Using a bi-axis scanning airborne coherent Doppler lidar to measure marine boundary layer winds and ocean waves

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Many of the performance expectations of a future space-based Doppler lidar assume idealized atmospheres and earth surfaces. The atmosphere is usually envisioned as being well mixed on both the scale of the illuminated volume and the scale of the shot clusters used in signal integration to produce a single data product. The earth's surface is often assumed to have a zero velocity and thus useful for individual line-of-sight velocity shot calibration. In the real world, neither of these assumptions hold, especially over the oceans. During the springs of 2002 and 2003, an airborne coherent 2 micron scanning lidar was flown over the ocean off the coast of central California. Details of the Twin Otter Doppler Wind Lidar (TODWL) can be found at www.swa.com/todwl and in Emmitt and O'Handley (2002a).

Of particular interest to the processing of coherent lidar returns from a structured (not well mixed) atmosphere is the possible existence of organized features where the wind motions are correlated with the aerosol size/concentrations. The marine boundary layer (MBL) is frequently characterized by organized large eddies (OLEs). In this case, the upward motions within the "roll" carry large and numerous aerosols from the Layer Adjacent to the Surface (LAS). The compensating downward motions tend to bring down smaller and fewer aerosols. This pumping action leads to a net flux of aerosols into the MBL until some equilibrium is reached or the depth of the MBL changes. While more of a fundamental problem for direct detection , there is still a potential bias for coherent detection in the weak signal regime.

As we investigated the OLEs with TODWL, we also obtained observations that related nadir angle to ocean surface reflectance and, in the zero degree nadir case, an estimate of wave spectra based upon the vertical motion of the waves (Emmitt and O'Handley, 2002b). In this presentation, we offer examples of a multi-layered MBL, OLEs and ocean waves obtained during flights over Monterey Bay in 2002 and 2003. The implications of these features to the interpretation of lidar wind sensing will be discussed.

Multi-layers and OLEs

The existence of inversions and consequential layers within the first km or two of the atmosphere above the oceans is well known. What is not known are the global frequency of occurrence and the vertical spacing of multiple layers. Off the west coast of the USA marine inversions are quite common. With these inversions there can be low level jets and very strong shears at the top of the "mixed" layer. In Figure 1 an example of such a situation is shown. The wind speed and direction change dramatically over just a few tens of meters. The shear is estimated to be .1 s^{-1} at 350 meters. In Figure 2, we see an example of multiple layers, 4 between the surface and 2000 meters MSL.

In Figure 3 there is an example of organized structures in the velocity and backscatter fields within the MBL. While there were no clouds seen at this particular location, elsewhere there were extensive patches of cloud streets indicating very organized "rolls". These rolls could be seen throughout the MBL on different flight legs and could even be detected above the MBL capping inversion.

The primary implication of these features on the processing of lidar data is the erroneous height assignment of velocity estimates. Inhomogeneous aerosol weighting of the velocity profile can produce "average" velocities over a vertical column that are not assigned the appropriate altitude (Emmitt,et al, 1995). This is particularly true below 1km where the wind profile under well mixed conditions is logarithmic. Linear averaging of a logarithmic profile leads to a slow bias in the wind estimates. The multi-layering only adds to the uncertainty of the height assignment (which is effectively a velocity error which can be spatially systematic or correlated)

Ocean surface motions

For a space-based lidar, a major error source is pointing knowledge. Given a 7 km/sec orbit speed, a 100 urad pointing error can introduce a ~1 m/s error in the horizontally projected line-of-sight error. Current space-based concepts include the use of surface returns to remove residual pointing and instrument errors. The assumption is that the surface is not moving relative to the fixed earth coordinates. Over land this assumption may be violated by swaying trees, blowing sand and smoke. Over water, the vertical wave motions and the horizontal motions (waves and currents) confound the zero velocity assumption (Emmitt, 1994).

