Estimating Wind Velocities in Mountain Lee Waves Using Sailplane Flight Data*

Computational Imaging Group, Department of Electrical and Computer Engineering, University of Canterbury, Christchurch, New Zealand
E. ENEVOLDSON AND J. E. MURRAY
NASA Dryden Flight Research Centre, Edwards, California

(Manuscript received 24 December 2008, in final form 4 May 2009)

ABSTRACT

Mountain lee waves are a form of atmospheric gravity wave that is generated by flow over mountain topography. Mountain lee waves are of considerable interest, because they can produce drag that affects the general circulation, windstorms, and clear-air turbulence that can be an aviation hazard, and they can affect ozone abundance through mixing and inducing polar stratospheric clouds. There are difficulties, however, in measuring the three-dimensional wind velocities in high-altitude mountain waves. Mountain waves are routinely used by sailplane pilots to gain altitude. Methods are described for estimating three-dimensional wind velocities in mountain waves using data collected during sailplane flights. The data used are the logged sailplane position and airspeed (sailplane speed relative to the local air mass). An algorithm is described to postprocess this data to estimate the three-dimensional wind velocity along the flight path, based on an assumption of a slowly varying horizontal wind velocity. The method can be applied to data from dedicated flights or potentially to existing flight records used as sensors of opportunity. The methods described are applied to data from a sailplane flight in lee waves of the Sierra Nevada in California.

1. Introduction

Atmospheric mountain waves, or lee waves, are a form of atmospheric gravity wave that is generated by flow over elevated terrain in a stable, stratified atmosphere (Corby 1954; Scorer 1997). Atmospheric gravity waves arise from buoyancy forces when an air parcel is vertically displaced from its equilibrium position, leading to harmonic motion. Hydrostatic mountain waves form above the mountain and propagate vertically (Gossard and Hooke 1975; Durran 1990). However, appropriate wind speed and temperature structures with altitude can form atmospheric waveguides or ducts in which trapped or resonant lee waves can propagate horizontally (Durran 1990; Scorer 1949). Trapped lee waves generally have shorter wavelengths than those of hydrostatic mountain waves (typically 2–20 km), and they can extend far downwind of the mountain. The waveguide is imperfect, however, and there is some propagation upward and the wave loses energy.

Lee waves are of significant importance in meteorology. They can influence the vertical structure of wind speed and temperature fields, cause fluctuations in wind speeds in the lower atmosphere, and affect ozone concentration (Gill 1982; Sato 1990; Bird et al. 1997). Wave momentum dissipation with height results in drag that affects the general circulation of the atmosphere (Gossard and Hooke 1975; Holton 1983; Medvedev and Klaassen 1995). Turbulence associated with mountain waves can produce strong vertical velocities, particularly downdrafts, that can be an aviation hazard (Doyle and Durran 2002; Vosper et al. 2006). Strong waves can generate thin layers of turbulence because of wave breaking (Gossard and Hooke 1975; Chunchuzov 1996). Mountain waves also play a role in the vertical transport of aerosols and trace gases.

Our interest here is in measurement of the three-dimensional (3D) wind field structure in mountain lee waves. The wind field in the atmosphere can be measured using a variety of methods. Radiosondes give a trace of

* This work is dedicated to Steve Fossett, a true adventurer.
the horizontal wind speed and direction over the ascent path, which is determined by the wind profile with altitude. Vertical speeds can be estimated from radiosonde data by subtracting out the balloon ascent rate, although this is somewhat error sensitive. Radiosonde soundings have been used to study mountain waves (Lane et al. 2000). Very high frequency (VHF) Doppler radar uses processing of backscattered signals from inhomogeneities in radio refractive index to estimate three-dimensional wind speeds (Sato 1990; Green et al. 1979; Ruster et al. 1986). This technique has good spatial and temporal resolution and a range of up to 100 km. The equipment used, however, is large and expensive. Satellite scatterometer synthetic aperture radar (SAR) measurements of wind speeds are based on measurements of the ocean surface roughness and appropriate processing to derive surface wind speeds. SAR images have been used successfully to study gravity waves by their effect on near surface wind field variations (Vachon et al. 1994; Vachon et al. 1995; Chunchuzov et al. 2000). However, this technique is suitable only over the ocean and for low-level phenomena.

