Measuring 3D wind fields in mountain waves using sailplane flight data

Ni Zhang, Alan Hunter, Rick Millane,
Einar Enevoldson and Jim Murray

Computational Imaging Group
Department of Electrical and Computer Engineering
University of Canterbury, Christchurch, New Zealand
and NASA Dryden Flight Research Center
Edwards, California, USA

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Objective

The idea here is to use a glider as a meteorological platform, or “sensor of opportunity.”

Our particular interest is in using basic flight data collected during wave flights to map out the three-dimensional wind field in the wave.

Flights may be conducted especially for this purpose, but there is also potential to use existing flight records.

My focus in this talk will be on the data processing methods used rather than on the meteorological results.

Other work in this area

OSTIV Mountain Wave Project (MWP)

Lindemann, Heise and Herold, Technical Soaring, 32, 93-96 (2008).

Data collected from a well-instrumented sailplane and results presented for flight in the Andes.

Jorg Dummann, Technical Soaring, 33, 109-116 (2009).

Comprehensive study of statistical characteristics of lee waves in Northern Germany using archived flight data.

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Use of a highly instrumented sailplane

With sufficient instrumentation, determining the 3D wind vector is relatively straightforward.

For example using an INS, IMU, and/or a 3D airspeed probe, allows a least the horizontal component of the wind vector to be easily calculated.

However, such systems are expensive and not normally installed in gliders.

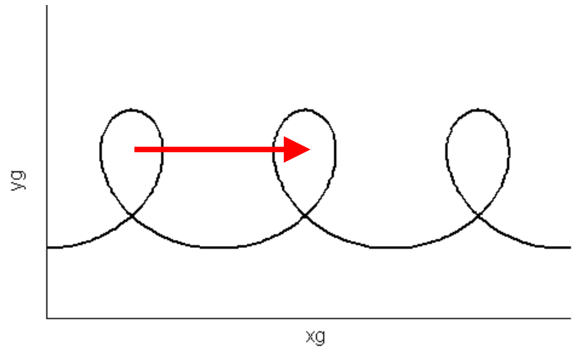
Furthermore, they do not usually make an accurate measurement of the vertical component of the wind vector.

Use of sailplane flight computers

Commonly used sailplane flight computers compute estimates of the wind speed and direction and, in effect, the vertical wind speed (TE or netto vario).

However, there are difficulties with these also.

- The wind speed and direction estimates are often not particularly accurate. For example, they are generally only accurate if the pilot is executing a constant rate turn.



Use of flight computers

- The algorithms for computing the horizontal wind speed and direction and the vertical wind speed (TE or netto vario) are proprietary and one is not certain of their limitations and precision.
- Not all sailplanes carry such flight computers.
- Although the horizontal and vertical wind speed estimates are calculated in real time, they are usually either not logged or logged only in summary form.

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Approach

Goal is to develop algorithms than can estimate the 3D vector wind field from basic data collected with minimal instrumentation during routine sailplane flights.

Consider:

1. GPS and airspeed data (and optional pressure and temperature data).

2. GPS data only.

Objective to estimate the 3D vector wind speed along the flight path.

For convenience, the wind vector is estimated in two stages:

The horizontal component

The vertical component

Initially we have developed algorithms for processing data collected from Perlan project flights.

The data sets consist of:

GPS

Air speed

Pressure and temperature

All logged at between 1 sec and 2.5 sec sampling periods.

Algorithm summary

1. Convert the indicated airspeed to true airspeed based on temperature, pressure and/or a standard atmospheric model.

2. Calculate the horizontal wind speed and direction using sets of sailplane horizontal ground velocities (from GPS) and the airspeed.

3. Calculate the vertical air velocity from the sailplane vertical velocity (from GPS altitude), the glider sink rate, and correcting for energy exchange due to glider acceleration.

4. Use the vector wind velocity to map out the wave in the vicinity of the flight path and relative to the topography.

True airspeed

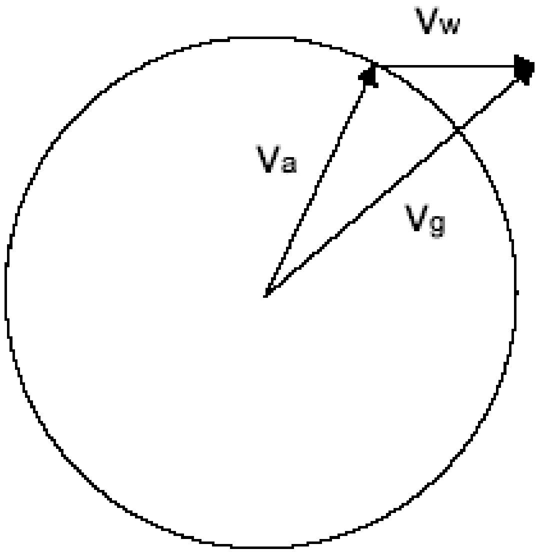
Calculate TAS from IAS using either temperature and pressure recording or values of the these from a standard atmosphere model.

$$\mathrm{TAS} = \mathrm{IAS}\sqrt{\frac{T}{T_0}\frac{P_0}{P}}$$

Horizontal wind velocity

Basic relationship:

The inertial, or “ground” velocity is the vector sum of the velocity relative to the air and the wind velocity.

