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Evaluating various Lidar-based wind analysis schemes against independent observations

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1. INTRODUCTION

Doppler lidar can observe the four-dimensional structure of the atmosphere at high spatial and temporal resolution, however its measurements of the wind are restricted to the component of the velocity parallel to the lidar beam (the radial velocity). Over the years, a number of schemes have been developed to infer, or *retrieve*, the unobserved components of the wind field from radial velocity observations. Generally, these methods have been applied to radar observations over domains on the order of 100 km. In the present study, we apply some of these wind retrieval methods to the much higher resolution observations from lidar. The methods that are tested are VAD (Velocity Azimuth Display, Lhermitte and Atlas, 1961), two versions of VVP (Volume Velocity Processing, Waldteufel and Corbin (1979) and a 4DVar data assimilation system, VLAS, (Variational Lidar Analysis System, see Sun and Crook, 1997 for a description of the radar version). The wind retrievals from the first three techniques are then verified against independent measurements from a SODAR over a month and half long intensive observing campaign.

2. WIND RETRIEVAL TECHNIQUES

We first briefly describe the wind retrieval techniques used in this study.

(1) Velocity Azimuth Display (VAD).

The VAD technique performs a harmonic analysis on radial wind data measured at constant range and elevation. The wind speed and direction are then determined from the amplitude and phase of the first harmonic. A vertical profile of the wind can then be calculated by performing the analysis at different heights, either by varying the range and/or the elevation angle.

(2) Volume Velocity Processing (VVP).

The VVP technique is similar to VAD, however it is applied over a sub-volume of radial wind data which is restricted in range, elevation and angle. In the traditional VVP technique, the Cartesian wind (u, v, w) is assumed to vary linearly in space over that volume. The components (u, v, w) are then determined by minimizing the fit between this model of the wind field and the radial wind observations. In the present study, we simplify the analysis by assuming that the wind field is constant across the sub-volume.

Two versions of VVP are tested in this study differing by the sub-volume that is used for the retrieval. In the first version, which we call VVP-1, the sub-volume spans an azimuth variation of 20 degrees, a range variation of 0.5 km and is applied to a single elevation angle. In the second version, VVP-2 developed by Rod Frehlich, the technique is applied to radial velocity data at constant range and elevation, but over an azimuth range of 90 degrees.

(3) Variational Lidar Analysis System (VLAS)

Here, we briefly describe the 4DVar method used in VLAS. The objective is to find the initial wind field that, upon integration of a numerical model, produces output fields that fit the observations as well as a background field as closely as possible. The background field is typically valid at the initial time, whereas the observations can be spaced at any time throughout a specified time window. A cost function measuring the misfit between the model forecast and both the background field and observations of radial velocity, v_r^{obs} is defined. Assuming that the observational errors are uncorrelated in space and time, the cost function, J is given by

$$J = \sum_{\sigma,\tau} \eta_v (v_r - v_r^{obs})^2 + J_b + J_p \quad (1.1)$$

where σ represent the spatial domain and τ represents the temporal domain. The term η_v is a weighting coefficient that represents the inverse of the observational error (squared) of the radial velocity data. The radial velocity v_r is

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calculated from the Cartesian velocity components (*u, v, w*) through:

$$v_r = u\frac{x - x_r}{r} + v\frac{y - y_r}{r} + w\frac{z - z_r}{r} \qquad (1.2)$$

The numerical model used in VLAS solves the dry, anelastic, nonhydrostatic equations of motion, (see Sun and Crook, 1997 for more details).

3. DATA AND METHODOLOGY

In the first part of this study, the wind field retrieved by the first three methods, VAD, VVP-1 and VVP-2 are compared against wind measurements from the SODAR. Figure 1 is a sample plot of the radial wind data (elevation 1.5^o, time 19:23 UTC, 5/7/2004) and also shows the location of the SODAR. At low levels the lidar scanned a 90 degree sector at elevations of -1, 1.5, 4, 6.5, 9, 11.5, 14, 16.5, 19 and 21.5 degrees. A full 360 degree scan was performed at the highest elevation of 24 degrees.