During the TODWL experiments, the issue of using the ocean surface for velocity calibrations was addressed with two questions; 1) what is the strength of the ocean surface return as a function of nadir angle and sea state? , and 2) what are the velocities of the surface under typical conditions? A prior hypothesis is that when the surface motions are inconsequential, the surface returns are likely to be very weak (low surface roughness), but when the surface is detectable it is likely that the surface motions are significant.

While we have not investigated a full spectrum of sea states during the TODWL experiments, we have been able to demonstrate the use of the lidar to measure the reflectance as a function of nadir angle and to infer wave spectra from the surface returns using a nadir-viewing angle of zero. In Figure 4, a summary of the reflectance as a function of nadir angles between zero and 43 degrees is given. The average wind speeds at 10 meters were on the order of 8-12 mps. While the signal falls off with nadir angle as expected (Tratt,et al, 2002), a return can still be detected at 43 degrees. It should be noted here that we have developed a signal processing scheme that can discriminate between the water surface return and the return from the aerosols in the LAS (Emmitt, et al, 2002c).

In Figure 5, a short time series of the vertical motions of the ocean surface and the air at 500 meters are shown to illustrate the ability to resolve the wave motions. Wave spectra derived from these data agree well with a nearby wave buoy.

The use of the ocean surface returns for LOS velocity calibrations thus problematic. More effort is needed to assess the impacts for larger footprints (2-4 cm for TODWL vs. 4-10 meters for space). However, both theory and observations suggest that vertical motions of several mps are common. That same theory also suggests a potential averaging bias due to the asymmetry of the wave form convolved with the lidar reflectance as a function of incident angle.

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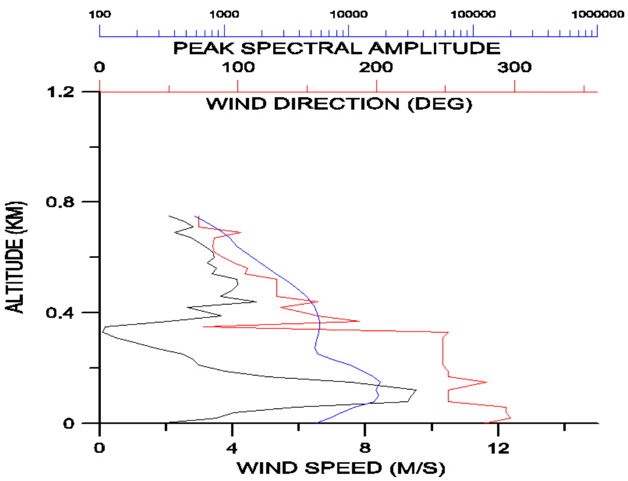


FIGURE 1

A TODWL profile taken over Monterey Bay, March 2002. TODWL was flown at a 1 km altitude with the scanner programmed for a downward conical pattern

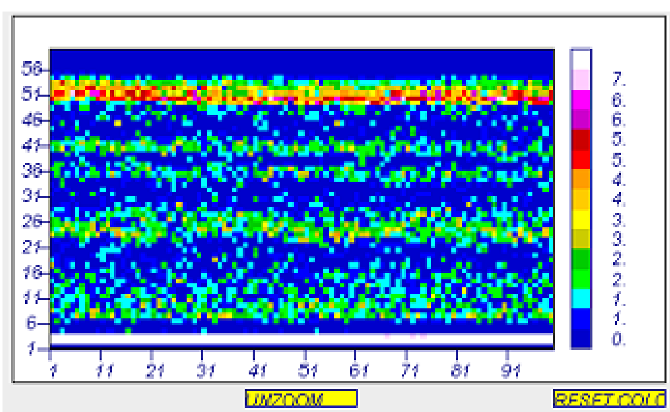


FIGURE 2

Deviation (dB) of the signal strength of TODWL returns looking nadir from a flight altitude of 2500 meters. Horizontal axis is in elapsed minutes; vertical axis is in range gates (50 meters).

