7B.8 INNOVATIVE CROSS-CORRELATION METHOD FOR DETERMINING THREE-DIMENSIONAL WIND

Guifu Zhang[1], J. Vivekanandan[1], and Richard J. Doviak[2]
(1) NCAR/RAP, P.O.Box 3000, Boulder, CO 80307
(2) NSSL, 1313 Halley Circle, Norman, OK 73069

1. INTRODUCTION

Wind velocity can be measured by either Doppler method or interferometry technique. The Doppler method is routinely used in obtaining radial velocity, while interferometry technique has the potential for obtaining transverse velocity. To obtain two- or three-dimensional wind, the Doppler technique requires large space or angular diversity such as multiple Doppler radar system, bi-static radar network (Binet), or Doppler beam swing (DBS) wind profiler.

A typical example of a radar system using the interferometry technique is spaced antenna (SA) system in which multiple receivers are co-located with the transmitter and the received signals are jointly processed to find the cross-correlation function and wind velocity. The original idea of SA was proposed by Briggs et al (1950). Liu et al (1990) related the complex cross correlation to the wind and refraction index Δn statistics. Doviak et al (1996) rigorously derived the cross-correlation function and extended to a large class of Δn statistics.

A number of processing methods were proposed and used to obtain the transverse wind. They are: full correlation analysis (FCA); intersection (INT) method; slope at zero-lag (SZL); and the most recently proposed cross/auto- correlation ratio by Holloway et al (1997). Shortcomings of the above techniques are: the FCA fits the cross-correlation using a Gaussian function which may not be practical and prone to more uncertainty and it is not optimal for small separation cases; the INT method requires estimation of both auto- and cross-correlation functions; the SZL is difficult to obtain with high accuracy in the case of time lag interval comparable to the time shift of the correlation peak; and the cross/auto correlation ratio method may be affected by system noise.

A recent study has found that the accuracy of velocity estimation depends on the retrieval method and signal-to-noise ratio (SNR) as well as system configuration. It is important to find an optimal algorithm that maximizes SNR and the accuracy of velocity estimation.

In this paper, we propose an innovative correlation method for wind retrieval using cross-correlation and multi-level coherent processing. Data collected by NCAR Multiple Antenna Wind Profiler (MAPR) is used to illustrate and test the method. Preliminary results show that the current method determines wind velocity correctly and multi-level processing increases SNR by 5 dB or higher. The standard error of the wind retrieval is reduced.

2. PRINCIPLE AND METHOD

The interferometry technique was developed based on the fact that the interference pattern produced by randomly distributed scatterers moves in association with the scatterer's motion. Here, we present an alternative way of understanding the interferometry technique based on direct interpretation of the correlation change (correlation and de-correlation) as the scatterer's motion with respect to the radar system.

As a basic statistical characteristic, the correlation function is a measure of similarity in a random process. The similarity changes when the structure of the medium changes. In radar measurements, correlation function is obtained using time averaging instead of theoretically defined ensemble average. Therefore, if the radar resolution volume follows the motion of the scatterers such that the relative phase is fixed, the correlation time is maximum and hence the correlation for a specific time lag is maximized; otherwise, the correlation of the received signal decreases. Correlation is minimum when the movement of the radar resolution volume and motion of sctterers are in the opposite direction. This is illustrated in Fig. 1. The explanation also applies to cross-correlation function that is the measure of two random signals received at two receivers. The cross-correlation reaches maximum at the time-lag such that scatterers move to a location that the wave propagation path for receiver 1 is the same as that for receiver 2 with the time lag difference. Therefore, the ratio of the cross correlation at positive and negative lags gives information about the scatterer velocity.

3. INNOVATIONS OF CORRELATION METHOD FOR VELOCITY RETRIEVAL

The proposed method consists of using cross-correlation ratio at positive and negative lags, and multi-level coherent processing to improve the accuracy of velocity retrieval.