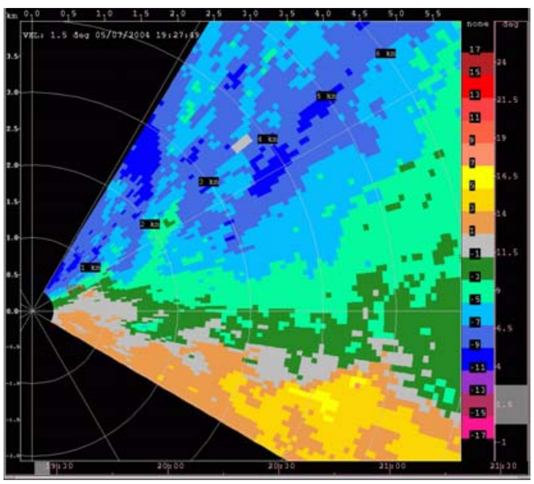

Figure 1. Radial velocity at an elevation 1.5 degrees, 19:23 UTC, 5/7/2004.

Before making this comparison, it is necessary to consider the area that the retrieved wind fields are representative of. The VAD method gives one profile centered on the lidar which is representative of the mean wind averaged over the circle from which the data are collected. The VVP-1 method estimates the mean wind over a sub-volume (in this case, of azimuth variation of 20 degrees and range variation of 0.5 km) and is representative of the mean wind at the center of that sub-volume. For comparison with the SODAR measurements, the VVP-1 winds are interpolated in the horizontal to the location of the SODAR. Finally VVP-2 gives the mean wind around a sector (in this case of 90 degrees azimuth variation at fixed elevation and range).

The SODAR measured wind speed and direction up to 200 meters by averaging acoustic returns over 5 minutes. An estimate of the averaging area can be determined by multiplying a mean wind speed by the averaging period of 5 minutes; i.e. for a mean wind of 5 m/s the SODAR gives a wind estimate by averaging over a distance of approximately 1.5 km.

The three retrieval methods were then run on the radial wind data collected for the entire project (from April 29, 2004, 00:30 UTC to May 13, 2004, 15:42 UTC). To examine the ability of the three methods in retrieving the unobserved component of the wind field, we calculate the azimuthal component (relative to the SODAR's position) of the retrieved wind field and compare that against the SODAR's azimuthal wind component.

4. RESULTS

(a) VAD. Figure 2 is a scatter plot of the VAD and SODAR azimuthal velocities calculated for the entire study. A best-fit to the data gives a slope of 0.261 and an R^2 value of 0.641. The r.m.s. difference between the measurements was 3.4 m/s. The reason for this low agreement between the VAD retrievals and SODAR measurements is a result of applying the VAD method to only a 90 degree sector of data. For a harmonic analysis to be successful, requires at least 180 degrees of data.

(b) VVP-1. Figure 3 is a scatter plot of the VVP-1 and SODAR azimuthal velocities calculated for the entire study. A best-fit line of the data yields a slope of 0.981 and an R^2 value of 0.736. The r.m.s. difference between the two is 1.6 m/s. These values represent a significant improvement over the VAD method, indicating that the VVP method is much more suitable for data which is restricted to sector scans of less than 180 degrees.

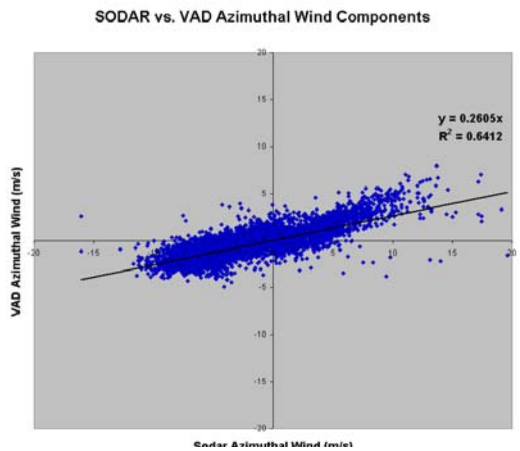

Figure 2. Scatter plot for the comparison of the azimuthal velocity from VAD and the SODAR.

