thermals come in all sizes and spacings. Many are large enough to enable a sailplane with a 70-foot wing span to circle comfortably and remain inside the rising vortex (see figure 2) of warm air. Thermal lift is the most commonly used type of atmospheric lift for soaring for either birds or man.



In the early days (from the turn of the century through the 1930s) sailplanes were designed to operate at very low speed and low sinking rate. Prevalent was the idea that the lighter a glider could be made, the easier it would be to use the dynamics of the atmosphere for sustained flight. This idea grossly underestimated the thermal energy present in the atmosphere. The early gliders were fragile structures similar to modern hang-gliders, with much the same performance. When thermals were discovered in the late 1920s and it was no longer necessary to depend upon the wind moving up the slope of a hill, soaring enthusiasts soon realized that very light machines were incapable of flying fast. After all, for a glider, the only force available for overcoming the increased drag of fast flight is the component of gravity along the glide slope, and this force can only be increased by making the glider heavier.

By the 1950s gliders were built with wing loadings of 4 to 6 pounds per square foot of wing area and strong enough to fly up to 100 miles per hour. Their best glide slopes were about 30-to-1 at 45 miles per hour, declining to 18-to-1 at 90 mph. With the advent of modern high-technology composite ma-

0031-9228 / 84 / 0400 34–08 / $01.00



Vector force diagram (**a**) for a sailplane with its center of gravity at the origin and flying at constant speed in a straight glide; (**b**) polar curve of sailplane performance. Figure 1

terials (such as fiberglass and, more recently, carbon-fiber materials), the performance of sailplanes has improved dramatically. Not only has the wing loading increased, but the extremely smooth surfaces of molded composite materials allow laminar air flow over the wings, which, together with new airfoils capable of maintaining laminar flow, has decreased the drag significantly. Today speeds exceed 170 miles per hour, and glide slopes are 60-to-1 at 60 miles per hour and still better than 25-to-1 at 140 miles per hour. The wing loadings are variable from 6 to 12 pounds per square foot using water ballast. It is performance of this level that makes the world records cited above possible.

Sailplane performance

The primary description of sailplane performance is given by a measured curve of sinking speed versus gliding speed. Such a curve, called a "polar curve," is shown in figure 1. Part **a** of the figure is a vector diagram showing the relation to lift L, weight W, drag D, sinking speed S, and gliding speed V for a sailplane in equilibrium at constant V in a straight glide. By similar triangles it can be seen that $L/D = V/S$. This ratio is defined as the glide ratio of the sailplane.

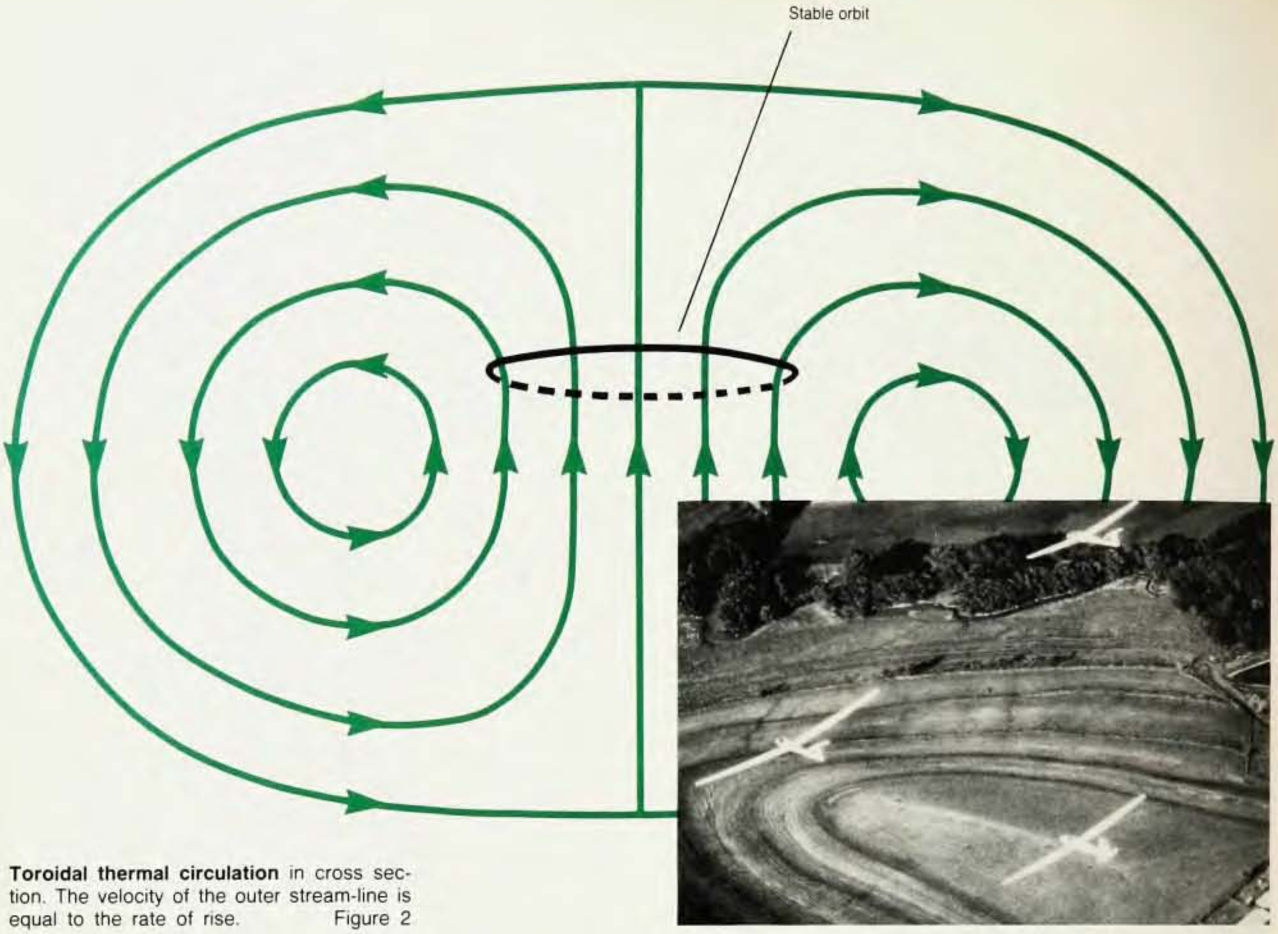
Part **b** of the figure shows a measured polar curve of a high performance sailplane. The slope of the curve is the reciprocal of the glide ratio (normally referred to as L/D): The solid line from the origin tangent to the curve represents the maximum L/D, in this case 50-to-1: At a one-mile altitude this sailplane has a range of about 50 miles in still air over flat terrain. To achieve this maximum the sailplane must be flown at 54 knots, the speed at the tangent point. The polar curve also allows us to calculate the performance under various conditions of wind and rising or sinking air masses. If there is a 20-knot headwind, one draws a tangent to the curve from the 20-knot point of the V axis. The dashed line in the figure is tangent at point B' at $V = 58$ knots. The reciprocal of the slope at this point is 33. This is the effective L/D ratio relative to the ground. The headwind reduces the range at an altitude of 1 mile from 50 to 33 miles. If there is a 20-knot tailwind, the result is shown by the short dashed line tangent at A'. For a speed of 52 knots the range downwind is 70 miles.

