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Performance of the NCAR CO_2 Doppler Lidar During the Coastal Ocean Probing Experiment

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Abstract. The NCAR 10.6 μm CO_2 Doppler lidar, designed for airborne application and also known as the NCAR airborne infrared lidar system (NAILS), was deployed in a 32-foot trailer with a scanner in September and October of 1995 for the Coastal Ocean Probing Experiment (COPE). The lidar, installed at the shoreline, was capable of measuring radial velocities from approximately 1 to 6 km range on most days when the lidar beam was pointed at very low elevation angles over the ocean. Occasionally, the lidar could make useful velocity measurements to much farther ranges when the signal to noise ratio (SNR) was above average. From fixed-beam, near-horizontal data, we show that the measured precision of radial velocities from 20 laser pulses is near 0.4 m s^{-1} in high SNR and how the random error changes as a function of SNR and range.

1 Introduction

The overall experimental objective of COPE was to develop optimal remote sensing methods for retrieval of ocean surface strains and fluxes in varying environmental conditions. A plethora of instruments and platforms were deployed in COPE including k- and x-band radars, and instrumented ships and aircraft, and the NCAR CO_2 Doppler lidar. The role of the Doppler lidar was to determine the spatial and temporal variability of the wind field in the region above the near shore internal wave field. This ground-based deployment of the NCAR CO_2 Doppler lidar on the Pacific coast near Arch Cape, Oregon, was the first field project for the instrument operating in heterodyne detection mode and was the result of a joint cooperation between NCAR/ATD and NOAA/ETL. Approximately 140 hours of Doppler data were collected on 23 days with the lidar at the shore. Approximately half of this data set contains fixed-beam measurements of radial velocity. The other half contains scanning data such as RHI and PPI type scans.

2 Uniqueness of the Lidar

Schwiesow and Spowart [2] provide a comprehensive review of the NCAR CO_2 Doppler lidar. Here, we briefly review the uniqueness of the instrument and summarize our operational experience with it during its first ground-based deployment.

Because the NCAR CO_2 Doppler lidar was intended for airborne use, the system uses a short TEA laser cavity (0.63 m) and only a single local oscillator (LO). This relatively compact design can be compared to the NOAA CO_2 Doppler lidar [1] which uses a 3.1 m TEA cavity and two local oscillators. Longer cavities are desirable for less pulse chirp but require heavier substrates to maintain rigidness. The use of two local oscillators allows TEA seeding and optical heteordyning to be independent; however, the NCAR system is able to use only one LO by employing a Faraday isolator which prevents the transmit pulses from disturbing the LO. A disadvantage of this design appears to be an enhanced tendency for the formation of a parasitic interferometer caused by two parallel optical surfaces in the system of which at least one is in the Faraday isolator. The undesirable effect of the parasitic interferometer is to induce variability in LO signal on the chilled detector, which affects system gain. Obtaining a precise optical alignment to minimize the variability is difficult. We suspect the variations are induced by thermal contractions and expansions of the lidar chassis. However, the effect can be minimized by carefully adjusting several optical components.

Another unique feature of this lidar is the real-time TEA laser control electronics and signal processor. The frequency of the transmit pulse is sampled by an analog discriminator which then controls the length of the laser cavity by a PZT holding the TEA output coupler in order to maintain an offset of approximately 10 MHz from the LO. The electronics also use the sampled reference frequency to heteordyne the 5-15 MHz intermediate frequency (IF) signal from the chilled detector to a baseband quadrature signal. Optimal filtering can be done on the IF signal due to the reduction in instantaneous center frequency shift afforded by this dynamically set coherent reference frequency. Our velocity data indicate that the frequency sampling, analog rf mixing, and TEA laser control work very well with the exception of a slowly varying bias in the radial velocities. We believe the bias is related to errors in sampling and weighting the transmitter-LO beat frequency at time of transmission. This frequency shifts during the one μs of the laser pulse time by several MHz while the amplitude of the output is varying. Although the frequency shift is only a few parts in 10^9 on the transmitter frequency, the weighted mean must be accurately determined to minimize velocity measurement bias.

Once the adjustment to minimize the effect of the parasitic interferometer has been made, we found the lidar be very reliable at 10 Hz, 100-200 mJ per pulse, operation. The servo loop maintains injection seeding for hours without operator adjustment. A typical operational day consisted of up to 10 hours of continuous data collection. For the COPE experiment, each day we ran the TEA cavity with a 110 KPa 3:2:1 mixture of He, N_2, and CO_2. The transmit pulse lengths were approximately 1 μs with spectral widths of 1 - 2 MHz FWHM.

During COPE, the Doppler lidar I and Q data were sent to two independent real-time computers. The NCAR data system recorded 67 μs (from -1 to 9 km) of I and Q data on to 8 mm tape from each laser shot at 12-bit, 10 MHz sampling (15 m range resolution) as well as provided a coarse time-range display of radial velocity and return power. The NOAA data system sampled at 15 MHz; computed data products such radial velocity and return power; displayed the data on an appropriate style display (RHI, PPI); and recorded the products, but did not record the I and Q data. We found it extremely valuable to have both real-time display and continuous I and Q data recording capability.