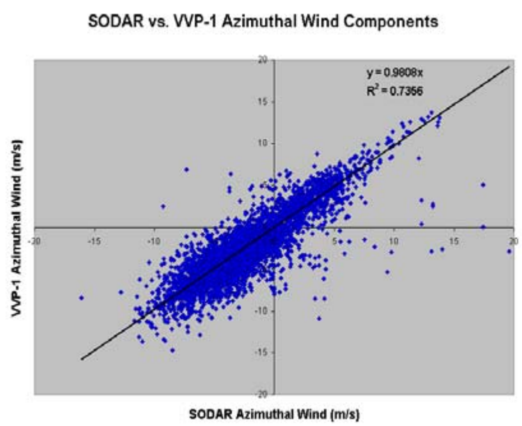

Figure 3. Same as Fig. 2 except for the VVP-1 method against the SODAR.

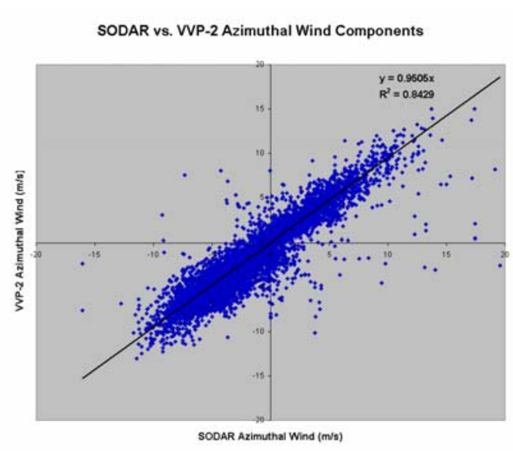

Figure 4. Same as Fig. 2 except for the VVP-2 method against the SODAR.

(c) VVP-2. Figure 4 is a scatter plot of the VVP-2 and SODAR azimuthal velocities calculated for the entire study. A best-fit line of that data yields a slope of 0.951 and an R^2 value of 0.843. The r.m.s. difference between the two is 1.4 m/s. With the exception of the slope of the best fit line, these values indicate that the VVP-2 method gives a slightly better agreement with the SODAR data than the VVP-1 method. The most likely reason for the better agreement is that the averaging area of the SODAR (1.5 km for a 5 m/s wind) is closer to the averaging area of the VVP-2 method (~1.2 km). It is quite possible that if we verified against a system that gave a more instantaneous measurement of the wind, that the agreement with the VVP-1 retrievals (which have a small averaging volume) would be closer. Unfortunately, the two such systems deployed during this project, the tethersonde and tower, had limitations in their spatial and temporal coverage, and could not be used for project-long verification

In Fig. 5 we plot the r.m.s. difference between the azimuthal components of the retrieved winds and the SODAR measurements as a function of time of day. As can be seen, the agreement is closest during the night and largest around midday. The most likely reason for this is that both retrieval methods make the assumption that the wind is constant across the averaging volume and this assumption is better at night and worse during the day, when turbulence produces sub-volume wind variability.

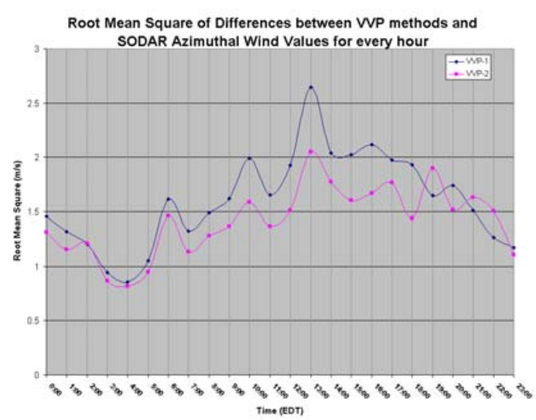

Figure 5. Diurnal variation of the r.m.s. difference between the azimuthal components of the retrieved wind and the SODAR. VVP-1 comparison is shown in blue, VVP-2 in pink.