The effect of rising or sinking air is determined by displacing the origin of the tangent line along the vertical sinking-speed axis. If we extend the tangent at B' back to the S-axis at point B, we see that the reduction in range produced by air sinking at a rate of about 0.7 knots is the same as that of a 20-knot head wind. The intercept A of the A' tangent on the S-axis shows that air rising at a rate of about 0.3 knots is equivalent to a 20-knot tailwind in extending the range. If there is both sinking air of 0.7 knots and a 20-knot headwind, one must draw a tangent from the point B'' at $S = -0.7$ and $V = 20$. This line is tangent at point C at $V = 63$ knots, and the slope indicates a range of only 21 miles. Pilots involved in serious competition carry calculators to give quick answers to these simple problems.

Thermal lift

The phenomenon of thermal lift has been described as bubbles of warm air rising through the atmosphere as part of the general atmospheric convection on a sunny day. But we need to describe thermals in more detail to understand the dynamics of thermal soaring.

The Sun heats the ground on a clear



Toroidal thermal circulation in cross section. The velocity of the outer stream-line is equal to the rate of rise. Figure 2

day, and the ground, in turn, heats a layer of air about 4 to 6 inches deep. Local wind currents stir up this layer of air, mixing it with the air above. When it encounters an obstacle such as a building or a windrow of trees, the warm air is displaced upward and begins to rise by thermal buoyancy. The surrounding air is drawn in to replace the displaced air, and in the process a considerable area is drained of its thin hot-air layer.

The bubble eventually breaks free from the surface and starts a free ascent (analogous to the nucleation, growth, and rising of a bubble of steam in a pan of boiling water). As the bubble ascends, the drag of the motionless air surrounding it sets up an internal toroidal pattern of circulation (like that of a smoke ring). A cross section of this pattern is shown in figure 2. The outside streamline of this pattern has a speed equal to the rising speed of the bubble, thus minimizing the surface drag at the equator of the bubble. The same streamline returns up through the center of the torus so that the rising speed of the air in the center is twice the rising speed of the bubble as a whole. To be of use to a sailplane the vertical component of the circulation pattern at the radius of the plane's circling flight path must exceed the sinking speed of the sailplane when in a steep turn. When this condition is fulfilled, the sailplane can rise above the equatorial plane of the vortex to a stable orbit where the vertical component of the circulation pattern just cancels the sinking speed of the sailplane. After the stable orbit is achieved, the sailplane's climbing speed will just equal the rising speed of the bubble. If the sailplane were to enter the thermal too far below the equatorial plane, its sinking speed would exceed the vertical component of the circulation pattern and it would eventually sink out of the bottom of the bubble.

Let us now examine some of the quantitative aspects of free thermals. From the typical geometry of a vortex, we can estimate their diameter as being at least three times the radius of the stable sailplane orbit (see figure 2). Typically, a thermalling sailplane completes a circle in about 25 seconds at a speed of 55 miles per hour. This represents an orbit circumference of 0.38 miles, or a diameter of 642 feet. Three times this gives a thermal diameter of 1926 feet. The measured rate of climb in a typical eastern US summer thermal is about 5 knots (5.8 miles per hour). For a steady rate of climb, the sailplane must have achieved the equilibrium orbit and the climb speed is therefore equal to the rising speed of the thermal bubble. This speed results from the equilibrium between the forces of buoyancy and drag of the bubble. If we simply model the bubble as a spherical balloon of diameter 1926 feet, we find:

$$D = C_D A d V^2/30$$

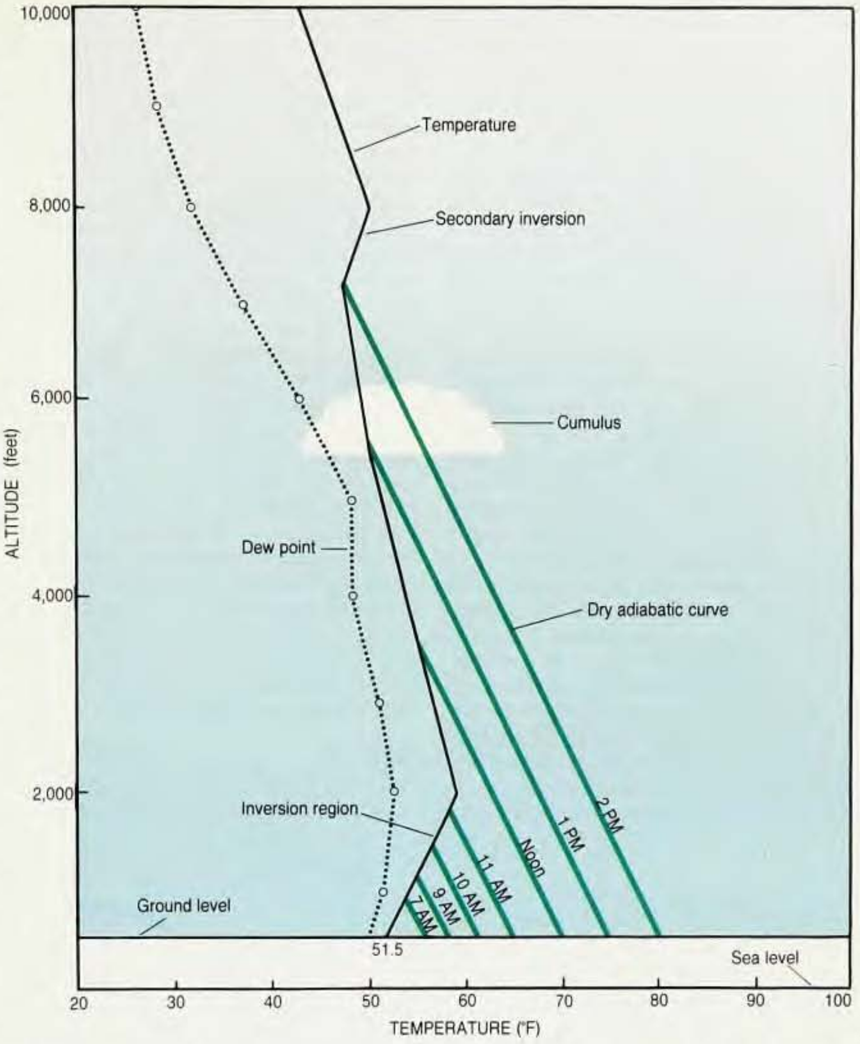
where D is the drag, C_D the drag coefficient, A the projected area in the direction of motion, d the air density (0.076 lb/ft^3 at sea level) and V the speed in miles per hour. For a large sphere C_D is 0.1 and A is πr^2 (here, 2.9×10^6 ft^2). Substituting the numbers, we find the drag force to be 24 829 lbs. This is also the buoyant force. Because a typical loaded sailplane weighs about 1000 pounds, it clearly does not load a typical thermal very heavily.

We have spoken of the thermal being a bubble of warm air rising through a cooler motionless air mass. It is instructive to calculate the average temperature difference required to give this typical thermal its buoyancy. A spherical air bubble of radius r and excess temperature T displaces an extra volume of air of $(\Delta T/300)\ (4\pi r^3/3)$ ft.^{3} The weight of this extra volume of air is the buoyancy of the bubble, $B = 4\pi r^3 \Delta T d/900$. Substituting our numbers, we get

$$B = 24\,829 = 9.4 \times 10^5\ \Delta T$$
$$\Delta T = 0.026\ ^\circ\mathrm{C}$$

It is astonishing that such a small temperature difference could create such a powerful lifting force. In the western deserts it is not uncommon to encounter thermals of 15 knots climbing speed. This speed implies buoyancy of 223 000 pounds and a ΔT of 0.24 °C for a thermal of the same size.

Thermals are not always isolated bubbles of warm air. They frequently are streams of bubbles originating from a fixed source. The most obvious example, perhaps, is the hot air rising from a fire. The initial chimney-like stream of hot air soon breaks up into a stream of bubbles, each with toroidal circulation and following each other up in a steady procession. A natural source of this kind of thermals is a long valley opening toward the prevailing wind. In such a valley a head wall or a major shoulder on one of the sides will direct a steady stream of bubbles upward in a close procession. The art of thermal soaring includes the ability to spot such likely thermal sources far enough ahead to make efficient use of them without spending too much time searching.



Profile of a typical summer atmosphere in the eastern US as function of time. Figure 3

Cumulus clouds

Every cumulus cloud you see in the sky on a fair day has been put up there by a thermal. So cumulus clouds are thermal markers if they are still building. Figure 3 illustrates the relationship between thermals and cumulus clouds and demonstrates a method of predicting soaring conditions from atmospheric soundings routinely made by the weather bureau. In this figure, the solid curve represents an atmospheric temperature sounding taken at 4 am. Temperature and dew point are measured at fixed pressure intervals as the weather balloon rises.

