P2.3 TODWL: AN AIRBORNE DOPPLER WIND LIDAR FOR ATMOSPHERIC RESEARCH

George D. Emmitt*, C. O'Handley, S. Wood and S. Greco
Simpson Weather Associates, Charlottesville, VA

Robert Bluth and Hans Jonsson
Office of Naval Research, CIRPAS, Monterey, CA

1. Introduction

In 2001, the Navy's Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) was funded jointly by the Navy and the Integrated Program Office (IPO) of NPOESS to install a coherent 2 micron Doppler lidar in a Navy Twin Otter (Figure 1). The lidar included a bi-axis scanner (Figure 2) that allowed vertical soundings of the wind profile above and below the aircraft as well as taking data with horizontal or vertical perspectives. In the springs of 2002 and 2003, the TODWL (Twin Otter Doppler Wind Lidar) was flown out of Monterey, CA to conduct a series of experiments related to general wind lidar issues and to examine the boundary layer circulations along and near the central California coast.

The lidar was built by Coherent Technologies Incorporated (CTI) for use by the US Navy. The system as flown during 2002 and 2003 is described in Table 1. A dedicated INS/GPS was installed on the transceiver to eliminate problems associated with aircraft flexing and data delays. A chiller used to cool the laser accounts for most of a 1.5 KW power requirement. The one feature that distinguishes this airborne Doppler lidar from most others is the side mounted two-axis scanner. This configuration allows for conical scans above, ahead and below the aircraft. In most instances, a complete 8 point step-stare conical scan takes approximately 15 seconds. At the nominal cruise speed of 50 m/s (IAS), a wind profile is obtained every 750-800meters. The scanner can also be pointed directly nadir (adjusted for aircraft pitch and roll). In the nadir setup, vertical motions of the surface and atmosphere can be observed to within 20 cm/sec accuracy. The range resolution depends upon the backscatter structure. Using a sliding range gate in the processing we are able to achieve 10-20 meter vertical resolution. In the case of the water or earth surface, the height resolution is better than 10 meters.

2. Experiments and Field Campaigns

The TODWL was flown for ~50 hours in two series of field experiments based out of Monterey, CA in 2002 and 2003.. The primary objectives of the flights were to measure wind profiles above and below aircraft as part of the development of a calibration/validation program for all wind profiling technologies as well as to develop an understanding of how to interpret DWL returns from the lower troposphere. Examples of the vertical wind profiles measured by TODWL both offshore and inland are shown in Figure 3. It should be noted that algorithms were developed in the course of processing the TODWL data which corrected for both aircraft induced pointing errors and lidar beam pointing errors as well as employing spectral peak threading near the ground.

In addition to examining the vertical structure of the circulations, various individual flight objectives were broadened to include, among other activities, intercomparison with existing observations, MM5 numerical model validation, OLE (Organized Large Eddies) investigations, satellite validation and surface returns. All but the latter two were detailed in other proceedings of this conference and as such will not be discussed in detail.

2.1 Validation of Observations

During the 2002 and 2003 field campaigns, several missions were planned to overfly locations where winds were routinely measured by more conventional platforms. An example of a comparison between the wind profiles measure by TODWL and by the

---

* Corresponding author address: George D. Emmitt, Simpson Weather Associates, Charlottesville, VA 22902; e-mail: gde@swa.com

Microwave wind sounder at Fort Ord, CA is presented in Figure 4. Both the magnitudes and vertical structure of the two independent wind profiles are very similar. In spite of the differences in integration or averaging times, this high degree of similarity between the TODWL profiles and those obtained from the automated and more conventional ground-based sounder provides encouraging validation of the TODWL measurements.

2.2 Model (MM5) Validation

This work is described in much more detail in Greco and Emmitt (2005). During the post-field campaign research, the output from the Naval Postgraduate MM5 fine scale grid analyses were compared with the nearest TODWL soundings taken over the water and complex terrain near Monterey during the same time period. Some examples of these comparisons are shown in Figure 5. At times, the comparisons look very acceptable while at other times the differences perhaps show a shortcoming of the MM5 on this day and at this location over the ocean just west of Monterey. The comparisons between the model and TODWL observations must be looked at in much further detail.