Aircraft are also used to measure wind velocities. The most comprehensive, as well as expensive, options are highly instrumented, specialized research aircraft that generally use GPS, inertial navigation (INS), and multi-hole pressure probes to derive ground velocities, platform altitude, and vector airflow, from which the 3D wind vector can be relatively easily calculated. Such systems have been used to measure mean and turbulent wind vectors (Bogel and Baumann 1991; Khelif et al. 1999) and to measure winds in mountain waves (Doyle et al. 2002; Smith et al. 2002). However, they provide a limited facility because of their expense in terms of capital outlay, maintenance, deployment, and operation. A number of less expensive options are available based on light aircraft (Wood et al. 1997) or autonomous aerial vehicles (AAVs; Holland et al. 2001; van den Kroonenberg et al. 2008). These usually incorporate similar instrumentation to research aircraft but in some cases use less expensive equipment, such as an inertial measurement unit (IMU) or a scalar airflow probe. However, they are still relatively expensive, require considerable calibration, and the lower-instrumented units require special flight maneuvers to derive the vector wind speed.

Sailplane pilots make extensive use of mountain lee waves as a source of energy with which to climb, and such flights can cover large distances and altitudes (Reichmann 2003). Indeed, sailplane flights provided some of the earliest information on mountain waves (Whelan 2000). In spite of this, little systematic and quantitative work has been done on using sailplane flights to study mountain waves. Here, we describe a novel and inexpensive method for determining three-dimensional wind speeds using data recorded during routine sailplane flights. We focus on the wind speeds in mountain waves because 1) the horizontal component of the wind speed is slowly varying in space and time for which the method is most suitable; 2) sailplane pilots often fly in and explore mountain wave systems; and 3) three-dimensional lee wave wind speeds, particularly the vertical component, are not readily measured by other means. Some preliminary results have been reported by Millane et al. (2004).

Our method makes use of relatively simple measurements that can be rather easily made from a lightly instrumented sailplane. The data used consist of post-flight logs of the sailplane GPS-derived position and airspeed. Onboard pressure and temperature measurements can be used if available, although estimates of these quantities, either from a nearby sounding or calculated from the altitude using a standard atmosphere model, would be sufficiently accurate. The horizontal component of the wind velocity is determined from the GPS-derived ground velocity and airspeed and does not require special flight maneuvers. The vertical component of the wind velocity is determined from the GPS-derived vertical speed and the sailplane sink-rate characteristics. The method has particular potential for research purposes because 1) a skilled pilot can systematically explore a lee wave system and 2) existing flight records may be used as “sensors of opportunity” for subsequent analysis. However, some modification may be necessary to compensate for the lower sampling rate of standard sailplane dataloggers used to produce existing flight records. Although our implementation is not in real time, a real-time system would be feasible.

Calculation of the true airspeed from the measured indicated airspeed is described in the next section. Algorithms for estimating the horizontal and vertical wind speeds are described in sections 3 and 4, respectively. Results obtained by applying the methods to a sailplane wave flight are presented in section 5. Concluding remarks are made in section 6.

2. Airspeed calculation

The algorithm we describe requires the sailplane airspeed (i.e., the sailplane speed relative to the air mass) as input. The airspeed is generally measured by a pitot-static system, which measures the so-called indicated airspeed (IAS), which we denote as $v_{\text{ind}}$. The IAS depends on the air density, and the actual or true airspeed (TAS), which we denote as $v_a$, is given by

$$v_a = v_{\text{ind}} \left( \frac{P_0}{\rho} \right) = v_{\text{ind}} \left( \frac{T}{T_0} \right)^{1/2} \left( \frac{P}{P_0} \right)^{1/2}, \quad (1)$$
where \( \rho, P, \) and \( T \) are the density, pressure, and temperature, respectively, and \( \rho_0, P_0, \) and \( T_0 \) are the standard sea level values, 1.22 kg m\(^{-3}\), 101 325 Pa, and 288 K, respectively. If the pressure and temperature are recorded during the flight, then \( v_g \) is straightforwardly calculated using (1). Note that pressure data are often recorded indirectly as pressure altitude, which can be converted to pressure using standard equations.

