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Observations of two-component wind fields from aerosol lidar and motion estimation algorithms including first results over rough sea states

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The purpose of this presentation is to provide an overview of what may be considered state-of-the-art capabilities for observing two-component and two-dimensional vector wind fields in the turbulent lower atmosphere. The work is inspired by the success of particle image velocimetry (PIV) in the engineering community [1]. For PIV to work in the atmosphere over a broad range of scales, *spatial variations* in the naturally occurring aerosol backscatter field must be relied upon to provide a tracer of the flow. The lidar does not observe individual particles. It does however provide images of aerosol backscatter intensity that are a proxy to relative particle concentration [2]. Therefore, aerosol lidars with powerful laser transmitters and sensitive backscatter detection subsystems that can provide high spatial and temporal resolution imagery are required.

PIV and prior work of estimating the wind from aerosol lidar data [3, 4, 5, 6, 7, 8] has relied largely upon cross-correlation algorithms to estimate vector motion fields between image pairs. In fact, cross-correlation has been a mainstay in the broader field of motion estimation (a branch in the field of computer vision). Cross-correlation involves the use of a spatial interrogation window to estimate each vector and each vector is expected to represent the mean velocity of the fluid in the window area. An alternative approach is that of *optical flow*, based on the seminal work of Horn and Schunck [9]. A discussion of the strengths and weaknesses of each is beyond the scope of this abstract. In 2013 the California State University (CSU) Chico Atmospheric Lidar Research Group, in collaboration with the The French Institute for Research in Computer Science and Automation (INRIA), began using a wavelet-based optical flow now named *Typhoon* [10]. Typhoon provides a global numerical solution containing a motion vector at every pixel. Extensive work has been performed at CSU Chico in recent years to optimize the implementation of the algorithms to deal with the idiosyncrasies of lidar imagery (polar coordinates, range dependent signal to noise ratio, etc.) and evaluate the accuracy and resolution of both approaches. Field work involved comparison of the resulting velocities with those from sonic anemometers (at CHATS) [11] and a compact Doppler lidar in Chico, CA [12, 13].

The factors that influence the accuracy and resolution of these approaches to observe the vector wind field are numerous and complex. They are related to the instrument performance and the atmospheric conditions. Fortunately for those interested in turbulent flow, the technique appears to work the best when turbulence is present because turbulence generates the coherent aerosol structures required to deduce motion. This conclusion is drawn based on approximately one years worth of round-the-clock observations over land with the Raman-shifted Eye-safe Aerosol Lidar (REAL) [14]. Figure 1 shows an example of a vector flow field observed in Chico CA at about 100 m AGL during convective conditions with light winds. Figure 1 is the result of the application of Typhoon to two scans separated in time by about 17 s.

The REAL provides outstanding performance for observing the wind field and it is capable of running unattended for up to 21 days, but it is housed in a shipping container and requires a significant amount of labor to deploy. Deploying the REAL on or near a beach for example to scan through the atmospheric surface layer over a rough ocean surface would be expensive. However, a compact aerosol lidar system that offers comparable performance exists. The name of the instrument is Scanning Aerosol MicroPulse Lidar

Eye-safe (SAMPLE). In 2015, the SAMPLE was in Chico for side-by-side comparisons with the REAL (See Fig. 2). Following the Chico experiment, we were able to deploy SAMPLE in the Eureka CA area to observe the horizontal aerosol distribution and wind field over the ocean. The SAMPLE was deployed from a rented moving truck on a daily basis. During the 10-day deployment to Eureka, SAMPLE observed rough ocean states (8 – 12 foot seas) on March 31. The atmosphere during this time was windy (from the NW) and the visibility was high which is expected result in reduced lidar performance. However, the SAMPLE was able to observe streaky, wind parallel aerosol structures from the just beyond the surf zone to about 2 km offshore. Figure 3 shows one nearly horizontal scan that is estimated to lie within meters of the tops of the wave crests. If the atmosphere had been more humid, or whitecaps more abundant, the aerosol conditions would likely have been better for motion estimation. A higher performance lidar would likely be able to provide higher signal-to-noise ratio images of the same environment.