During the proceeding night, the surface of the Earth had radiated some of its accumulated heat of the previous day into space, thus cooling the surface to a temperature of 51.5 °F by 4 am. A layer of air adjacent to the surface was cooled by contact with the surface, and this cool layer was deepened by turbulent mixing as the air moved over the surface with the prevailing wind. Higher in the atmosphere, some of the heat of the previous day was retained because the atmosphere is a poor radiator compared to the surface. The temperature aloft was still about 60 °F at an altitude of 1500 feet. The region of the temperature curve that shows increasing temperature with altitude is called an inversion layer. Above 1500 feet the measured temperature drops as the balloon continues to rise. The dew-point–temperature measurements are shown as open circles. One can see that the dewpoint averages about 50 °F up to about 4500 feet above sea level.

The dashed curves are adiabatic curves plotted for measured ground temperatures at the times indicated. An adiabatic curve represents the temperature of a parcel of air moved aloft and allowed to expand adiabatically, keeping its pressure equal to the ambient air pressure aloft. To a good approximation, the temperature of a thermal follows the adiabatic curve as it rises.

Using figure 3 to follow the development of the day's thermal convection, we see that about an hour after sunrise (7 am) the surface temperature has risen to 56 °F and the early thermals have heated the lower atmosphere to a height of about 400 feet above the ground. An atmospheric sounding taken at this time would start at 56 °F at ground level and follow the 7 am adiabatic up to the solid curve, joining it at 400 feet, and following the 4 am sounding data on up. A bird would be able to soar in this convection layer, but only to a height of four or five times the height of the trees. By 11 am with a ground temperature of 65 °F, the convection layer has approached the top of the inversion, about 1400 feet above ground. This is still too low for satisfactory soaring, but, as one can see from the corner in the sounding, five more degrees in ground temperature will move the convection layer up to more than 3000 feet above ground; soaring is now quite possible. On the day represented by this curve, soarable conditions appeared at about 11:30 am.

Recalling that the average early morning dew point was about 50 °F and that thermals transport air from ground level to the top of the convection layer, we see that at an altitude of 5500 feet above sea level the sounding temperature has dropped to 50 °F, the condensation point. When the convection layer reaches this altitude, the first wispy cumulus clouds should appear. From the figure, this should occur at about 1 pm, and the cloud bases should be at about 5000 feet above ground level.

By 2 pm the convection layer has risen to 7000 feet above sea level, and the average dew point to this level is about 48 °F. Accordingly, the bases of the cumulus clouds have risen to 6800 feet above sea level, where the sounding temperature is 48 °F. Shortly after 2 pm the top of the convection layer has reached the bottom of a secondary inversion layer. If the peak surface temperature of the day is 80 °F, then from 2 pm on, the convection layer does rise much and thermal soaring is limited to about 6800 feet above ground level. Also, the dew point drops rapidly in the secondary inversion layer, so when the convection layer reaches this level, the cumulus clouds disappear.

From the above discussion it is clear that one needs two pieces of information to predict the soaring conditions on a specific day—the atmospheric sounding taken at about 4 am at a weather station about 200 miles upwind of the soaring site and the local prediction of the maximum temperature of the day.