2.3 Organized Large Eddies

Although the DWL is usually configured to scan for vertical profiles of the wind, considerable flight time was spent at 30 meters above the water with the lidar beam pointed straight ahead (Bowdle et al., 2004). The goal was to collect data on the correlations between horizontal (and vertical) wind variation and aerosol backscatter variation. On some flights, the objective was to investigate the 3D flow patterns beneath subtle indications of organization. Quantifying such correlations was needed to design data processing algorithms for space based lidars. As expected, there was considerable correlation found as evidenced by the Hovmuller plots presented in Emmitt et al., 2005. In these plots, the clearly linear and semi periodic features in both the wind and signal (aerosol) amplitude suggest that the flight leg was flying across organized rolls within the marine boundary layer and gave evidence that the DWL is an excellent tool for observing and quantifying the spatial and temporal variations in such organized structures which have significant non-linear impacts on the net air/sea fluxes on the submesoscale.

2.4 Surface Returns

The primary purpose of the first series of flights in 2002 was to investigate the DWL returns from water surfaces. In the advent of a space-based deployment of a DWL, surface returns will be needed for final corrections of Line of Sight (LOS) velocities to insure the full accounting for satellite motion. For this reason the first series of flights in the spring of 2002 were devoted to over-flights of various water bodies that included ocean, rivers, lakes, canals and wetlands.

The first series of experiments were conducted over and near the Monterey Bay in California during February, 2002. A brief summary of the experiments is given in Table 2. The wind conditions favored waves of a meter or so in height during all flights. The goal of the experiments was to collect DWL data from different nadir angles ranging from 0 to 50 degrees. Flight paths were executed that allowed sampling in both the cross and along wind directions. The scan patterns were primarily of three types: conical (from which the complete wind profile could be derived), step/stare at different nadir angles along the flight path, and near nadir dwells or dithers. Long flight legs allowed for the acquisition of statistically meaningful observations.

A second series of overflights were conducted over a segment of the San Joaquin River located to the east of San Francisco. The river offered a water surface that was weakly disturbed (optical reflectance wise) and was moving with a fairly constant (in time) surface speed. The challenge in the river case was to fly the river in a manner that allowed the side to side scan to be centered on the river. A ground spotter observed the aircrafts alignment as well as obtained data on winds and surface currents. The surface speed was measured with in situ flow gages spaced several meters across the river. Eight passes were made over the same segment of river.

A third set of data was collected during the overflight of the San Luis Reservoir. On this occasion the surface appeared to be quite smooth with very little evidence of wind disturbances.

While the experiments described above were conducted in the interest of understanding surface returns for use in obtaining reliable wind observations from a moving platform, there were several “non-wind” findings that generated interest from TODWL investigators: wave spectra, wave and aerosol backscatter correlations, and surface horizontal motions (river currents).

In the nadir view, the vertical wave motion can be sensed. The reflectance of the water surface changes with location relative to wave crests and troughs. However, the velocity measurement accuracy with a coherent DWL remains independent of the signal strength until the signal gets close to the threshold sensitivity of the instrument. At 80 Hz repetition rate and a ground speed of ~ 50 m/s, the TODWL was able to make single shot velocity measurements spaced approximately .5 meters. In regions where the single shot return signal was near or below threshold strength, several shots were accumulated before processing for LOS observations.

The issue of discriminating the water surface returns from those associated with the aerosols in the Layer Adjacent to the Surface (LAS) was addressed with two processing tools. First, the TODWL had a frequency chirp which produced a very clear velocity signature with time for “hard” targets. Second, by using a sliding range gate to process the LOS data stream, we were able to isolate the water surface returns from the LAS returns. In Figure 6, an example of this process is shown.