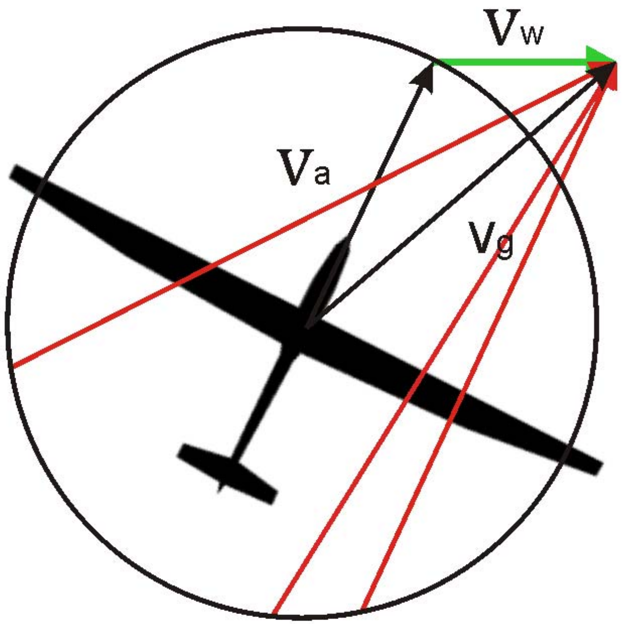


$$\mathbf{V}_g = \mathbf{V}_a + \mathbf{V}_w$$

Horizontal wind velocity

However, if we don't have heading information, we know only the length, but not the direction of the vector v_a.

There is then a one-parameter family of solutions for the wind velocity that lie on a circle.

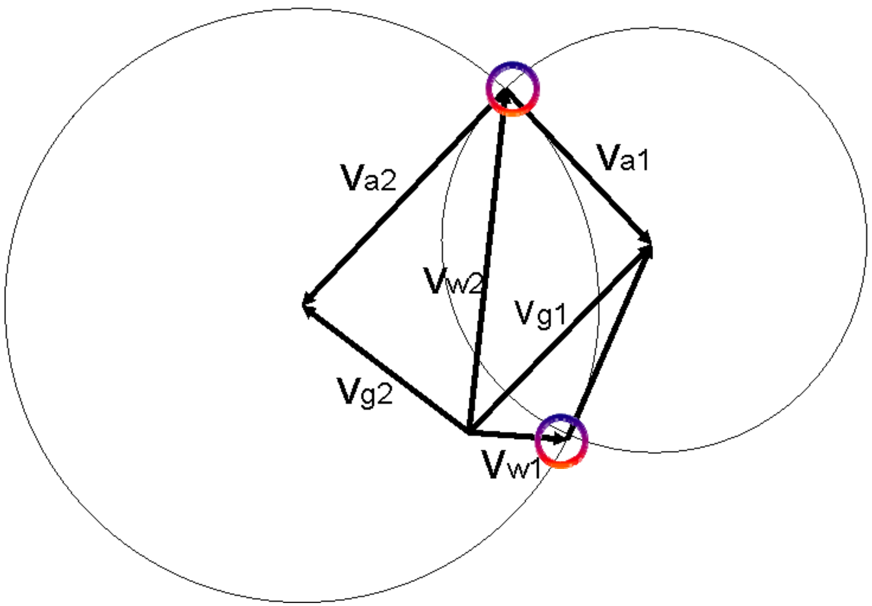


Horizontal wind velocity

Consider now the wind velocity constant in a small region (generally the case for mountain waves).

Two sets of data (ground speed and airspeed) are collected in this region.

Then the solution corresponds to the intersection of two circles.



Horizontal wind velocity

So the one-parameter set of solutions for the wind velocity is reduced to a two-fold ambiguity.

The ground velocities need to be different for the two circles to be distinct.

A more stable solution is obtained the more different the two ground velocities

Horizontal wind velocity

Now imagine that we make a (large) number of measurements within such a region.

We will then get multiple sets of two-fold ambiguous solutions.

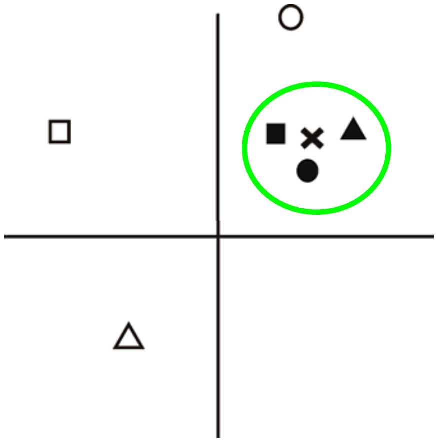
It should then be possible to find the member of each pair that is "most consistent." This resolves the two-fold ambiguities.

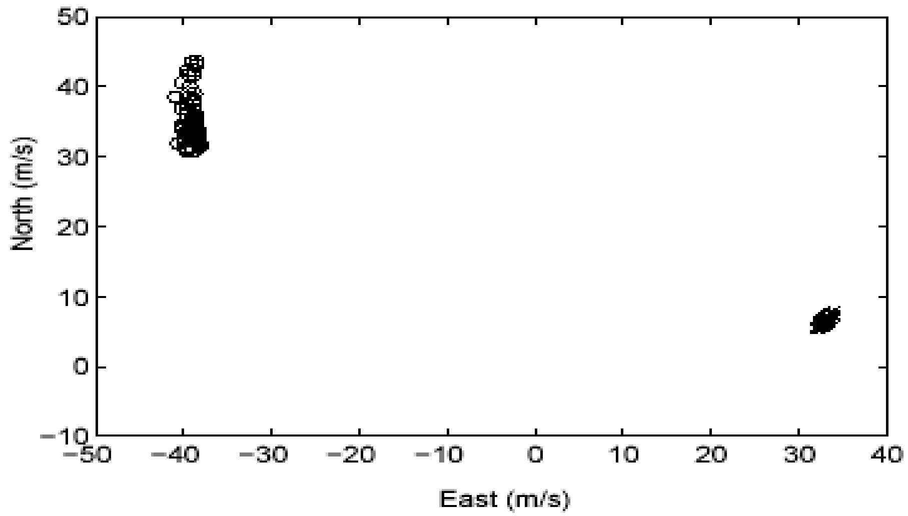
This is done using a clustering analysis.

Also make use of a sensitivity analysis based on the differences in the ground velocities for each solution pair. This allows removal of unreliable solution pairs.

The horizontal wind velocity is then estimated as the centroid of the most compact cluster of solutions.