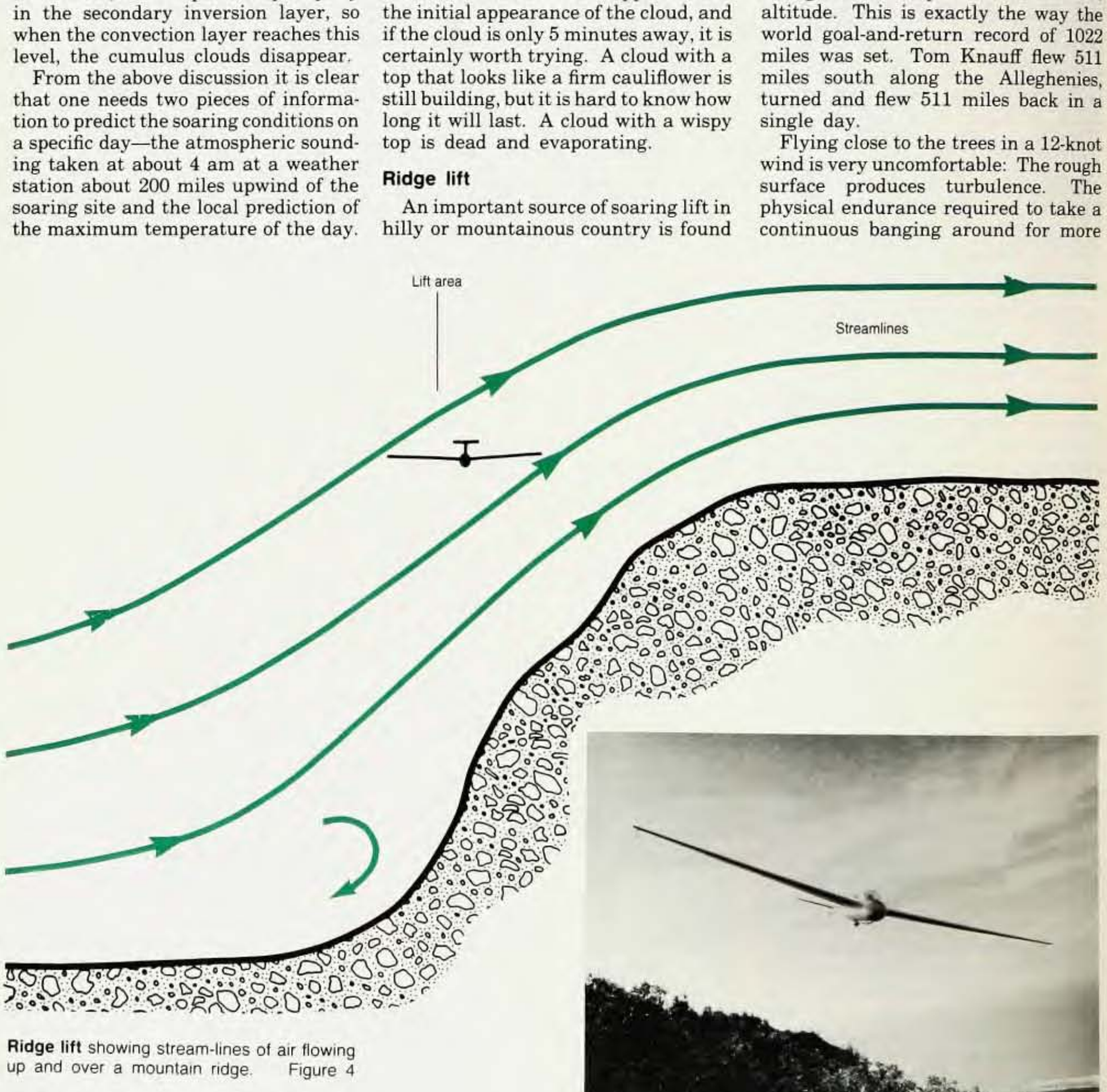
Each cumulus cloud has a life cycle. As the top of a thermal bubble reaches the condensation level, the cloud begins to form. As the cloud builds, the heat of condensation augments the thermal temperature and extends the top of the cloud beyond the average convection level. After a time, the thermal dies as the warmer air mixes with the ambient atmosphere, and the cloud begins to evaporate. The problem presented to a soaring pilot is to learn to tell by inspection from a distance whether the cloud is in the building or evaporating state, and if it is still building, whether it will continue long enough to allow him to get to the cloud and make appreciable use of the remaining thermal energy. A typical cloud may last for 30 minutes but only build for the first 10 minutes. If one happens to see the initial appearance of the cloud, and if the cloud is only 5 minutes away, it is certainly worth trying. A cloud with a top that looks like a firm cauliflower is still building, but it is hard to know how long it will last. A cloud with a wispy top is dead and evaporating.

Ridge lift

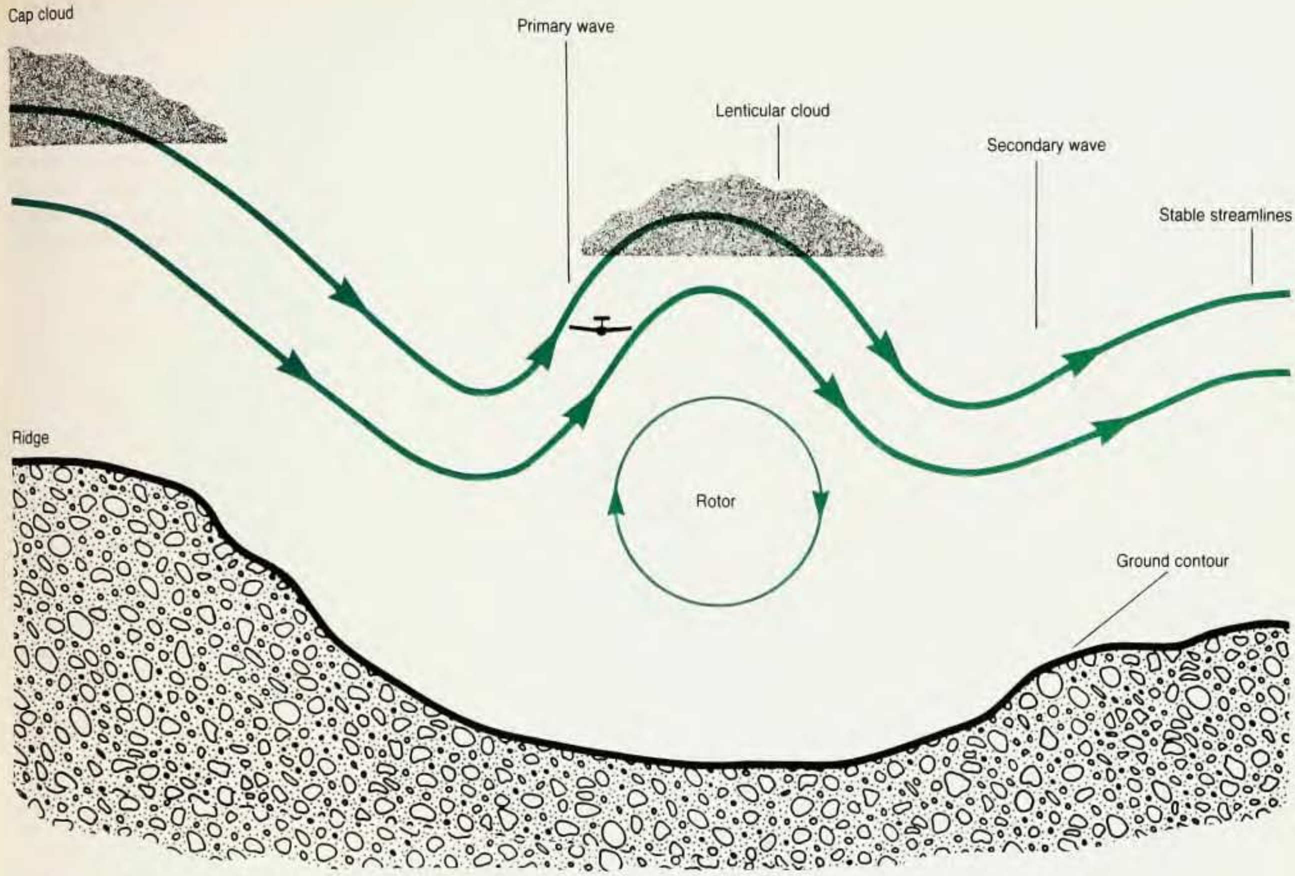
An important source of soaring lift in hilly or mountainous country is found in "ridge lift." Figure 4 depicts the streamlines of air carried by the wind over a mountain ridge. It is clear that a sailplane flying parallel to the ridge at a low altitude and slightly upwind of the ridge will be flying in air with a reasonably steady vertical component of motion.