Flight Level LOS Velocity (30 meters altitude)

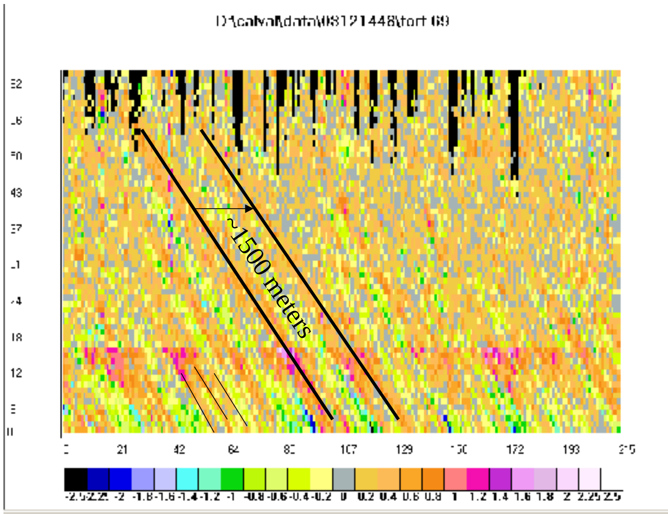
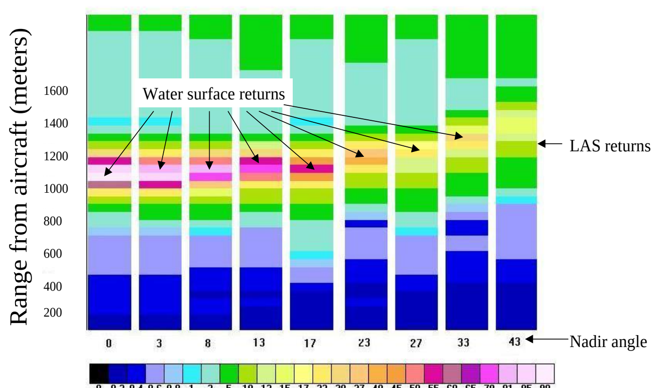


FIGURE 3

Line-of-sight velocity with TODWL pointed straight ahead of the aircraft which is flying at 30 meters above the ocean surface. The horizontal axis is time along flight path; the vertical axis is range ahead of aircraft. The sloping features denote organized (in waves) structures in the wind field.

TODWL returns collected over Monterey Bay, 12 March 2002



Relative spectral amplitude (range corrected)

using 400 shot integration

FIGURE 4

Relative signal strength (dB) of returns from the ocean surface and the LAS for different nadir angles ranging from 0 to 43 degrees. Note the air returns are not changing with nadir angle while the surface returns are. A surface return is still detectable at 45 degrees.

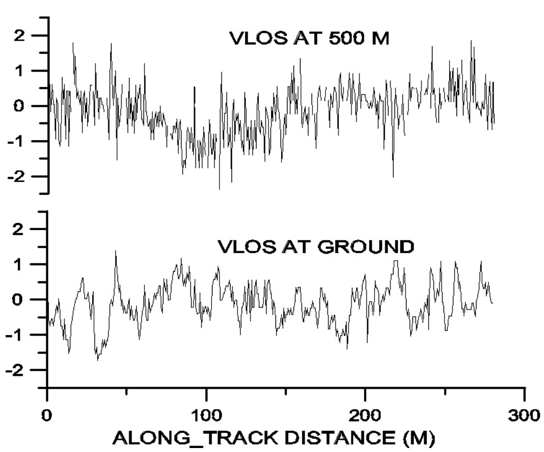


FIGURE 5

Line-of-sight velocity with TODWL pointed straight down at surface of the ocean (not ground). The LOS velocities at 500 meters are shown to illustrate the scale of organized vertical motions; the ocean waves having much longer wavelengths.