Horizontal wind velocity



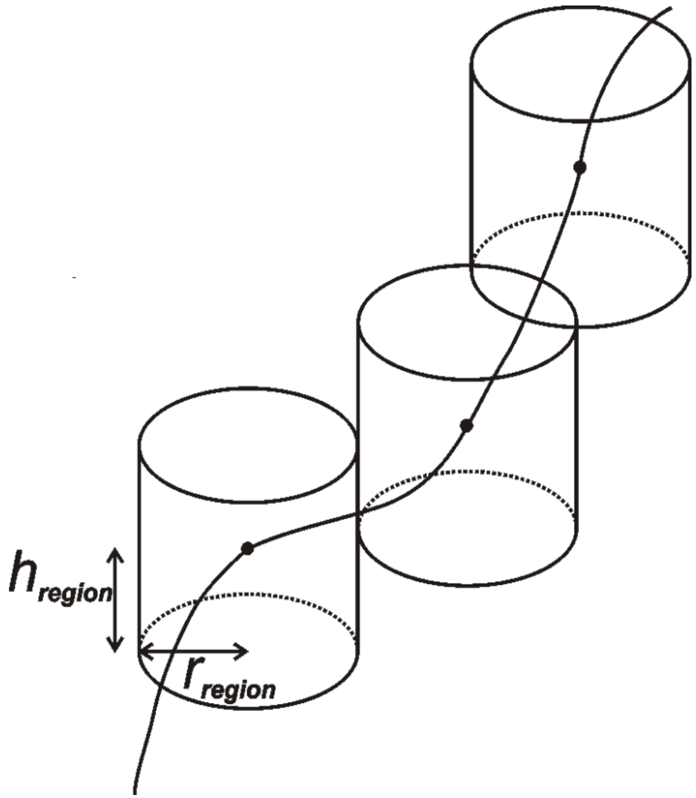


Horizontal wind velocity

Partition the flight path into cylindrical regions of suitable size.

Run the above algorithm on pairs of data points within each region to estimate the horizontal wind speed at the center of the region.

Conclusion: An algorithm for estimating the horizontal wind speed from GPS and airspeed data for general flight paths.



Vertical wind speed

- Calculate glider vertical velocity from GPS altitude.
- Correct for glider sink rate and energy exchange to get the vertical wind velocity.

$$v_{vw} = v_{vg} - v_{vs} - v_{ve}$$

$$v_{vw} = v_{vg} - \frac{TAS}{IAS} p(IAS) + \frac{v_a}{g} \frac{dv_a}{dt}$$

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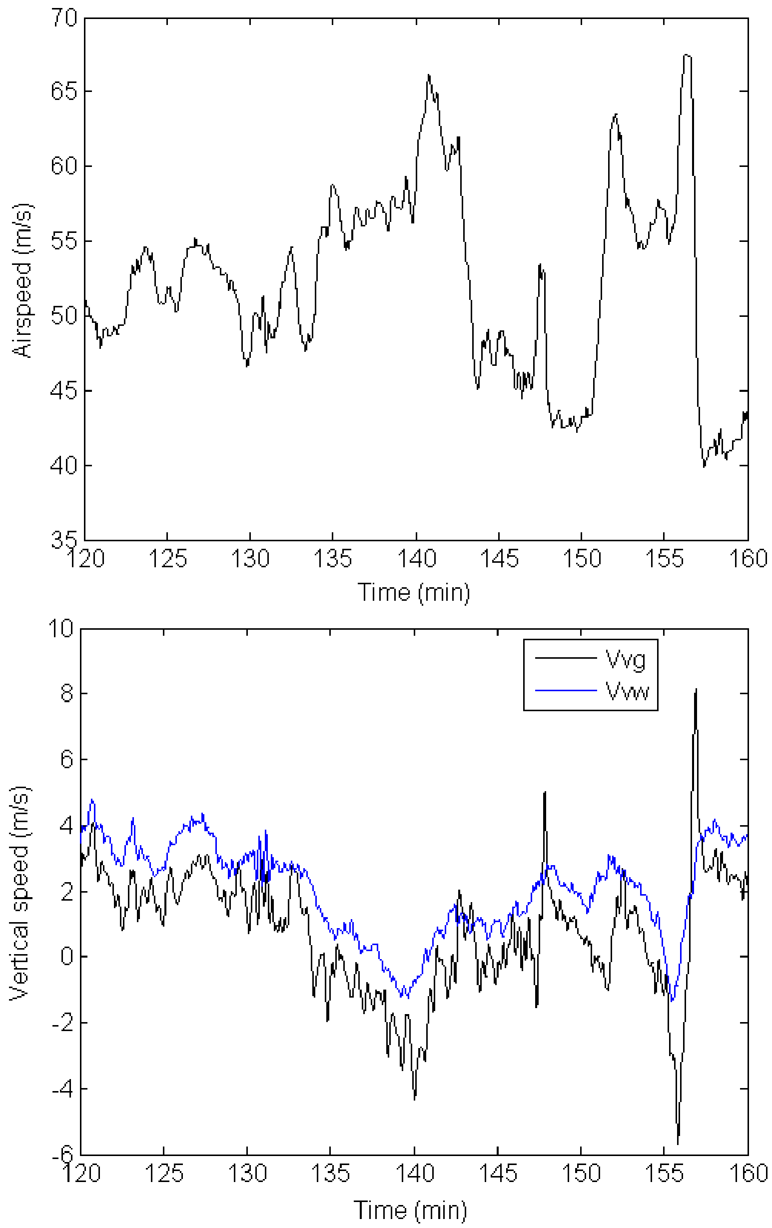
Corrections to vertical speed