(4) VLAS. At present we have only run VLAS for selected case studies and not for the entire project. Here, we present the analysis for one case which showed significant horizontal variation in the wind field. On May 7th 2004, a gust front propagated from the north through the observing array. The wind field at z = 25 meters analyzed by VLAS at two times 1923 and 1927 UTC is shown by the white arrows in Figure 6. The VLAS winds are overlaid on the observed radial wind at an elevation of 1.5 degrees. At 1923 UTC, the gust front can be seen in the northern half of the VLAS domain. By 1927 UTC, it has moved into the southern half of the domain, giving a propagation speed of approximately 6 m/s.

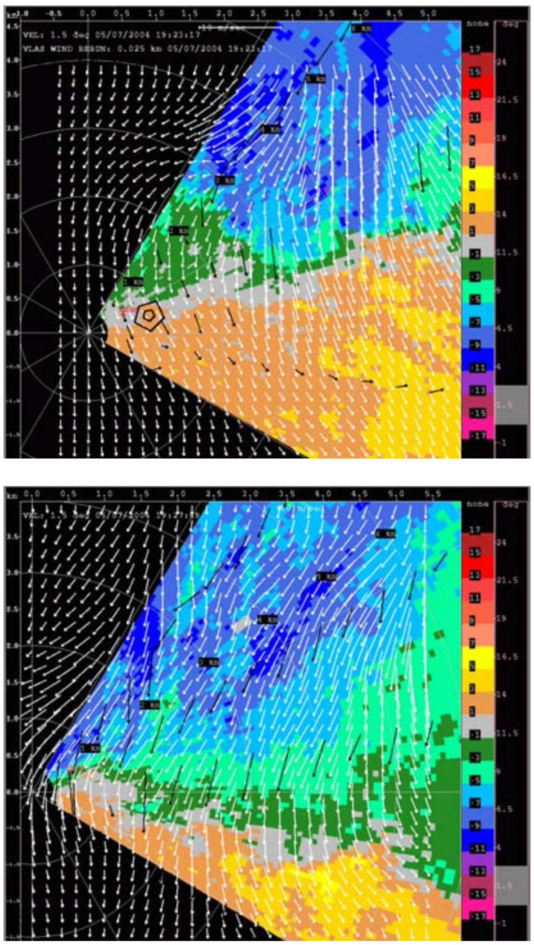

Figure 6. VLAS vectors (white) at z=0.25 km overlaid on the 1.5^{o} radial velocity data at (a) 1923 UTC and (b) 1927 UTC, May 7th, 2004.

Also overlaid on Fig. 7, are the wind vectors calculated by the VVP-1 technique (shown in black). It should be noted that the VVP vectors are calculated on the original elevation surface of 1.5 degrees, whereas the VLAS vectors are on a horizontal surface of 25 meters, AGL. Hence, the vectors should only be compared within a range of ~3 km from the lidar, where the Cartesian and elevation surfaces are within 50 meters of each other. Within this region, the two vector fields appear to agree reasonably well, with the VVP-1 retrievals indicating higher wind speeds behind the gust front. We hope to perform a more systematic verification of VLAS wind fields in the near future.

5. CONCLUSIONS

We have performed a systematic comparison of three wind retrieval schemes against independent data from a SODAR for the entire period of an intensive observing project. Our main results are summarized below:

(1) Winds calculated using the VAD method gave a very poor comparison with the SODAR data. The primary reason for the poor comparison is that the harmonic analysis used in the VAD method requires data spanning at least 180 degrees, whereas most of the data collected covered only a 90 degree sector.

(2) The retrievals were improved significantly when the VVP method (which can effectively use data over limited sectors) was applied. With the VVP-1 method, the r.m.s. difference with the SODAR azimuthal velocity was 1.6 m/s, with a correlation coefficient R^2 = 0.736. For the VVP-2 method, the r.m.s. difference was 1.4 m/s with an R^2 = 0.843.

(3) A diurnal analysis of the VVP retrievals indicated that the retrieved wind fields matched the SODAR data better during the night than during the data, when turbulent features tend to violate the wind-uniformity assumption of the VVP technique.

6. REFERENCES

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Waldteufel, P., and H. Corbin, 1979: On the Analysis of Single-Doppler Radar Data. *J. Appl. Meteor.*, **18,** 532-542.