If temperature and/or pressure are not measured, then it is necessary to estimate \( T \) and/or \( P \) using a standard model of the atmosphere. Consider a single layer atmosphere (the troposphere) with a linear temperature gradient (lapse rate) \(-\Gamma\) with respect to altitude \( z\). A single layer is generally sufficient for sailplane flight, although multiple layers are easily incorporated. Using the hydrostatic equation, it is easily shown that the pressure varies with altitude as (Stull 2000)

\[
\frac{P}{P_0} = \left(\frac{T}{T_0}\right)^\alpha = \left(\frac{T_0 - \Gamma z}{T_0}\right)^\alpha,
\]

where \( \alpha = g/(R\Gamma) \), \( g \) is the acceleration due to gravity (9.81 m s\(^{-2}\)) and \( R \) is the gas constant [287 J (kg °C\(^{-1}\)] for dry air]. The lapse rate \( \Gamma \) is 9.8°C km\(^{-1}\) for dry or unsaturated air and about 5.5°C km\(^{-1}\) for saturated (moist) air. The standard atmospheric lapse rate is 6.5°C km\(^{-1}\).

Using (1) and (2) shows that, if pressure but not temperature is recorded, \( v_a \) can be calculated as

\[
v_a = v_a^{\text{ind}} \left(\frac{P}{P_0}\right)^{(1-\alpha)/2\alpha},
\]

where \( \alpha \) is calculated using an estimated value of \( \Gamma \). If temperature but not pressure is recorded, then \( v_a \) can be calculated as

\[
v_a = v_a^{\text{ind}} \left(\frac{T}{T_0}\right)^{(1-\alpha)/2}.
\]

Finally, if neither temperature nor pressure is recorded, then \( v_a \) must be calculated using (4), and an estimated value of \( \Gamma \) must be used to calculate \( \alpha \) and \( T \).

### 3. Horizontal wind velocity estimate

In this section, we describe an algorithm to estimate the horizontal wind velocity from the flight data. The horizontal components of the sailplane’s ground velocity and air velocity (velocity of the sailplane relative to the air mass) and the wind velocity are denoted \( v_g, v_a, \) and \( v_w \), with magnitudes denoted \( v_g, v_a, \) and \( v_w \), respectively. Because the glide angle of a sailplane is very small, the difference between the airspeed and its horizontal component is very small. For convenience, we therefore do not distinguish between the airspeed and its horizontal component, and we use \( v_a \) to denote both. Note that because the airspeed is the sailplane speed relative to the air, the relationship between the airspeed and its horizontal component is unaffected by flying in moving air.

We use the fundamental relationship

\[
v_g = v_a + v_w.
\]

to estimate the wind velocity from derived ground velocity and airspeed data. The ground velocity is calculated by differentiation of the GPS coordinates. At a particular time, the vector relationship (5) is shown in Fig. 1. Because only the magnitude of \( v_a \) is known, \( v_a \) is restricted to lie on a circle; therefore, there is a one-parameter family of solutions for \( v_w \). Therefore, there is insufficient information at a particular time point to uniquely determine the wind velocity.

Consider now the case where two ground velocities, \( v_{g1} \) and \( v_{g2} \), and the two corresponding airspeeds, \( v_{a1} \) and \( v_{a2} \), are known in a region of constant wind velocity. The two corresponding vector diagrams as in Fig. 1 are translated such that the origins of the vectors \( v_{g1} \) and \( v_{g2} \) coincide as shown in Fig. 2. With this construction, the solution for the wind velocity must lie on both circles, and the one-parameter family of solutions reduces to two possible solutions at the intersections of the two circles. Referring to Fig. 2, the angle \( \theta \) is given by

\[
cos \theta = \frac{v_{a1}^2 + c^2 - v_{a2}^2}{2v_{a1}c},
\]

where

\[
c = ||c|| = ||v_{g1} - v_{g2}||,
\]
and the two solutions for the wind speed are given by

\[ v_w = v_{g1} - v_{a1} R_{\theta} \cdot \mathbf{c}, \] (8)

where \( R_{\theta} \) denotes rotation by \( \theta \) and \( \cdot \) denotes a unit vector. If the circles do not intersect (because of errors in the data), then no exact solution can be obtained. In summary, given two ground velocities and the corresponding airspeeds in a region of constant wind velocity, the wind velocity can be determined up to a twofold ambiguity.