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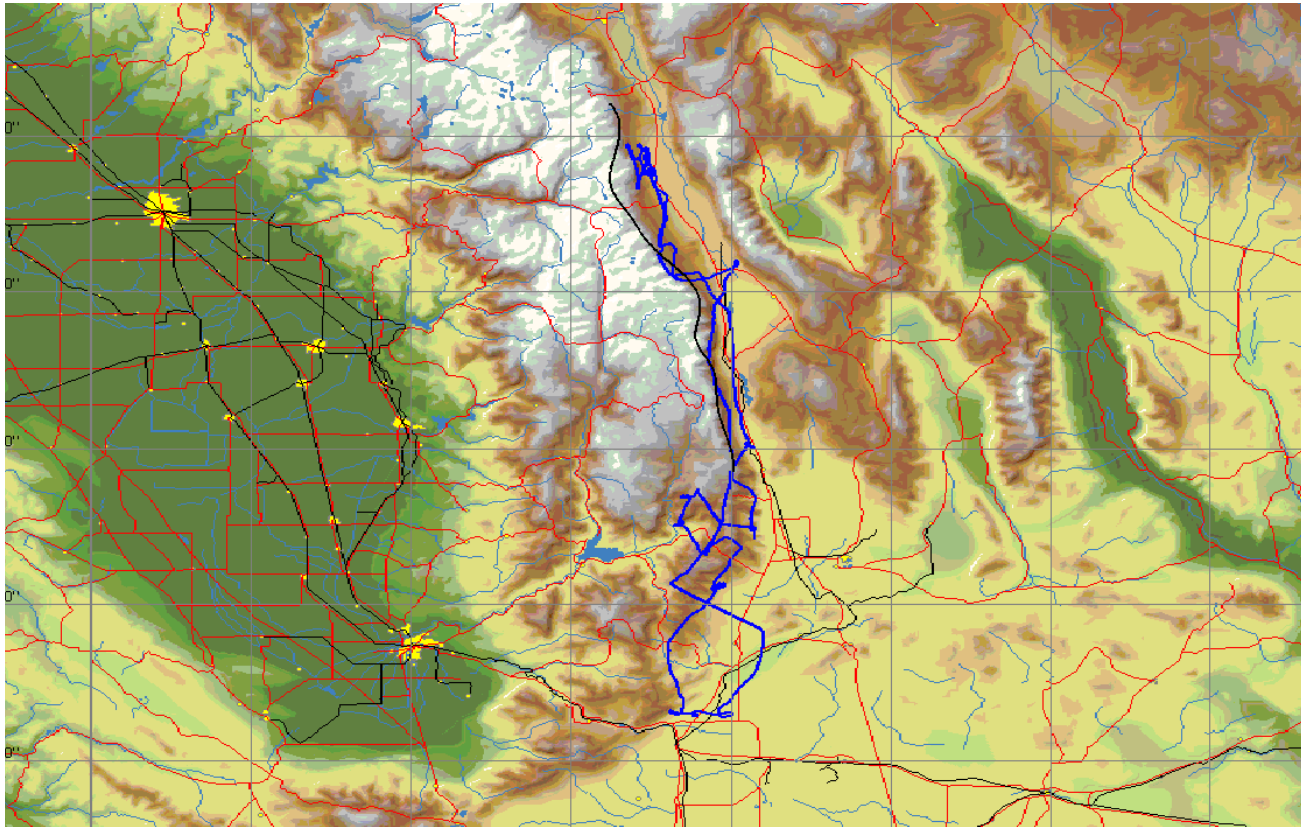
Results: Perlan flight in the SN wave