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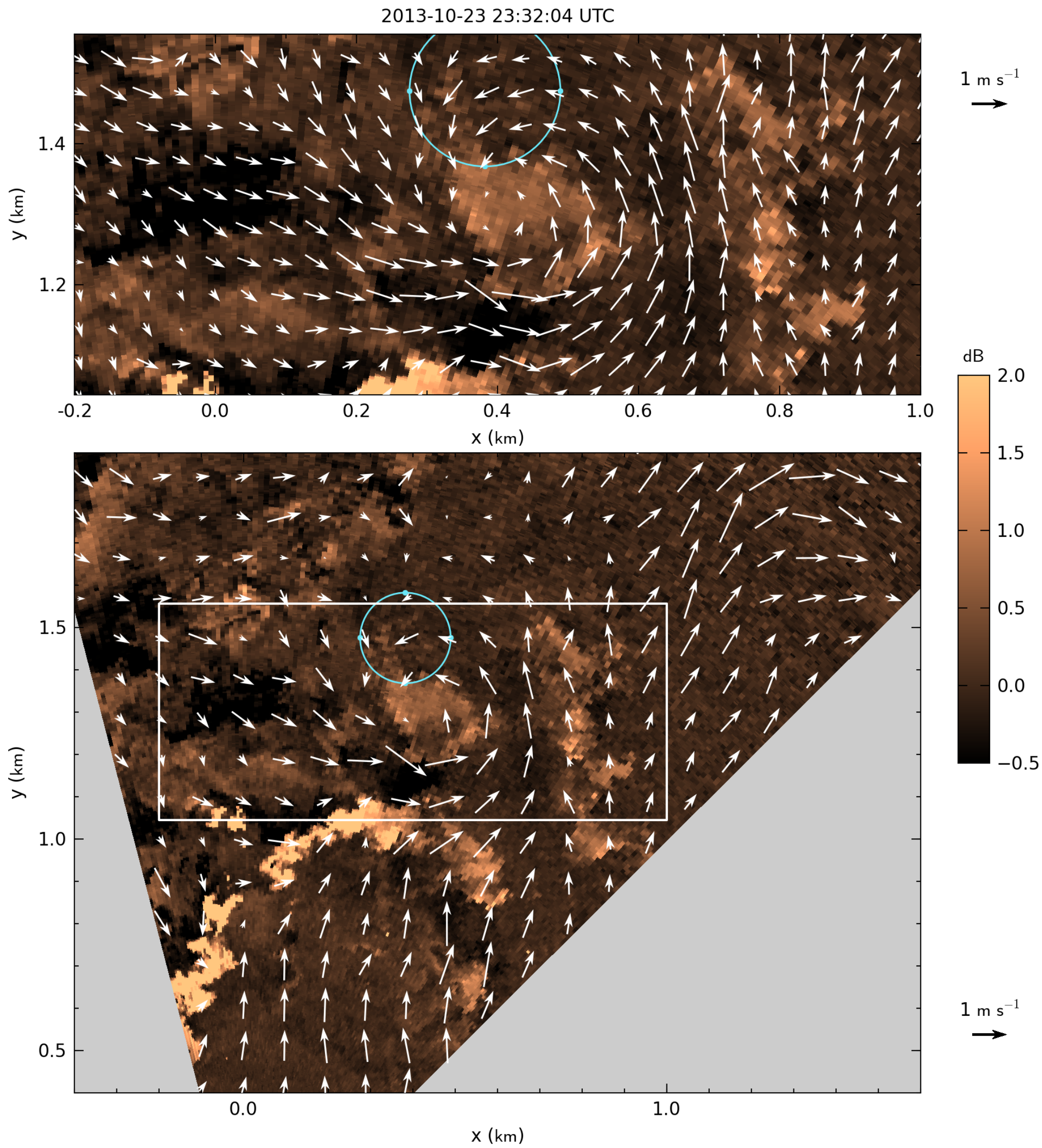

Figure 1: *Wind field obtained by* Typhoon *on 23 October 2013 at 23:32:04 UTC, superimposed on the first scan of the pair used for estimation. The upper panel shows a close up on a vortex of radius* ≈ 200 *m. The motion field was decimated along both dimensions by a factor of 6 and 12 for the top and bottom panels, respectively. The turquoise circle represents the region sampled by the Doppler lidar for validation.*

Figure 2: *SAMPLE on the left and REAL on the right during a side-by-side comparison experiment on 9 March 2015 in Chico, California.*

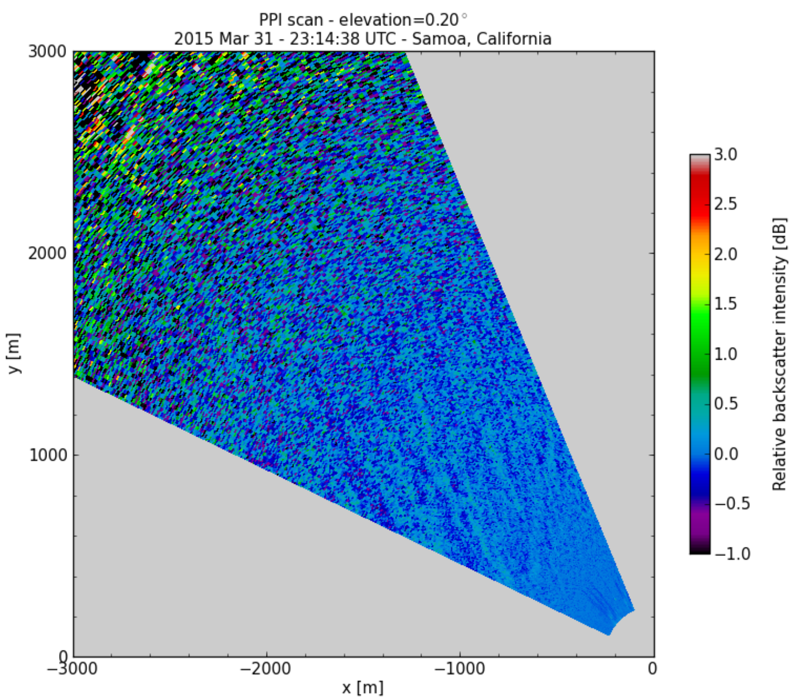

Figure 3: *Aerosol backscatter perturbations from one horizontal scan of the SAMPLE over a rough ocean state on 31 March 2015 at Samoa, CA, during strong NW winds. Wind parallel streaks are present and time-lapse animations show coherent movement. Future application of motion estimation algorithms to images like this are expected to reveal the horizontal wind fields in these difficult to observe environments.*