3 Error Analysis

To estimate the uncorrelated error in our velocity estimates, we selected segments of data where the lidar beam remained in a fixed, near-horizontal position and computed autocovariance functions (ACF) of the mean-subtracted radial velocity time series as a function of range. For each ACF, we recorded the value of the zero and first lags. If we assume the first lag is a good measure of the variance due to correlated fluctuations in the time series, we can subtract the first-lag from the zero-lag leaving us the uncorrelated variance. We may then plot the uncorrelated variance as a function of range or signal to noise ratio (SNR) which steadily decreases as a function of range. These results show us that in high SNR regions, we approach 0.4 m s^{-1} precision for velocity estimates composed of 20 laser pulses. This is in agreement with the precision predicted by Schwiesow and Spowart [2].

Fig. 1 shows the uncorrelated standard deviation of 226 consecutive twenty-pulse (2-s) radial velocity estimates as a function of the mean SNR during that period. The radial velocities were computed using 16 pairs of I and Q data (240 m range) and single-lag complex autocovariance processing. These data were collected on 16 September 1995 from 22:33:02 to 22:40:32 UTC when the beam was held in at 270 degrees azimuth and zero degrees elevation (pointing west just above the ocean surface). These data represent a standard case of the lidar's velocity measurement performance during the COPE experiment. Fig. 2 shows the same uncorrelated standard deviation data plotted in Fig. 1, but as a function of range instead of SNR. This plot shows us that the lidar typically obtained useful velocity data from about 1 to 6 km offshore during COPE. The minimum range was limited by detector saturation from the transmitted pulses.

Fig. 3 and Fig. 4 show the lidar's radial velocity measurement capability on a day with excellent SNR. These data were collected on 22 September 1995 from 17:16:39 to 17:45:29 UTC while the beam was pointed toward 270 degrees azimuth and 0.50 degrees elevation. These data demonstrate that the lidar was capable of measuring radial velocity out to 9 km range (limited by digitizer capability) with random error less than 0.86 m s^{-1} when atmospheric conditions were ideal for the lidar.

Hard-target testing of the lidar and comparison with other wind sensors near Boulder, Colorado, after the COPE experiment indicated that correlated radial velocity errors are very small and velocity biases on the order of 1 - 2 m s^{-1} with long time constants (hours) are rather typical for this system.

4 Conclusions

Despite modest pulse power, relatively large frequency chirp, and two currently unresolved engineering problems (parasitic interferometer, and velocity bias), the NCAR CO_2 Doppler lidar operated reliably during COPE. It provided researchers more than 140 hours of radial velocity data, performing as well as predicted. These data will be used to help meet COPE science objectives.

References

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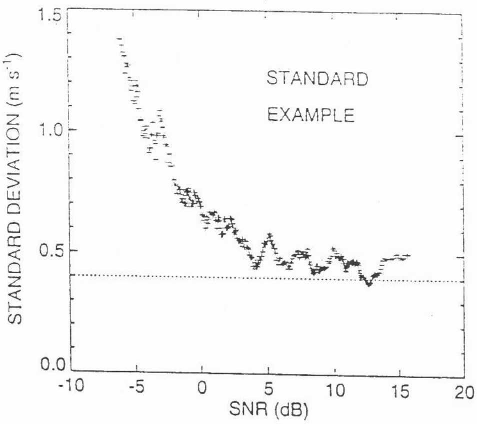


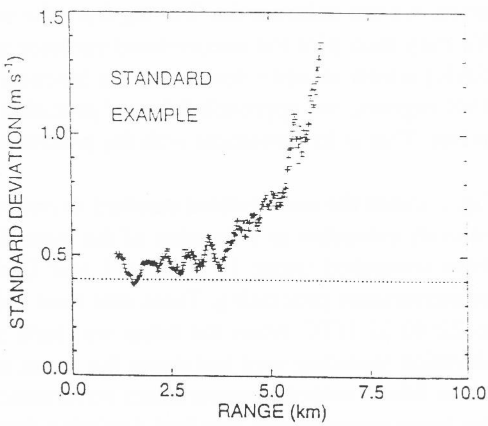
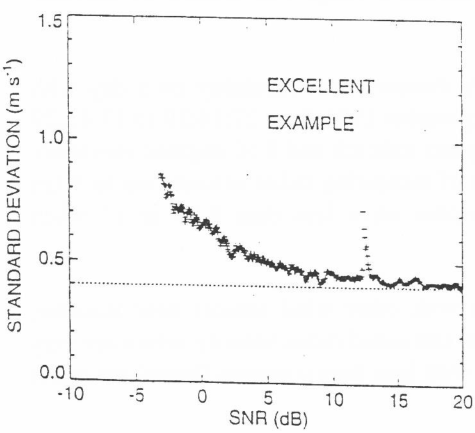


Fig. 1 (left) Random error of radial velocity as a function of SNR with standard conditions.

Fig. 2 (right) Random error of radial velocity as a function of range under standard conditions.



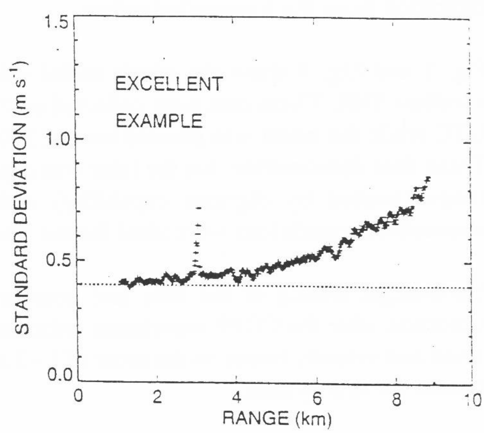


Fig. 3 (left) Random error of radial velocity as a function of SNR with excellent conditions.

Fig. 4 (right) Random error of radial velocity as a function of range under excellent conditions.