Black: Ridge line

Blue: Flight path

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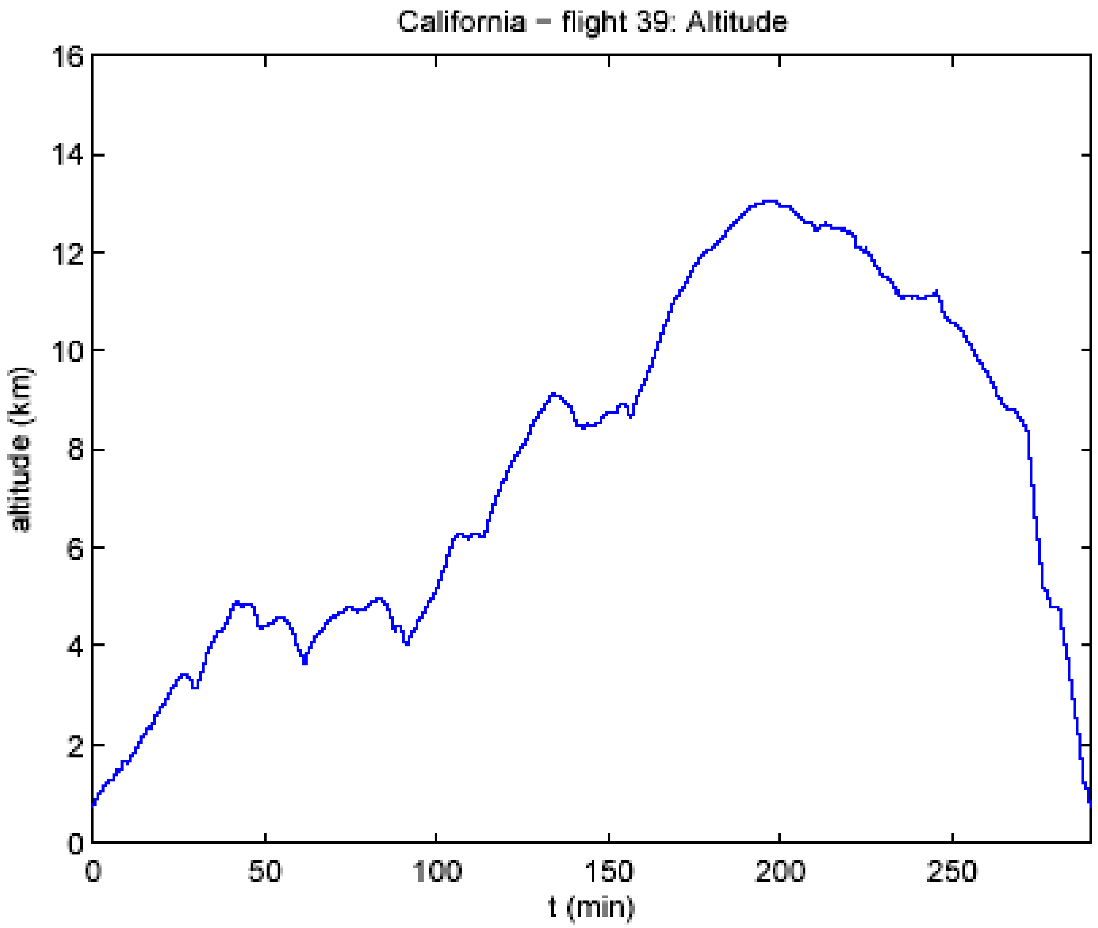
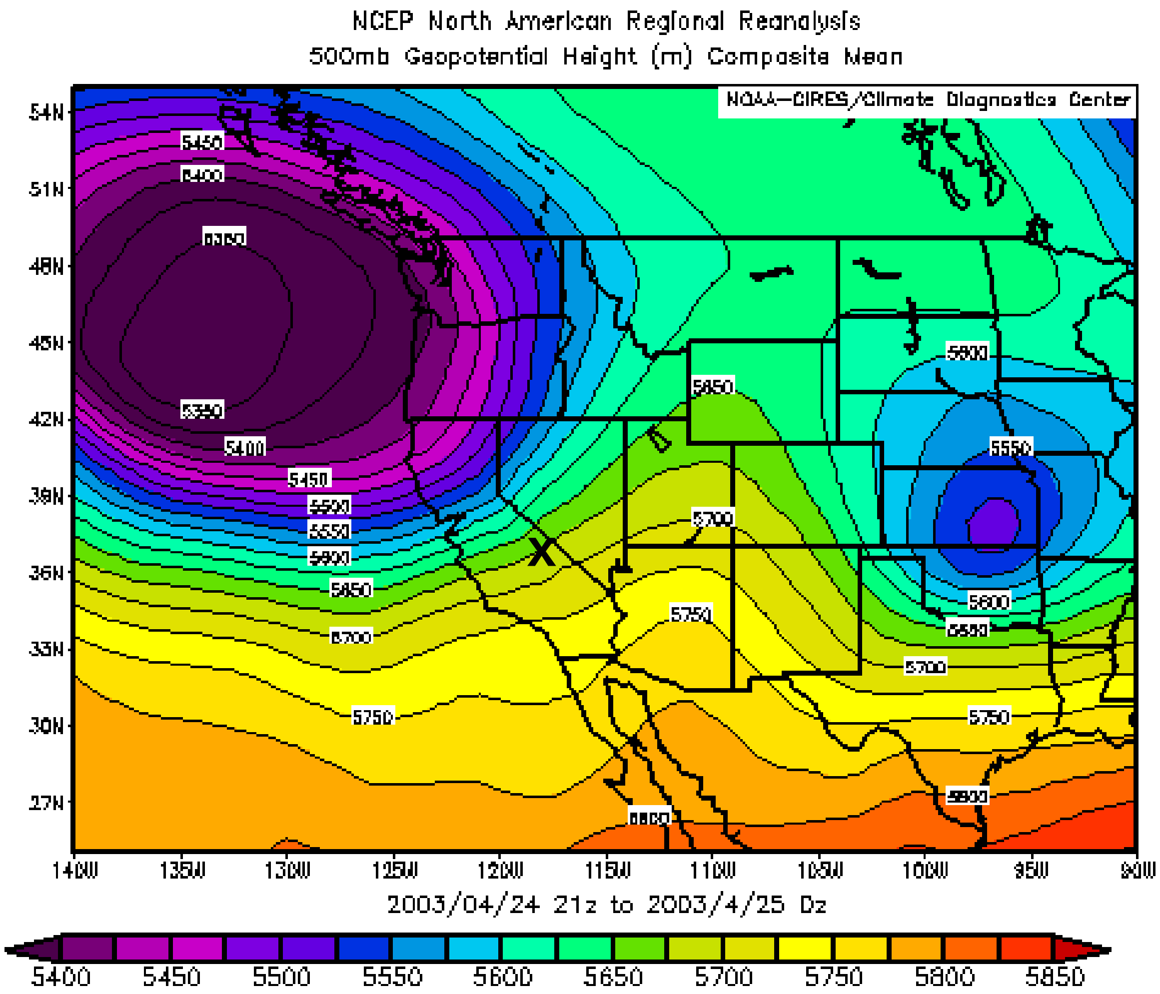

California – flight 39: Altitude
altitude (km)
t (min)
0
2
4
6
8
10
12
14
16
0
50
100
150
200
250


NCEP North American Regional Reanalysis
500mb Geopotential Height (m) Composite Mean
NOAA-CIRES/Climate Diagnostics Center
54N
51N
48N
45N
42N
39N
36N
33N
30N
27N
140W
135W
130W
125W
120W
115W
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105W
100W
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2003/04/24 21z to 2003/4/25 0z
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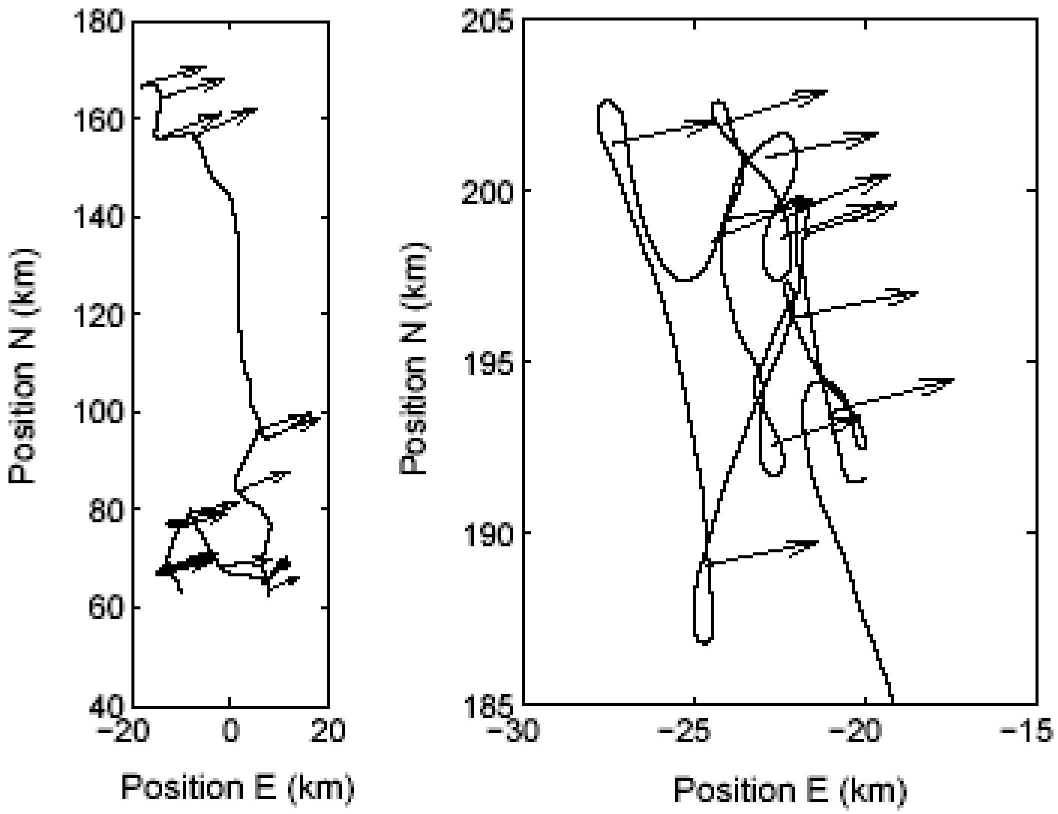