Before discussing resolution of the twofold ambiguity, it is necessary to consider the sensitivity of the solutions to errors in the measured airspeeds and ground velocities. Referring to Fig. 2, the one-parameter family of solutions is reduced to two solutions only if the two circles have different centers (i.e., the two ground velocities are different). The more different the ground velocities, the less sensitive the solutions are to errors in the data. In fact, the two solutions for the wind velocity are least sensitive when the circles intersect at 90°. The sensitivity of the wind speed estimate to errors in the airspeed measurements can be derived as follows: consider the change \( dv_w \) to the wind speed resulting from a small change \( dv_{a2} \) in the airspeed \( v_{a2} \), for fixed \( v_{a1} \) and ground velocities, as shown in Fig. 3. The sensitivity \( s \) of \( v_w \) to errors in \( v_{a2} \) is then

\[ s = \frac{dv_w}{dv_{a2}}. \] (11)

Errors in the ground velocities will have a similar effect to errors in the airspeeds. For fixed Gaussian errors in the data, \( s \) is proportional to the standard deviation of the wind speed estimate. We make this assumption and treat \( s \) as a relative standard deviation. Note that \( s \approx 1 \). For a pair of ground velocity and airspeed data, the sensitivity can then be calculated and used as a measure of the suitability of the data for wind velocity estimation.

In a region of constant wind velocity (i.e., speed and direction), multiple pairs of data at multiple time points can be used to find multiple sets of twofold-ambiguous wind velocity estimates. The ambiguities can then be resolved by choosing one of the two estimates from each pair of data such that the set of resulting estimates are most similar (or most consistent) among all choices. The measure of consistency is made more quantitative later. A final unique wind velocity estimate is then obtained by averaging these consistent estimates. Because data at adjacent sample points (times) may be highly correlated, every \( N \)th datum is used for the analysis. The value of \( N \) used depends on the sampling period.

The horizontal wind velocity in high-altitude mountain waves will generally be a slowly varying function of position and time. Our approach therefore is to partition the flight path into a sequence of regions and to assume
that the horizontal wind velocity is constant in each region. The wind velocity can then be estimated using the data within each region. We use cylindrical regions as shown in Fig. 4, with the radius and half-height of the cylinder denoted $r_{\text{region}}$ and $h_{\text{region}}$, respectively. The parameters chosen will also depend on the spatial resolution desired and the number of data points needed within a region to obtain good estimates. The entire flight path is partitioned into such regions using a simple algorithm. Note that the cylinders abut each other either at their sides or on their ends, depending on the shape of the flight path.

The wind velocity estimate in each region is found by selecting pairs of data, using each pair to generate a pair of solutions, and then selecting the members of each solution pair that are most consistent. A full solution to this problem would involve finding the solution from each pair that is the most consistent over all possible combinations of the pairs. For $d$ data within a region, there are $m = d^2/2$ pairs of data that give $m$ pairs of wind velocity estimates. An exhaustive search to find the most consistent set of solutions would require considering $2^m = 2^{d^2/2}$ partitions of the estimates into two sets. Such a computation is not feasible. We therefore limit the search by using only those pairs with sensitivity $s < s_{\text{max}}$ and also limit the number of pairs $m$ used to $m < m_{\text{max}}$. We have found that $s_{\text{max}} \simeq 1.5$ and $m_{\text{max}} \simeq 100$ are generally suitable.

The algorithm proceeds as follows for each region: all pairs of data in the region are determined and the sensitivity is calculated for each pair. The $m$ pairs of data with the lowest sensitivity $s < s_{\text{max}}$ and such that $m < m_{\text{max}}$ are selected, and the $m$ wind velocity solution pairs are calculated. For typical values of $m$ used, however, an exhaustive search of all the $2^m$ partitions is still not computationally feasible. Therefore, we select the $m' < m$ solution pairs with the lowest sensitivity and calculate all $2^{m'}$ partitions of these pairs. We typically use $m' \simeq 10$, giving about 1000 partitions. The partitions are denoted $\{A_i, B_i\}$, where $A_i$ and $B_i$ are the two sets of a partition and $i$ indexes the $2^m$ partitions. The variance of the wind speed vectors in the set $A$ is denoted $\sigma_A^2$, and the labels $A_i$ and $B_i$ for each $i$ are assigned such that $\sigma_A^2 < \sigma_B^2$. Hence, the set $A_i$ contains the putative correct solutions, and $B_i$ contains the incorrect solutions. The best (i.e., the most consistent) partition $\{A_{\text{best}}, B_{\text{best}}\}$ is that which gives the closest wind velocity estimates in the set $A_i$; that is,

$$\{A_{\text{best}}, B_{\text{best}}\} = \arg\min_{\{A_i, B_i\}} (\sigma_A^2). \quad (13)$$