Using data from a .3 km segment of nadir viewing we obtained the results shown in Figure 7. Included is a sample of single shot data obtained from a portion of the same flight leg that occurred over land. It is clear from the land returns that the velocity accuracy is within the .2 m/s resolution used in this analysis. The time series of the water surface return suggests periods consistent with our expectations. The air returns from 500m above the water, indicate a higher frequency component as one would expect from the sheared profile in Figure 8.

The generation of spray and foam by the wind and wave action is a confounder to the interpretation of the lidar returns and to the estimation of energy and momentum fluxes at the air/sea interface. The initial attempt to investigate the distribution of spray in the LAS relative to the wave geometry found a pattern consistent with the following: within a wave there are two areas responsible for the strongest signals, the bottom of the trough and the crests. Within the trough the probability of water facets that are very close to perpendicular to the lidar beam is high. Within the crests there is a high probability of foam and spray that would have a high reflectance. In Figure 9 we show an example of this relationship.

These results have shown that an airborne Doppler lidar can be used to study water surface motions and their correlations with aerosols. These correlations may have meaningful impacts on the interpretation of data obtained with a space-based wind lidar and also on the parameterization of fluxes over water surfaces at wind speeds above those that produce whitecaps. The authors are continuing to explore the spring 2002 data for more information on these issues.

2.5 Satellite Validation

During the 2003 field campaign, there was a TODWL mission planned to coincide with four hours of NASA ER-2 NAST overflights along the California coastline between Los Angeles and Monterey. The primary objectives of these coordinated missions were to compare wind measurements form NAST with those obtained by TODWL as well as satellite-based cloud motion vectors. TODWL missions were also flown to “underfly” the swaths of both RADARSAT and QUIKSCAT. The analysis of these comparisons is still in the preliminary stages.

3. Summary

Results from the Navy and IPO sponsored 2002 and 2003 TODWL field campaigns based out of Monterey, CA were described herein as well as in companion papers by Emmitt et al., 2005 and Greco and Emmitt (2005). These results show that the airborne TODWL can indeed provide accurate high space and time resolution vertical wind profiles over open waters and complex terrain. The TODWL soundings of wind speeds have been corrected for discovered errors in both lidar beam and aircraft pointing and processed to obtain accuracies <.10 m/s for u, v, and w. In addition, it has also been demonstrated that TODWL can be used to investigate circulations and OLEs within the marine boundary layer. Such information may prove beneficial to the tuning of parameterization schemes (including flux parameterization schemes) used in models. Finally, it was also shown how TODWL could be used to measure to measure surface returns off bodies of water (which can be used for final corrections of LOS velocities to insure the full accounting for satellite motion) and to investigate water surface motions.

Wavelength (microns)	2.05 (eyesafe)
Energy per pulse (mJ)	2-3
Pulse repetition frequency (Hz)	500
Scanner/telescope	2 axis (+- 120; +- 30)/ 10 cm aperture
Range resolution (meters)	50-100
LOS measurement accuracy (m/s)	< .05 per single shot w/ground calibration (LADSA)
Wind component accuracy (m/s)	u,v,w < .1 m/s nominal using a 30 degree VAD and LADSA
Aerosol backscatter threshold sensitivity	Range dependent: ~ 10 -08 m sr-1 at 10km
Nominal range to insensitivity (km)	Aerosol dependent: nominal 15-20 km in PBL and 2-5 km above PBL.

Table 1: Description of CIRPAS DWL

Target	Types of scans
Ocean with white caps	RHI (-5 to +10); RHI (-5 to +30); RHI (-10 to + 50)
	VADS (10 and 30 degree nadirs); Nadir find (±5)
Ocean no white caps	RHI (-5 to +10); RHI (-5 to +30); RHI (-10 to + 50)
River (San Joaquin)	± 5 degree left/right at 0,10,20,30 degrees forward off nadir; 40 scans during 6 overflights
Lake (San Luis)	RHI(-5 to +20)
Canals	± 5 degree left/right at 20degrees forward off nadir
Land	VADS, RHI’s and fixed
Cloud tops	VADS and RHI (-5 to 30)
Dropsondes	2 over buoy
Aerosol Backscatter experiments	Fixed angles at various altitudes