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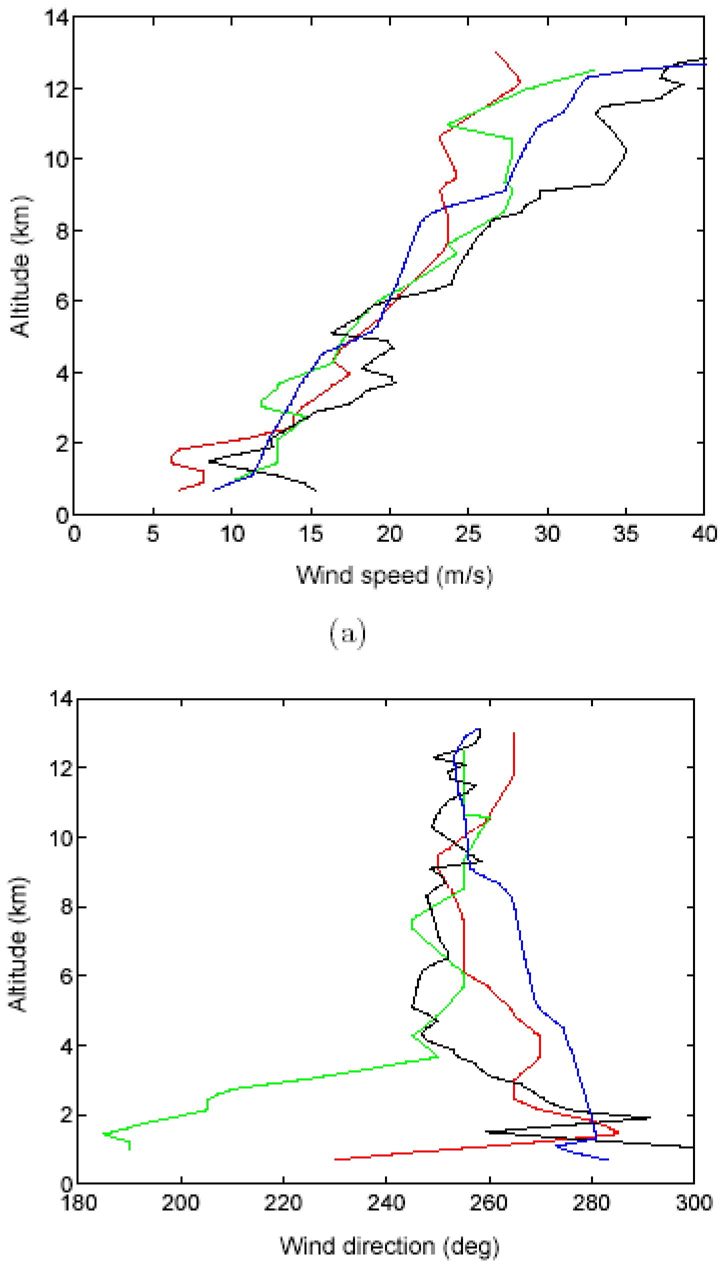
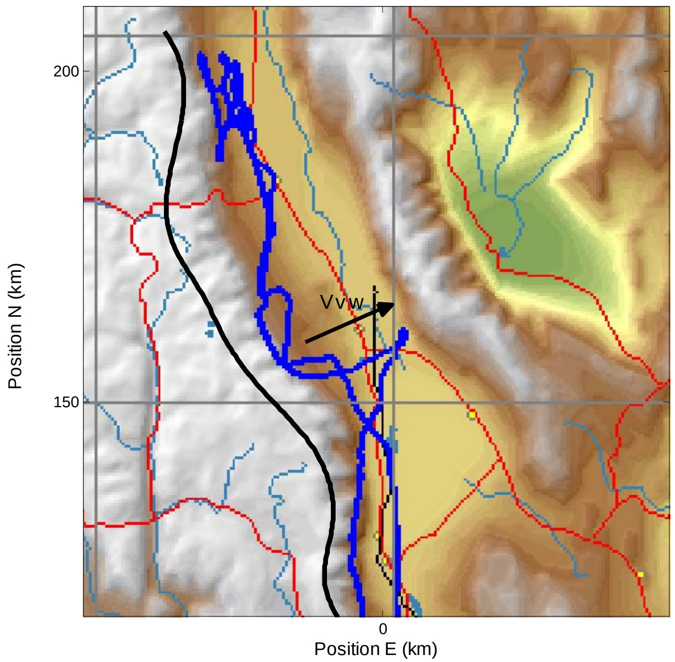
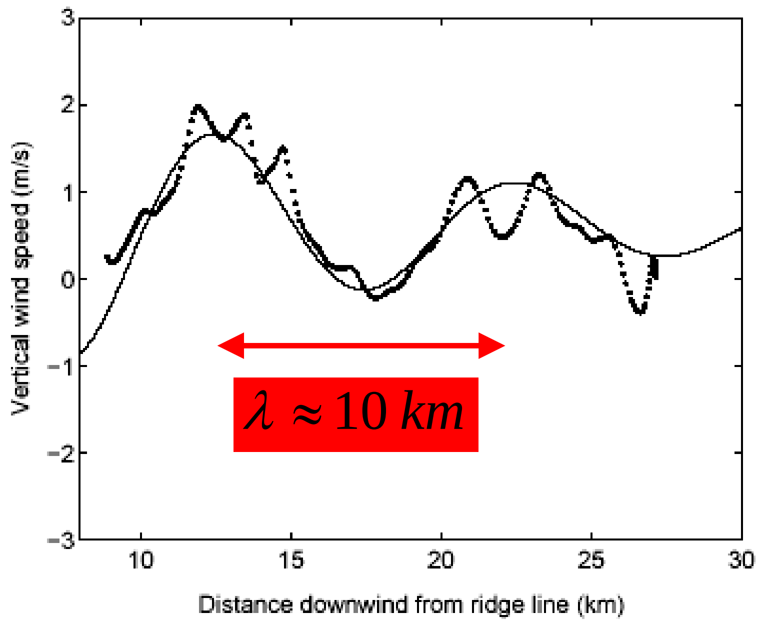