To get a feel for the performance, suppose the slope is 3-to-1 (typical of Allegheny Mountain ridges) and there is a 12-knot wind blowing perpendicular to the ridge, the maximum vertical component of the streamlines would be found very close to the ridge and would be $12/3 = 4$ knots. Referring to figure 1, we see that our sailplane would be able to cruise at 100 knots while flying parallel to the ridge just above the trees; the updraft would provide just enough lift for the plane to maintain its altitude. This is exactly the way the world goal-and-return record of 1022 miles was set. Tom Knauff flew 511 miles south along the Alleghenies, turned and flew 511 miles back in a single day.

Flying close to the trees in a 12-knot wind is very uncomfortable: The rough surface produces turbulence. The physical endurance required to take a continuous banging around for more



Ridge lift showing stream-lines of air flowing up and over a mountain ridge. Figure 4



Lee-wave system in cross section. Figure 5

than 10 hours is a considerable price to pay for flying this fast for so long a time. If one is not attempting the ultimate in speed or distance, one can slow down to, say, 70 knots, where the sailplane sink rate is only 2 knots. Under the same 12-knot wind conditions, one could now rise to perhaps 800 feet above the ridge and still maintain altitude. The ground turbulence is greatly reduced at these altitudes, and the flight would be relatively smooth.

When using ridge lift, the sailplane pilot must be careful not to wander downwind of the ridge. Not only is the air descending behind the ridge, but it is very difficult to come back upwind if one is low over the ridge: The headwind encountered in coming back is much greater than the average wind speed because of the Venturi effect. The ridge represents a one-sided constriction in the flow, and low over the top of the ridge one can find the wind to be almost twice the average wind velocity.

Lee-wave lift

Another interesting phenomenon that provides some very exciting soaring is "lee-wave lift." Figure 5 illustrates the major features of a classical lee wave in the atmosphere. A lee wave is formed in stable (non-convective) air. It occurs downwind of an escarpment or ridge. The front range of the Rocky Mountains is a prolific source of lee waves in the spring and fall. The prevailing westerlies flow over the continental divide and drop down over the great plains. The descending air rebounds into a primary wave as shown in figure 5. A horizontal vortex is formed under this wave and is called a rotor. The most vigorous waves are found where there is a vertical wind gradient with only light surface winds but steadily increasing wind speed aloft. Because air is compressible and has no upper surface, increasing wind speed can be converted into increasing wave amplitude aloft, so that the crest of the primary wave may be orders of magnitude higher than the escarpment that creates the wave. The world soaring altitude record of 46 000 feet cited earlier was set in the primary of a lee-wave system behind the Tehachapi Mountains of California. In this instance the escarpment was only about 3500 feet high.

A basic feature of a lee-wave system is that it is stationary with respect to the ground. The air flow through the wave is laminar; only the rotor is turbulent. If the air is dry, the entire system is invisible. If there is a layer of air with sufficient humidity to produce clouds, there will be one or more lenticular clouds spanning the peak of the primary wave. These lenticular clouds may look like a stack of pancakes if the wave system involves a relatively localized peak. As illustrated in figure 5, the lenticular cloud condenses at its upwind edge, as the wave lifts a stratum of air to its condensation level, and evaporates at its downwind edge as the same stratum of air descends on the back side of the wave and is subject to adiabatic compression heating. The lenticular cloud is therefore stationary with respect to the ground, even though a 50-knot wind may be blowing through it. In the Air Force collection of photographs of UFOs there is a sprinkling of good pictures of lenticular clouds, which can easily appear as hovering "flying saucers."

Sailplane pilots use lee waves by having the sailplane towed into the upwind side of the wave ahead of the rotor. Once the sailplane's flight is established in this region of rising air, one can "surf" along the face of the wave and climb to the top of the system. Because the wind speed usually increases with altitude, one can often head directly into the wind and adjust flying speed to maintain a fixed ground position just upwind of the leading edge of the lenticular cloud. If the winds are strong, the turbulence in the rotor may be strong enough to throw the sailplane out of control and perhaps even damage its structure. When towing into a wave, it is safest to avoid the rotor completely. It is a great experience to soar in the absolutely stable laminar flow of a lee wave: The air is so smooth that one can trim the ship to a constant speed and fly hands-off for extended periods. It is like a perfectly smooth elevator. The ground steadily recedes, and the hands of the altimeter wind up with clock-like regularity.