Table 2 Summary of experiments (11-15 February, 2002)

Figure 1 CIRPAS Twin Otter with DWL scanner mounted in right side door

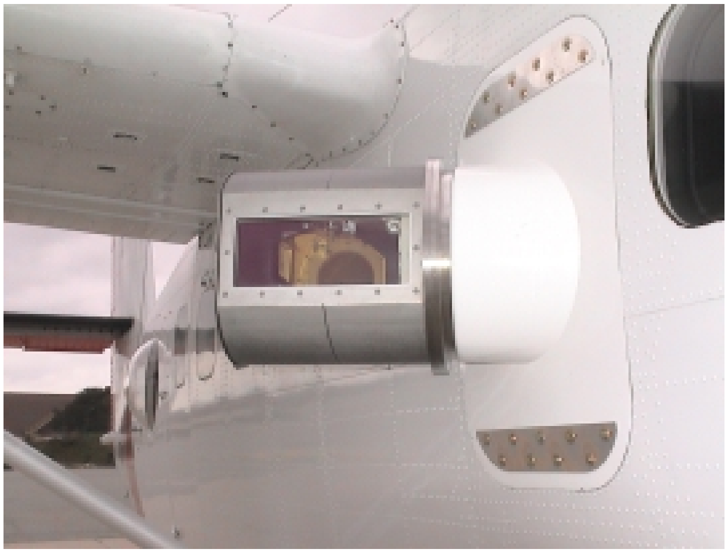


Figure 2 Twin Otter Doppler Wind Lidar (DWL) bi-axis scanner

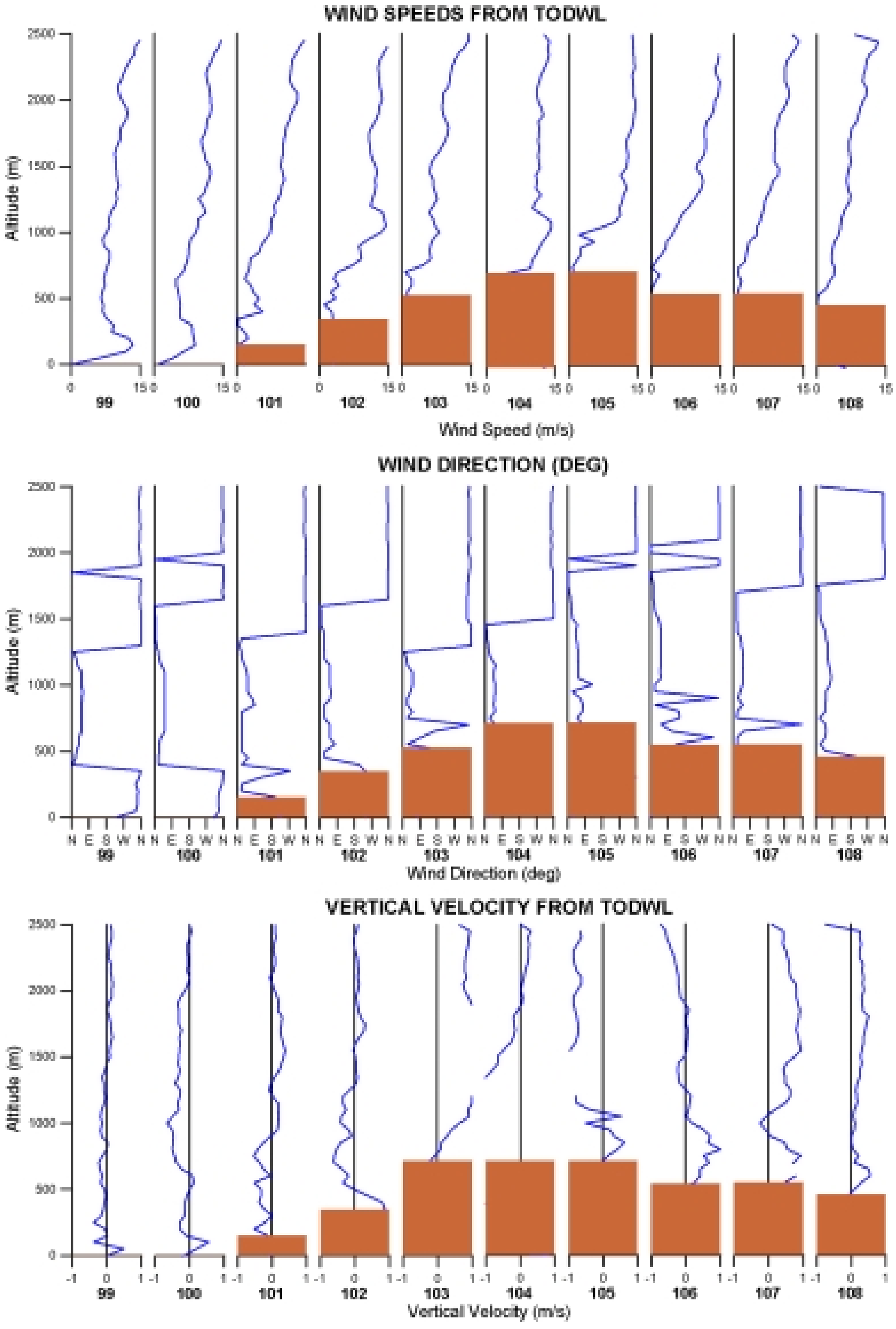