Ascending
Descending
AFB
DR





Wavelength calculated from the Brunt-Vaisala (buoyancy) frequency (calculated from the temperature and lapse rate) gives

Wavelength = 9 km at an altitude of 3 km

Wavelength = 18 km at an altitude of 12 km

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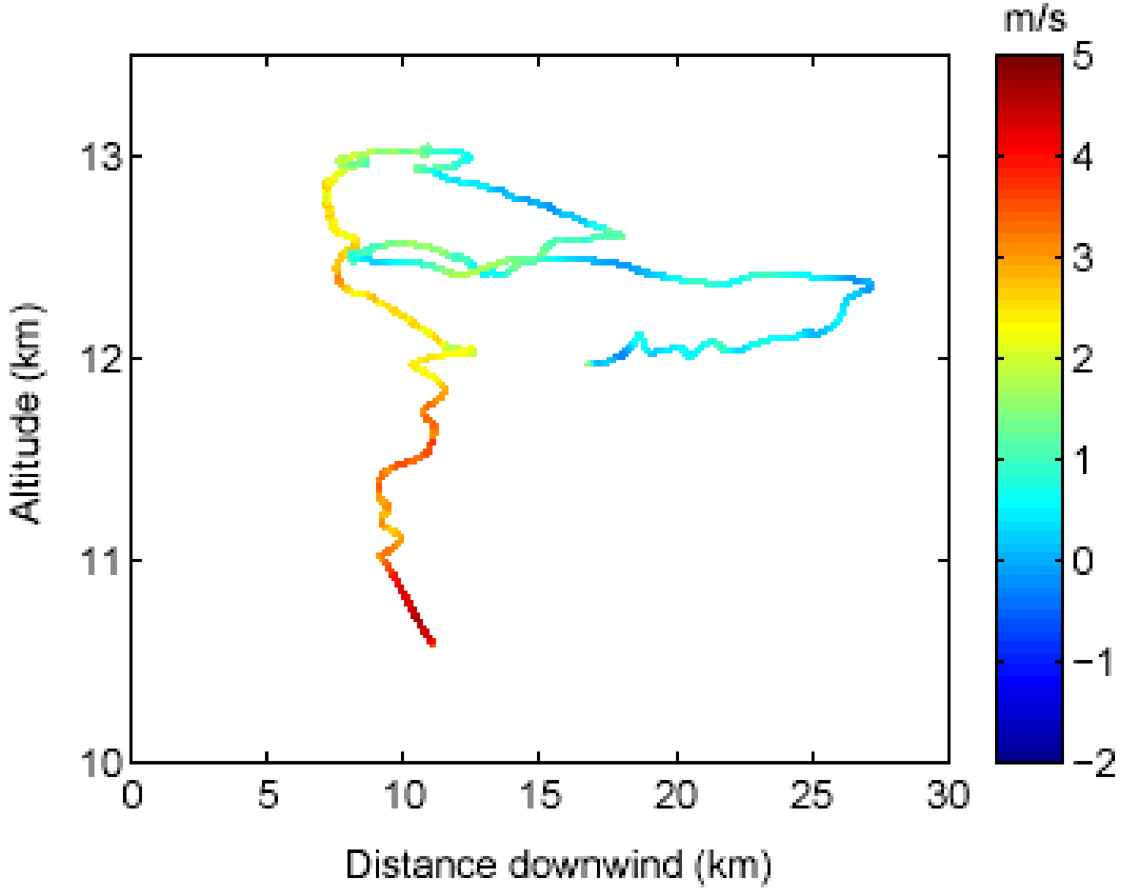
Vertical wind speed



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Can we do this without airspeed data?

Need to incorporate other information to make up for the loss of airspeed data.

For example:

- Approximate horizontal wind velocities from reanalysis.
- Special (but maybe infrequent) flight maneuvers (e.g. circling).
- Incorporate other known constraints, e.g. slowly varying wind direction (over a larger region), slowly varying sailplane heading, etc.
- Combine the data with this information as a statistical estimation problem.