Soaring as sport

Soaring brings different things to different people. It is, in some ways, analogous to sailing. Many can enjoy a weekend of just flying locally around the airport. Others prefer the challenge of racing sailplanes at various regional and national championships. In addition to these activities, there is also an internationally governed system of soaring badges and records to be achieved.

Distance records and racing require the optimization of cross-country speed. The three most important factors involved are:

▶ Finding useful lift quickly
▶ Centering in the area of the maximum vertical component of the lift
▶ Determining the optimum speed to fly between climbs in lift.

Cross-country soaring can make use of all forms of lift but normally uses only thermal and ridge lift. Because ridge lift is only available when winds of 10 miles per hour or more are nearly normal to the slope of the ridges, an average cross-country flight has little opportunity to use ridge lift. The record goal-and-return flights, which have used ridge lift over most of the distance, were planned to take advantage of very special synoptic weather conditions, such as the combination of a low-pressure area at the northeast end of the Allegheny ridge system and a high-pressure area at the southwest end funnelling a strong northwest flow between them over a 500-mile stretch of the ridges.

Let us discuss the three factors involved in cross-country soaring speed in connection with thermal lift. First, finding useful lift involves a number of careful observations. One must, for example, keep track of the direction of the surface wind. If the surface wind is not more than 10 to 15 knots, there are, in general, thermal sources on the upwind side of hills or the higher parts of cities or towns. The junction between areas of radically different ground temperature will often act as sources (for example, the downwind shore of a small lake, or the upwind edge of a large blacktop parking area). When approaching such a suspected source, one must take the wind drift of the thermal into account. At 2000 feet, for example, one would expect to find lift about 0.8 miles downwind of the source when there is 10-knot wind and a 5-knot thermal. If there are cumulus clouds present and one is looking for lift no more than 2000 feet below cloud base, one should search the area under a cloud that appears to be still actively building. If one is looking for lift at an intermediate altitude, one should start under a cloud and move directly upwind to intercept the next thermal rising from whatever source produced the thermal that created the cloud. One can estimate the wind direction accurately by observing the movement of the cloud shadows on the ground.

Centering in a thermal is a skill that develops slowly, and different pilots have different methods. Figure 6 shows one common method, which involves using a fast-acting rate-of-climb meter called a "variometer"—essentially a sensitive altimeter with a very small leak in the bellows. As the sailplane rises and the external air pressure drops, the bellows expands due to the relatively unchanged internal pressure, and the hand indicates the relative change in pressure. But because of the small leak, the hand stops moving and gives a constant reading when the sailplane rises at a constant rate so that the leakage of air out of the bellows can maintain a constant pressure difference between the interior of the bellows and the outside. By connecting an insulated sealed-air reservoir to the air in the bellows, one can make the instrument as sensitive as desired. The variometer is the single most important instrument for soaring. As illustrated in Figure 6, one will enter a thermal and see that climb is indicated on the variometer. Often one has no idea of which way to turn to stay in the thermal. In the illustration, the pilot begins a right turn. The variometer soon shows the climb is gone. The right turn is continued until 270° of a complete circle are reached (so that the heading is at right angles to the original heading and in the direction of the center of the thermal). At this point the turn is interrupted for a segment of straight flying lasting about 3 or 4 seconds. The right turn is then resumed. Now the variometer is found to indicate climb all around the circle but shows a lower rate about 180° after the turn is resumed. Again, straight flight is resumed for about one second at the 270° point. The final circle shows more nearly uniform climb around the full 360°. One has now centered the lift in the thermal. This initial centering may take a few minutes for a novice but less than a minute for an expert. Once centered, the optimum orbit will usually require continual correction as the climb progresses.

The optimum cruising speed between thermals depends upon the average achieved rate of climb in thermals and the wind speed and direction relative to the desired course of the flight. We will first calculate the optimum cruising speed for negligible wind. Define the following symbols:

Average time for one climb $= t_c$ (hours)
Average time for one cruise $= t_d$ (hours)
Average cross-country speed $= U$ (knots)
Average length of a cruise $= L$ (nautical miles)
Depth of convection layer $= D$ (nautical miles)
Minimum altitude to start climb $= h$ (nautical miles)
Cruising speed $= V$ (knots)
Sinking speed (function of V) $= S(V)$ (knots)
Average climbing speed $= c$ (knots)

Now

$$U = L/(t_c + t_d)$$
$$= t_d Q/(t_c + t_d)$$
$$= V/(1 + t_c/t_d)$$
$$t_d = D - h/S$$
$$t_c = D - h/c$$

So that

$$t_c/t_d = S/c$$
$$U = V/(1 + S/c)$$

As a first approximation, let us fit the polar curve with a parabola,

$$S(V) - S_0 = B(V - V_0)^2$$

where S_0 and V_0 are the coordinates of the point of minimum sinking speed on the polar curve and B is a constant. Thus

$$S/c = [B(V - V_0)^2 + S_0]/c$$
$$U = Vc/[c + B(V - V_0)^2 + S_0]$$

Maximizing this expression with respect to V gives:

$$V = [V_0^2 + (c + S_0)/B]^{1/2}$$

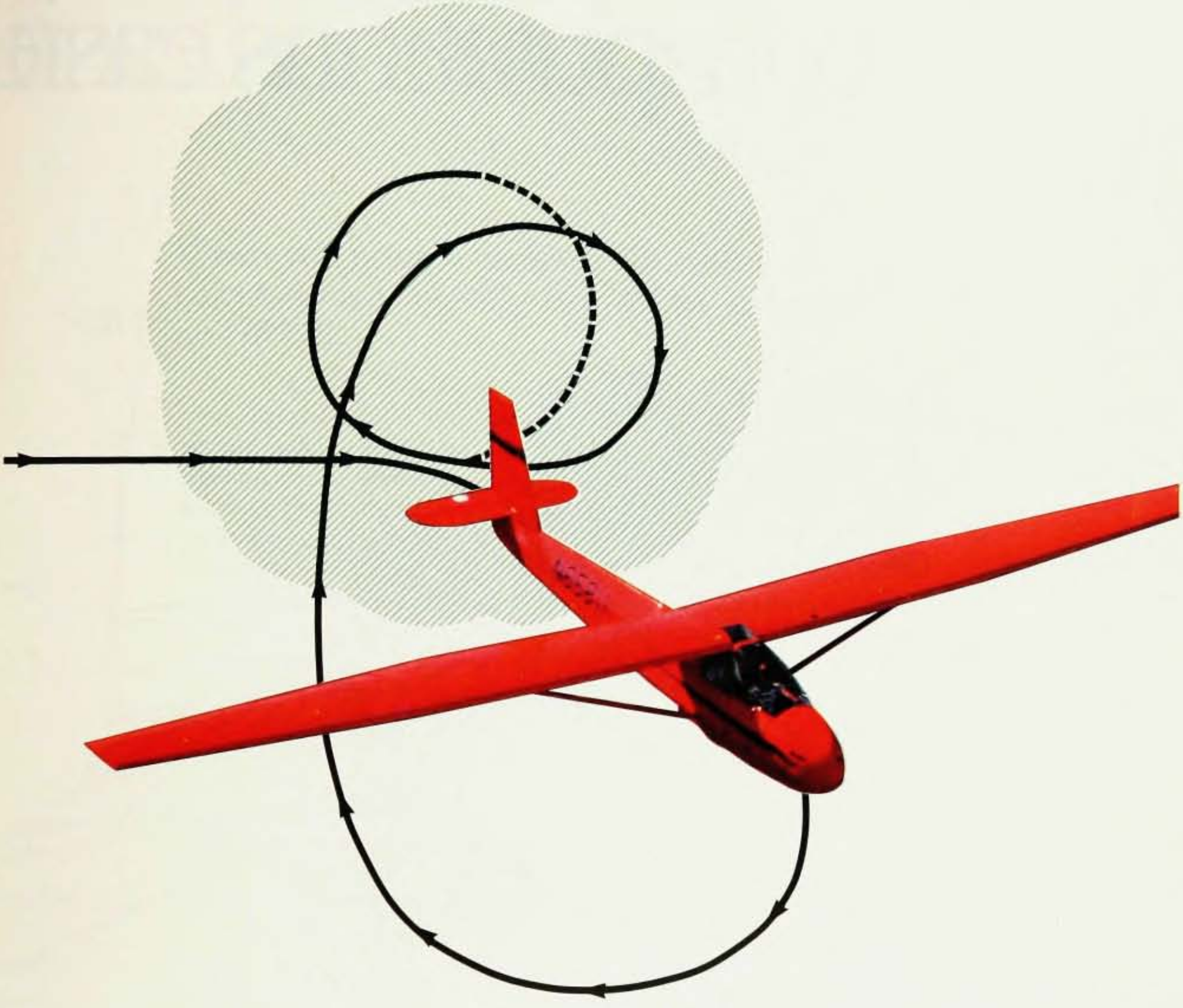
From the polar curve of Figure 1 we find,

$$S_0 = 1 \text{ knot}$$
$$V_0 = 50 \text{ knots}$$
$$B = 1/625.$$

As a result,

$$V = [2500 + 625(c + 1)]^{1/2}$$

and if $c = 5$ knots, V becomes 79 knots and the $U(\max) = 53.8$ knots. This shows that the maximum cross-country speed possible for the sailplane represented by the polar of figure 1 in conditions of no wind and with an average thermal climb rate of 5 knots is



Flight path of a sailplane (shown somewhat out of scale: wingspan is on the order of 70 ft) in a thermal, attempting to center its circling orbit (about 600 ft diameter) in the region of maximum lift. Figure 6

53.8 knots and that it requires a cruising speed of 79 knots to achieve this.

Let us see what a 20-knot headwind will do. As pointed out in the discussion of the polar curve, the effect of a headwind can be found by displacing the origin along the V axis by the wind speed v. The optimum cruising speed is then,

$$V - v = [(V_0 - v)^2 + c + S_0/B]^{1/2}$$
$$U = (V - v)c/[C + B(V - V_0)^2 + S_0]$$

Substituting $v = 20$ and still keeping $c = 5$, we get

$$V = 20 + 900 + 625 \times 6^{1/2}$$
$$= 88.2 \text{ knots.}$$
$$U(\max) = (68.2)5/[6 + (38.2)^2/625]$$
$$= 40.9 \text{ knots.}$$

With the 20-knot headwind, we require a cruising speed of 88 knots to achieve 41 knots cross-country speed.

When racing or trying for record flights, sailplane pilots often carry some sort of computer to help them determine quickly what cruising speed they should use.

Finally, I would like to point out that one of the most fascinating things about the sport of soaring is the exploration of the dynamics of the atmosphere. No two days are alike. No two thermals are the same. Scarcely a week goes by without encountering a new situation that surprises you and requires concentration to master. Soaring certainly beats driving around behind a propeller. □