Figure 3: Series of TODWL soundings mainly inland and just east of Monterey on 2/21/2003..

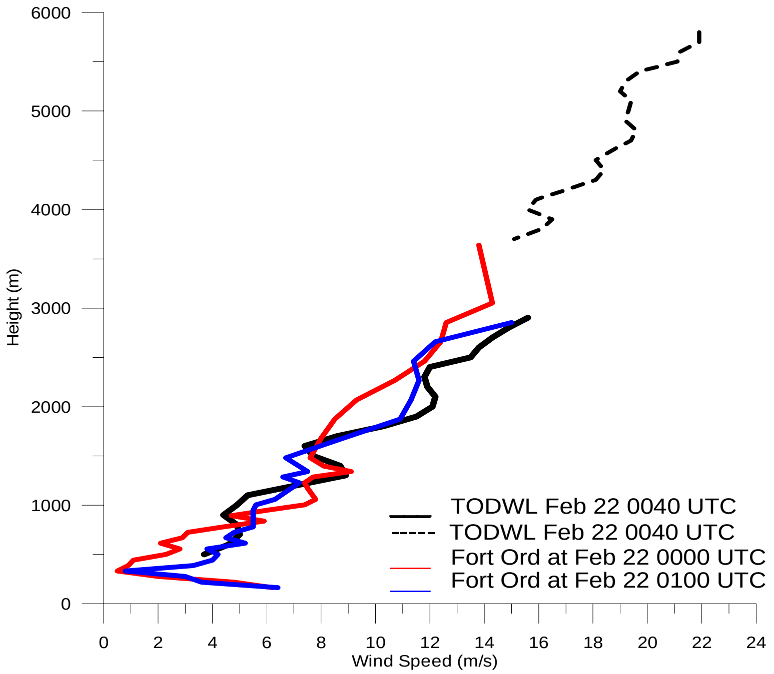


Figure 4: Comparison of one TODWL sounding (up and down portions) with two soundings from the Ft Ord microwave sounder taken one hour apart on February 22, 2003.