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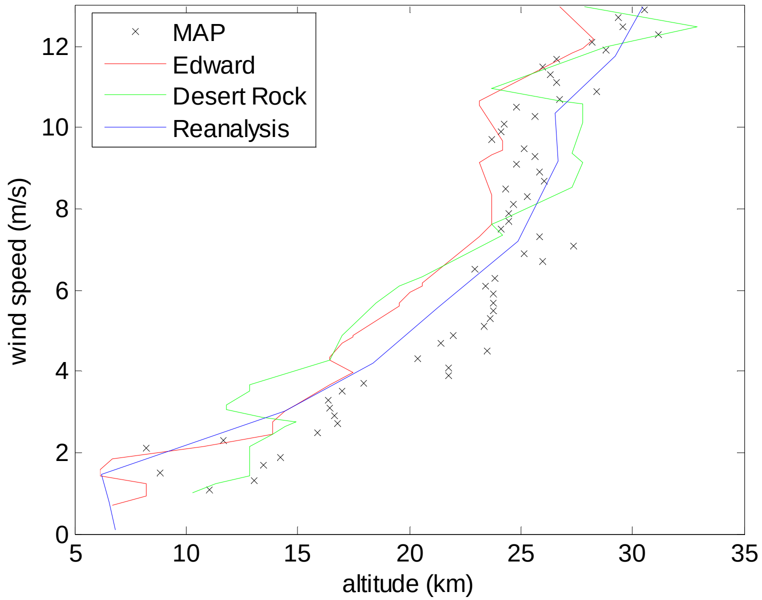
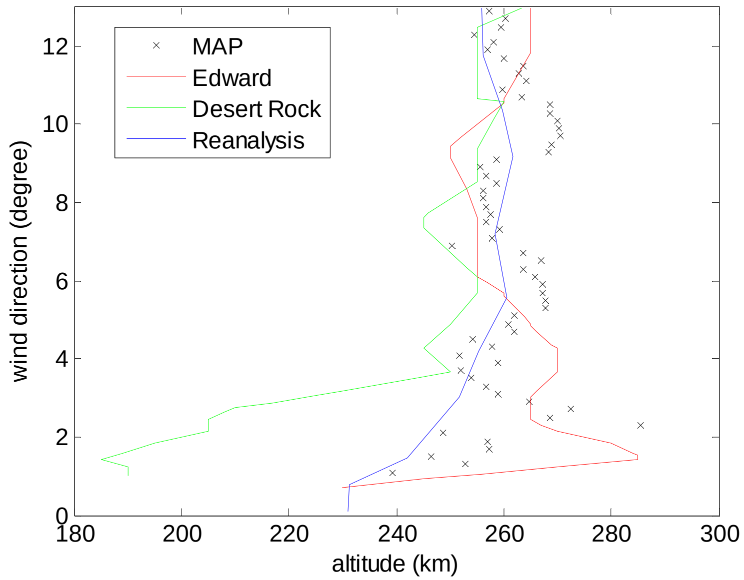
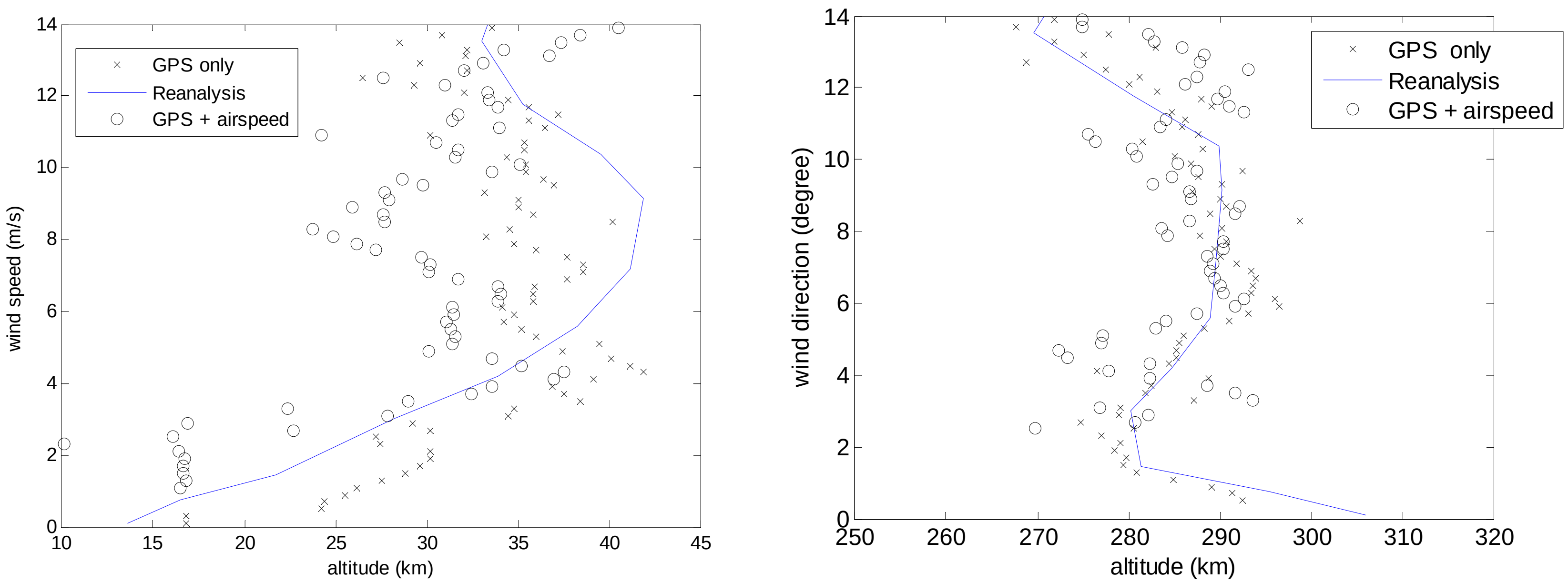
Eg. Use GPS data only and use reanalysis as an initial estimate of the wind velocity.





Sierra Nevada flight

Eg. Use GPS data only and use reanalysis as an initial estimate of the wind velocity.



Argentina flight

Conclusions

- Algorithm developed for estimating 3D wind fields in mountain waves using sailplane GPS and airspeed data.
- Applications show potential of the technique.
- Has some advantages over other techniques (radiosonde, radar) since a skilled pilot can systematically explore the wave system.
- Potential for using more limited routine flight data.