The weighted (by $s^{-2}$) average of the wind velocity estimates in $A_{\text{best}}$ gives the best estimate based on the $m'$ pairs of solutions. The estimate is improved by adding one of the solutions from each of the remaining $m - m'$ pairs to $A_{\text{best}}$, one at a time in order of increasing sensitivity, such that the variance at each addition is minimized, and a new weighted average calculated. This gives the final optimum partition $\{A_{\text{opt}}, B_{\text{opt}}\}$ and the final wind velocity estimate. The wind velocity estimates in $A_{\text{opt}}$ will not generally all be independent, so the standard deviation of the final estimate $\sigma_w$ will be between $\sigma_{A_{\text{opt}}}^2$ and $\sigma_{A_{\text{opt}}}^2 / \sqrt{m}$. Because $m$ is generally large, we estimate $\sigma_w$ as $\sigma_{A_{\text{opt}}}^2 / 2$. This will generally be a conservative estimate. We also calculate the quantity $D = \sigma_{A_{\text{opt}}}^2 / \sigma_{A_{\text{opt}}}^2$, which is a dimensionless measure of the discrimination between the partitions $A_{\text{opt}}$ and $B_{\text{opt}}$, with $D = 1$ meaning no discrimination. Wind velocity estimates for which $D < D_{\text{min}}$ are discarded, and we generally used $D_{\text{min}} = 3$.

The algorithm we have described is applied to the data within each cylindrical region to determine the wind velocity estimate at the center of that region. If the flight path in a particular region is relatively straight, then the ground velocities will be similar and the sensitivities will be large. If the sensitivity is greater than $s_{\text{max}}$ for all pairs of data within a region, then no estimate is made for that region.

The GPS and airspeed data contain errors typically on the order of 10 m and 0.5--1 m s$^{-1}$, respectively. The effect of the GPS uncertainty, in particular, is potentially significant. The data are prefiltered before applying the algorithm (see section 5), which provides some reduction in these errors. However, the effect of these errors on the wind velocity estimates is ameliorated primarily by averaging the estimates in each region. For example, for the value $m = 100$ typically used, a reduction in the rms errors of the wind velocity estimates...
by a factor of approximately \(\sqrt{100} = 10\) is expected. For the results presented in section 5, with a data sampling interval of 1 s, the standard deviations \(\sigma_\omega\) are usually less than 1 m s\(^{-1}\), which is consistent with these error estimates.

4. Vertical wind speed estimate

The vertical component of the wind velocity is estimated using the vertical component of the sailplane velocity (relative to the ground) \(v_{vg}\), which is obtained by differentiating the GPS altitude. If the sailplane did not sink and the airspeed was constant, then the vertical speed of the sailplane would equal the vertical wind speed \(v_{vw}\). However, to obtain the vertical wind speed, the sink rate of the glider in still air and the effects of changes in airspeed must be taken into account.

Consider first the sailplane sink rate, which refers to the speed at which it descends in still air. The sink rate \(v_s\) is negative, because the altitude decreases with time. For a particular sailplane, the sink rate depends on the airspeed, the weight of the sailplane, and the air density. The glide angle \(\gamma\), the angle between the flight direction and the horizontal in still air, is related to the sink rate and airspeed by \(\sin \gamma = v_s/v_{a}\). Although the sink rate depends on air density, \(\gamma\) is a function of the IAS and is independent of the air density. This information is provided by the manufacturer in the “flight polar,” which is a plot of the sink rate at sea level air density \(v_{o0}\) versus IAS for different sailplane weights. We denote this function by \(v_{o0}(v_{a}^{\text{ind}})\). Because the glide angle for a particular IAS is independent of air density, the sink rate \(v_s\) can be calculated at any altitude (air density) from the flight polar as

\[
v_s = \frac{v_{a}^{\text{ind}}}{v_{o0}(v_{a}^{\text{ind}})},
\]

where \(v_a\) is calculated from \(v_{a}^{\text{ind}}\) as described in section 2.

The flight polar applies to unbanked flight so that the above calculation of sink rate is less accurate when the sailplane is turning. However, significant bank is typically present during only a small proportion of a wave flight; because its effect is not straightforwardly incorporated, we simply calculate the bank angle \(\alpha\) at each position along the flight path and exclude points where \(\alpha\) exceeds some specified maximum value \(\alpha_{\text{max}}\) to calculate the vertical wind velocity. We typically used \(\alpha_{\text{max}} = 30^\circ\). The bank angle is calculated as follows: first, the flight path relative to the air is determined by subtracting out the integrated horizontal wind velocity (determined as in section 3) from the flight path over the ground. This removes the effect of wind drift. The curvature of the flight path (relative to the air) is then calculated at each point. The bank angle is then calculated by determining the centripetal force required to produce the measured curvature. We found that typically less than 5% of the vertical air velocity estimates are excluded because of excessive bank.