Airborne wind lidar comparisons with MM5 model profiles

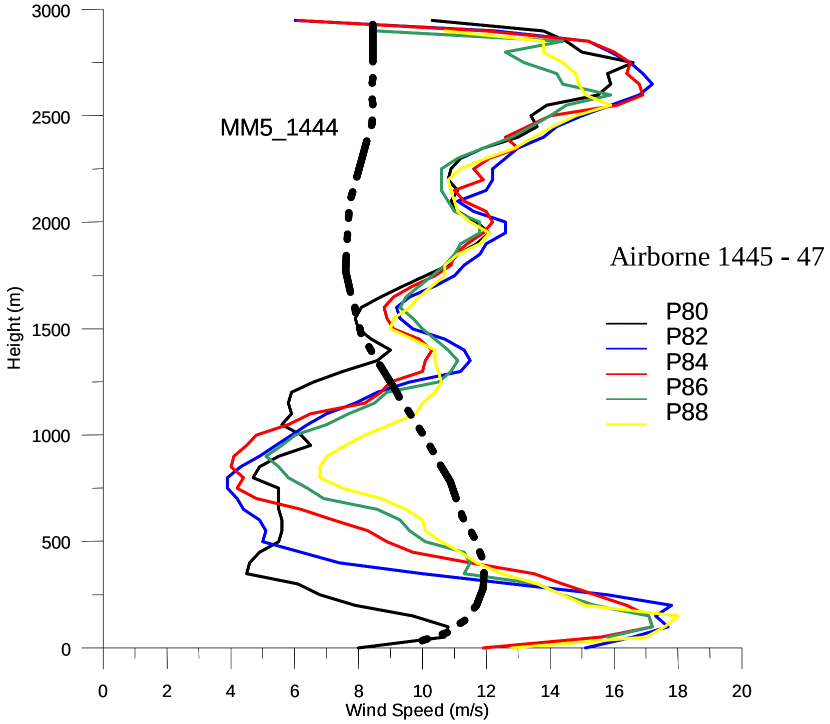


Figure 5a: Example of DWL wind profiles compared with MM5 predicted profiles over the ocean near Point Sur, California.

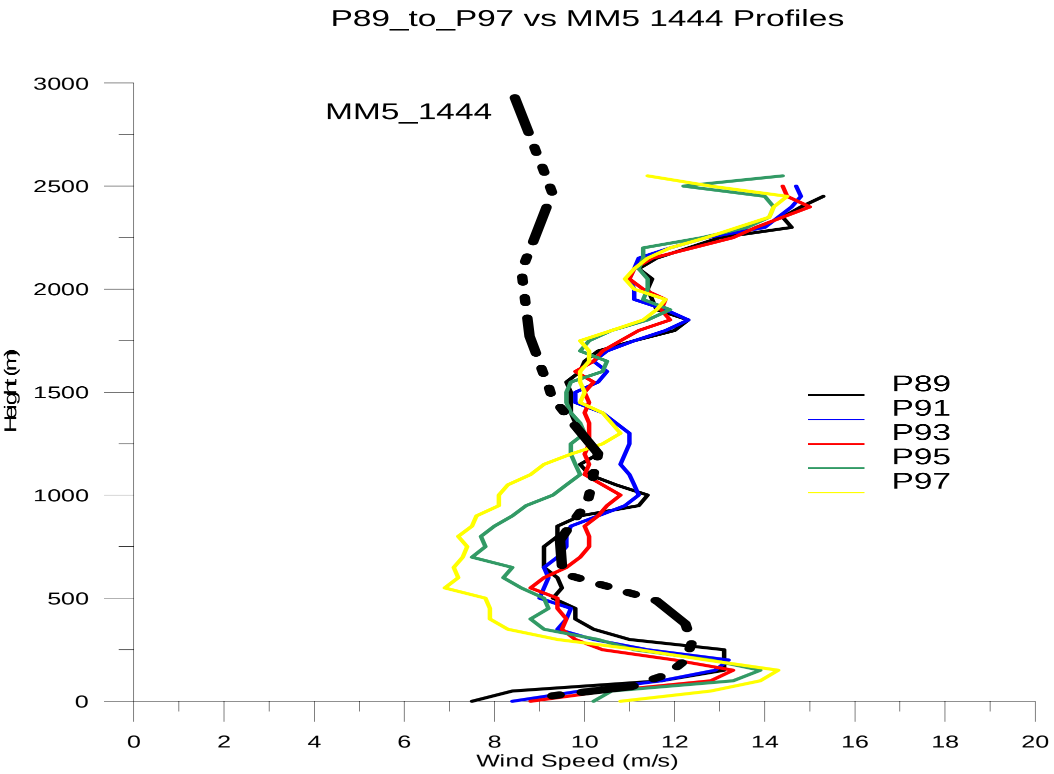


Figure 5b: Comparison of selected TODWL vertical profiles with closest (in time and space) MM5 model analyses profiles

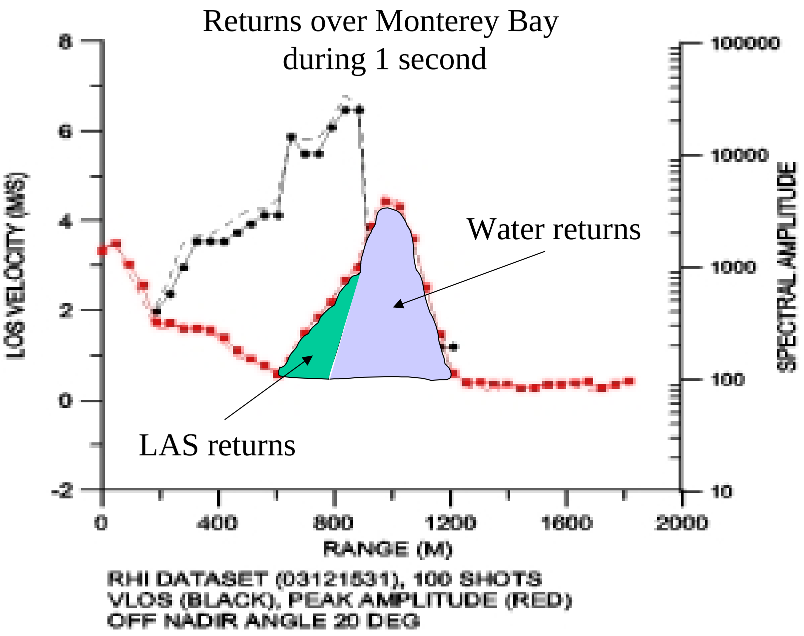
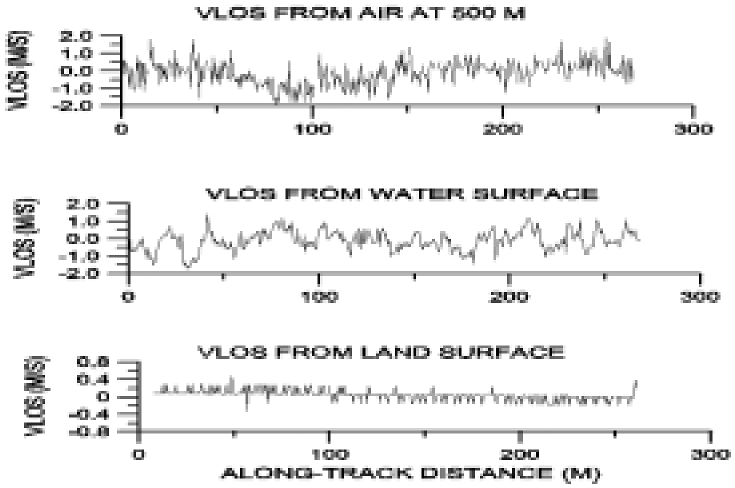


Figure 6: Surface Returns over Monterey Bay



Nadir view over water

Figure 7: Line of Sight Velocities measured using a nadir view over the water.