The second effect that needs to be considered is that of changing sailplane airspeed. Consider, for example, the case where the sailplane airspeed is decreasing. In this case, the kinetic energy of the sailplane is decreasing; aside from the effects of drag, it is being converted to potential energy (i.e., the sailplane is climbing, or descending more slowly, relative to its normal sink rate at constant airspeed). The opposite occurs if the sailplane airspeed is increasing. This additional vertical speed must be subtracted out when calculating the vertical wind speed. This effect can be significant, even for modest rates of change of airspeed. The additional vertical speed component \(v_e\) is calculated by equating the rates of change of kinetic and potential energy, giving

\[
v_e = -\frac{v_{a} \, dv_{a}}{g \, dt},
\]

recalling that \(g\) is the acceleration due to gravity and \(dv_{a}/dt\) is the rate of change of airspeed.

Incorporating these two effects, the vertical wind speed is estimated as

\[
v_{vw} = v_{vg} - v_s - v_e.
\]

In practice, the effect of \(v_e\) is fairly small except at high airspeeds, but the effect of \(v_s\) can be significant. The vertical air velocity estimates are calculated using these calculations at each point in the flight path (except those excluded because of excessive bank) and averaged over a suitable time window.

5. Results

The methods we have described were applied to data from a flight in lee waves of the Sierra Nevada in Southern California. This is flight 39 of the Perlan Project (Carter et al. 2003). The flight began at California City (35.2°N, 118.0°E, altitude 750 m) at 2140 UTC 24 April 2003 (1340 LT). The sailplane was launched by towing behind a powered aircraft and releasing from tow approximately 30 min after takeoff at an altitude of approximately 3500 m. The pilots were E. Enevoldson and S. Fossett. The flight lasted 4.8 h and proceeded along the Owens Valley to the east of the Sierra Nevada to Big Pine and returned to California City. The flight path is shown in Fig. 5. A plot of flight altitude versus time is shown in Fig. 6. The maximum altitude was...
13 044 m. There was extensive middle cloud upwind of the Sierra Nevada and lenticular clouds were present in layers up to 14 000 m. Large lee rotors were present in the Owens Lake area.

The sailplane was a production Glaser-Dirks DG-505M (DG Flugzeugbau GmbH, Bruchsal, Germany) specially equipped for high-altitude flight and flown at an all-up weight of 805 kg (wing loading 44 kg m$^{-2}$). In addition to the usual instruments, the sailplane was equipped with a modified Volkslogger GPS positioning system and pressure transducer (Garrecht Avionik GmbH, Bingen, Germany), a Borgelt B-50 airspeed indicator (Borgelt Instruments, Toowoomba, Australia), and a Platinum resistance temperature detector (RTD) outside air temperature probe. GPS fixes were obtained at 1-s intervals from the Volkslogger, and pressure recordings were made at 8-s intervals. Airspeed and temperature measurements were made at approximately 2.5-s intervals. All data were merged into a serial data stream and recorded on a custom datalogger. All data (except GPS fixes) were linearly interpolated onto the 1-s GPS time stamps post flight. The sailplane flight polar was determined using a combination of the 45 kg m$^{-2}$ flight polar from the DG-505M flight manual and measurements made by comparison flights with another standard sailplane. The sink rate varies between approximately 0.5 and 1.3 m s$^{-1}$ at 25 and 40 m s$^{-1}$ IAS, respectively.

FIG. 5. Flight path shown in blue (displayed with SeeYou; available online at http://www.seeyou.ws). The cross at the bottom denotes the takeoff point at California City. Position as labeled is relative to the takeoff point. The black line denotes the ridge line, as described in the text.

FIG. 6. Sailplane altitude vs time after takeoff.

The GPS coordinates and airspeed were low-pass filtered with a cutoff frequency of 1 Hz. The ground velocity was calculated, separately for the longitude and latitude components, by differentiating the filtered position data using central differences. The horizontal wind speeds were estimated as described in section 3 using the parameters $r_{\text{region}} = 2$ km, $h_{\text{region}} = 100$ m, $s_{\text{max}} = 1.5$, $m_{\text{max}} = 100$, $m' = 10$, $N = 5$, and $D_{\text{min}} = 3$. Typical values obtained for $\sigma_w$ were in the range of 0.2–1.0 m s$^{-1}$, and typical values for $D$ were in the range of 2–25. An example of the clustering analysis for one horizontal wind speed estimate is shown in Fig. 7. In this example, there are 100 pairs of data, and the partition into the sets $A$ and $B$ are shown by the circles and crosses, respectively. The partition gives a clear solution in this case, as shown with $\sigma_w = 0.6$ m s$^{-1}$ and $D = 5$.

Close-ups of two portions of the flight path and the corresponding horizontal wind velocity estimates are shown in Fig. 8. The flight segment in Fig. 8a is near the center of Fig. 5, and that in Fig. 8b is near the top of Fig. 5. Note also that estimates of the horizontal wind velocity are obtained where the flight path is changing direction but not where it is relatively straight. Therefore, more estimates are obtained in Fig. 8b than in Fig. 8a as a result of the more convoluted flight path in the latter than in the former. The horizontal wind velocity is expected to be relatively constant in thin altitude layers and over fairly large horizontal areas. This is evident in Fig. 8, indicating stability of the method.

The estimated wind velocities for the whole flight were collected into altitude bins 200 m thick and averaged, separately for the climbing and descending portions of the flight, and the speed and direction are shown versus altitude in Fig. 9. Note the increasing wind speed with altitude and the fairly constant west-southwest
direction. For comparison purposes, the wind speeds and directions recorded by radiosonde soundings at Edwards Air Force Base (AFB), Edwards, California (approximately 120 km south of the center of the flight path), at 1500 UTC 24 April 2003 and at Desert Rock, Mercury, Nevada (approximately 180 km east of the center of the flight path), at 0000 UTC 25 April 2003 are also shown in Fig. 9. These soundings are approximately 9 h before and at the time at the midpoint of the flight, respectively. Inspection of the figure shows good consistency between the estimated wind speeds and the soundings, given the different locations and times and keeping in mind that the radiosondes are drifting east. Note the good agreement between the wind speeds at low levels derived from the ascending flight path data and from the Edwards AFB radiosonde data, where the flight path and the radiosonde location are geographically quite close.

The rms differences between the sailplane-derived estimates of the wind speed and direction and the average of the two soundings are 6 m s\(^{-1}\) and 8° (above 4000 m), respectively. In comparison, the rms differences between the two soundings are 3 m s\(^{-1}\) and 9°. Wind speed and direction estimates obtained from other aircraft-based systems have given standard deviations of 0.5–1.0 m s\(^{-1}\) and 10° for AAVs (van den Kroonenberg et al. 2008) and 2 m s\(^{-1}\) for light aircraft (Wood et al. 1997). Overall then, the precision of the estimates we obtain is reasonable, given the variations in the radiosonde soundings, and comparable to other similar aircraft-based methods.

The vertical wind speed along the flight path was estimated as described in section 4. The maximum bank angle was set to \(\alpha_{\text{max}} = 30°\), resulting in 5% of the data points being excluded because of excessive bank. The rate of change of airspeed, used to calculate the correction \(v_r\) described in section 4, must be calculated over a time interval longer than the time constant of the low-pass filter to obtain a good estimate. We found that using finite differences over a time interval of 8 s gave good results. The vertical wind speed estimates were thus obtained every 1 s and were low-pass filtered with a cutoff frequency of 0.2 Hz.

Because the flight path traverses a small region of the total volume of airspace in which the wave exists, the estimates obtained are a sparse sampling of the wave structure. An inherent problem then is how to interpret this sparse information. Furthermore, although the wave structure is likely to be stable over periods on the order of 10–30 min, it may vary over hours. A denser sampling in space and time may be feasible using special purpose flights or multiple sailplanes, as described in section 6. For this flight, we present the vertical wind speeds in small regions to show the local wave structure.

For fixed meteorological conditions, the wave structure is, in principle, fixed relative to the topography. A convenient reference point for a hill or ridge is the center of the ridge. For complex terrain, the situation is more complicated. However, particularly for the northern part of this flight, the dominant topography is the eastern ridge of the mountain range, running north-northwest to south-southeast, to the west of the flight path. We therefore take as a reference the center line of this ridge, which we refer to as the “ridge line.” Points at maximum altitude along this ridge were located manually, and the ridge line was determined by spline interpolation. The resulting ridge line is shown as the black line in Fig. 5.