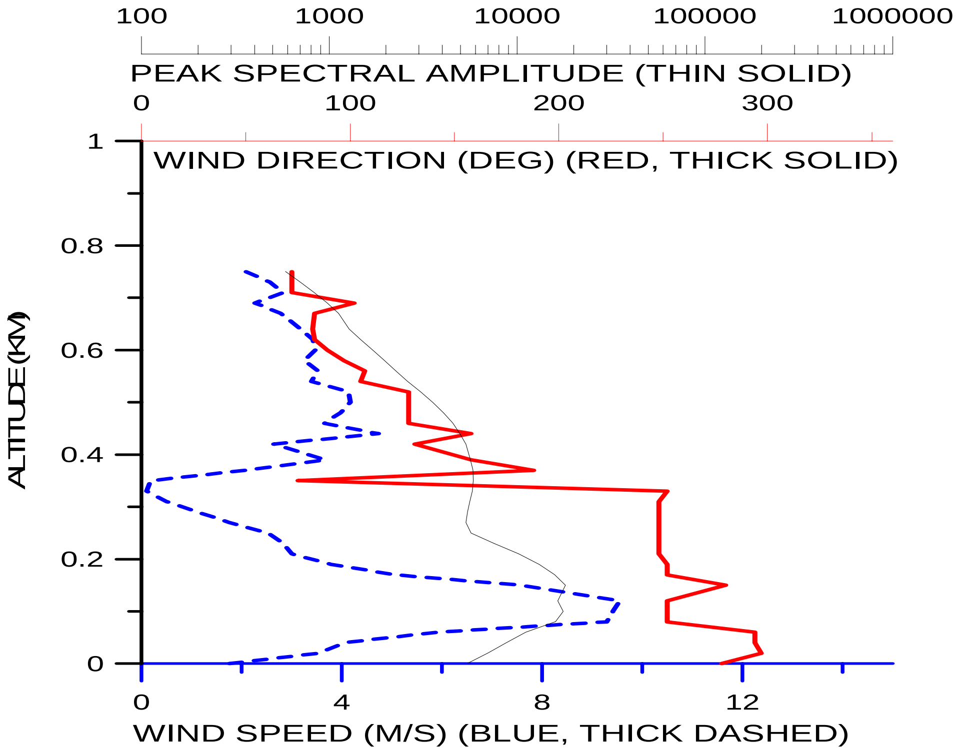


Figure 8: Sheared vertical profile as measured by TODWL

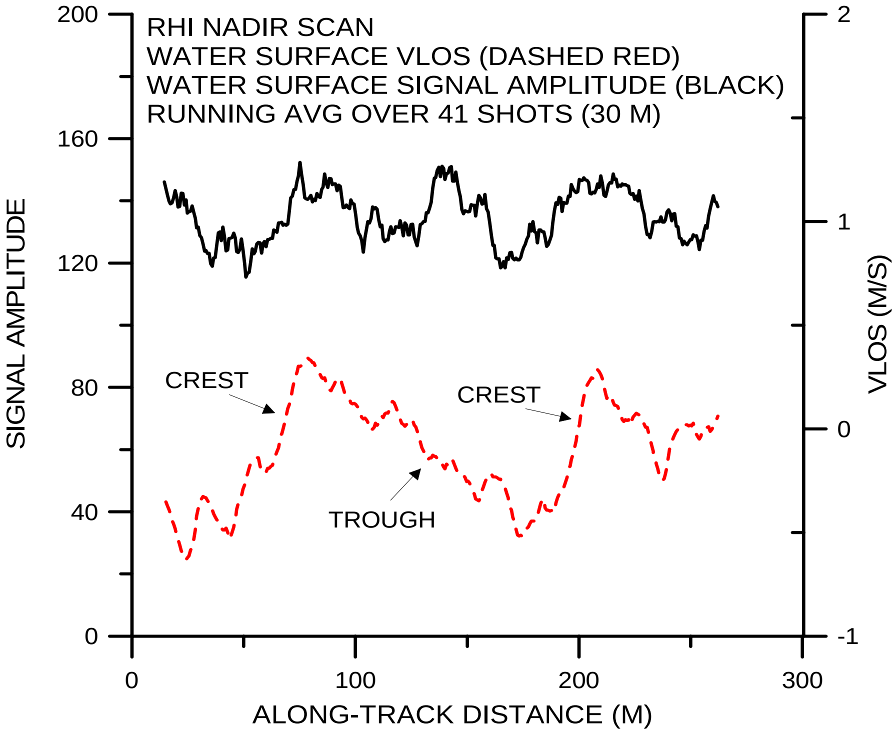


Figure 9: Surface returns as measured by TODWL