The wave structure is most clearly evident in a plot of the vertical wind speed versus distance downwind from
a particular point on the ridge line and at a fixed altitude. The streamlines in such a plot are expected to approximately follow an exponentially damped sinusoid; for a constant horizontal wind speed, the vertical wind speed is also an exponentially damped sinusoid that is phase shifted relative to the streamlines. The only primarily downwind segment of significant length in this flight is a 4-min segment near the maximum altitude of the flight, south of Lone Pine. A close-up of this flight segment is shown in Fig. 10a; it extends approximately 20 km downwind, the altitude varies between 12,360 and 12,500 m, and it is downwind of a 6-km section of the ridge line. The estimated vertical wind speed versus distance downwind from the ridge line is shown in Fig. 10b. Inspection of the figure shows a wave structure, and a least squares fit of an exponentially damped sinusoid to the data is shown in Fig. 10b. The fit is quite good and gives a wavelength of 10 km. A calculation of the buoyancy wavelength using the temperature and wind speed data (Stull 2000) gives values varying between 9 km at the ridge height of 3000 m and 18 km at an altitude of 12 km. Given the simplicity of the buoyancy wavelength approximation, the varying wind speed with altitude, and the complex terrain, the agreement is reasonable. We note that the vertical wind speed estimates appear to be offset from zero by approximately 0.7 m s$^{-1}$. The reason for this is unknown and did not occur with the analysis of data from other flights.

A close-up of a 30-min flight segment that is approximately parallel to the ridge line is shown in Fig. 11a. The flight path is replotted in Fig. 11b as a function of distance downwind from the ridge line and color coded by the derived vertical wind speed. The flight altitude versus position north is shown in Fig. 11c. The results in Fig. 11b show a strong vertical wind speed for positions between 6 and 12 km downwind from the ridge line, corresponding to the leading edge of the wave. The short excursion of the flight path upwind to between 1 and 5 km downwind from the ridge line takes it out of the leading edge, and weaker vertical speeds are evident. This is consistent with expected behavior.

Derived vertical wind speeds for longer flight segments are more difficult to interpret because of the complicated effects of complex terrain upwind of the flight path. However, if the ridge cross section was uniform and conditions were time invariant, then the vertical speed would depend approximately only on the altitude and the distance downwind from the ridge. We consider a 1-h flight segment that is around the maximum altitude of the flight and is downwind of a 50-km length of the ridge line. The derived vertical wind speed in this flight segment, as a function of distance downwind
from the ridge line and altitude is shown in Fig. 12, with
the vertical wind speed coded by color. An inspection of
the figure shows the sailplane tracking the leading edge
of the wave with large vertical wind speeds, the leading
edge tilted upwind with increasing altitude, a well-
known phenomenon resulting from viscous drag (Stull
2000), and the expected decrease of wave strength with
increasing altitude. A secondary weaker wave crest lo-
cated approximately 10 km downwind is evident and is
the same as that shown in Fig. 10. Hence, despite the
sparse sampling and the complex topography and wave
structure, this plot shows some expected characteristics
of the wave relative to the topography.

6. Conclusions

Data collected during sailplane flights are potentially
useful for atmospheric studies. Existing data or routine
flights can be treated as “sensors of opportunity,” and
there is also the potential of conducting flights specifically
for this purpose. Basic flight data consisting of
logged position and airspeed can be used to estimate the
three-dimensional vector wind speed along the flight
path. This approach is suitable for estimating wind ve-
icities in mountain lee waves where the horizontal
component is assumed to vary slowly in space and time.
Methods for effecting this estimation have been de-
scribed. Implementation of the algorithm and applica-
tion to a sailplane wave flight show that it is effective,
with good agreement between derived horizontal wind speeds and those from radiosonde soundings and with derived vertical wind speeds that are overall consistent with expectations in terms of geometric relationships with the topography.

The utility of results obtained using this method depends largely on the flight path taken by the sailplane pilot. More comprehensive and useful results can potentially be obtained with different flights. For example, with dedicated flights, particular areas of the wave system could be repeatably transversed to obtain data that are quite dense in space and time. Also, there are occasions when many sailplanes are flying in the same airspace, and data collected by multiple sailplanes would also provide a denser sampling. One potential application of the kind of results obtained, even if rather sparse in space and time, is for comparing with results from numerical modeling of mountain waves.

Acknowledgments. We are grateful to the University of Canterbury for award of a summer scholarship to RGB, the NZ TEC for award of Top Achiever Doctoral scholarship to NZ and VLL, the Electrical and Computer Engineering Department at the UOC for a research grant, and NASA for support. Perlan Project flights are supported by the Steve Fossett Challenges. We also acknowledge our late friend Harman Halliday, who encouraged us and provided us with the first flight data in the early stages of this project.

REFERENCES