3.1 Velocity Retrieval Using Cross-correlation Ratio

With a separation of (x_d, y_d, z_d) between two sample volume, the cross correlation coefficient for spaced receivers can be derived (similar derivation can be found in Doviak, 1996) and given as

$$C_{12}(\tau) = \exp\Big(-\alpha^2 (x_d/2 - v_{0x}\tau)^2 - \alpha^2 (y_d/2 - v_{0y}\tau)^2 - (z_d - v_{0z}\tau)^2/(8\sigma_r^2) - 2(k\sigma_v\tau)^2 + 2ikv_{0z}\tau\Big) \quad (1)$$

where $\alpha = 2\pi\gamma/D$, is inversely proportional to the scale of the interference pattern. v_{0x} and v_{0y} are transverse velocity, and v_{0z} is the radial velocity, D is the receiver antenna aperture size, and γ is the antenna efficiency. Standard derivation of the velocity is denoted as σ_v and range resolution is σ_r.

Based on the understanding of the correlation change due to motion, we take a ratio of cross correlation coefficients at positive and negative lags and then a logarithm as

$$\ln \frac{C_{12}(\tau)}{C_{12}(-\tau)} \approx \alpha^2 2\Delta x v_{0x}\tau + 4ikv_{0z}\tau \quad (2)$$

Therefore, the logarithm of the ratio of the cross correlation coefficients is proportional to the mean velocity. The real part is linearly related to transverse velocity, which is the same as that of slope at zero-lag and the cross/auto correlation ratio except for a factor of 2, while the imaginary part is proportional to radial velocity as that in Doppler phase. Because of the linear relation, the multi-lag information is combined by using least-square fitting to minimize the fluctuation.

3.2 Multi-level Coherent Processing for SA System

It is known that SNR is a key parameter in wind measurements and affects the accuracy of velocity estimation. The question is how to increase SNR with current system. In this subsection, we illustrate a spatial multi-level correlation processing using NCAR Multiple Antenna Profiler (MAPR) configuration (Cohn, 1997).

MAPR has four antennas acting as one transmitter and four individual receivers. Complex signals (I, Q) are measured and recorded at each receiver as E_1, E_2, E_3, and E_4 that allows cross-correlation processing. Previously and currently, cross-correlation processing is conducted for each pair of the time series signal received by each receiver. It is shown in Fig. 2 as called first-level processing. There are six of these pairs as four of them: (1, 2), (2, 3), (3, 4), and (1, 4) with a separation of d and 2 pairs: (1, 3) and (2, 4) with a separation of $\sqrt{2}$ d.

To increase the SNR, we propose a spatially coherent processing in which the complex signals are combined before the correlation processing. For a system with four receivers like MAPR, we can do the 2nd and the 3rd level coherent processing as shown in Fig. 2. In the 2nd level processing, 2 pairs of correlations can be constructed as (1+2, 3+4) and (2+3, 1+4) with the same separation d as that in the 1st level. In the 3rd level processing, three complex signals are combined and then correlation functions are calculated based on the combined signals such as (1+2 +3, 1+4+3) and (2+1+4, 2+3+4). Since signals add coherently while noise add incoherently, the SNR increase a 3dB in the 2nd level processing and 5 dB in the 3rd level processing with a separation $\sqrt{2}$ d/3.

Another way of increasing SNR is to perform temporally coherent averaging, which is used in current MAPR processing. It is a blocked averaging, in which signal is obtained by averaging over 254 pulses. The problem is that the time lag interval is increased by a factor of 254 while time-lag interval is also important in velocity retrieval. To allow long time coherent averaging and also maintain fine time lag interval, we suggest moving coherent averaging is used instead of blocked averaging.

4. RESULTS AND DISCUSSIONS

Fig. 3 shows an example of velocity retrieval results using the cross-correlation ratio and spatially coherent processing. Both auto and cross correlation functions are calculated. The left column of the figure shows the magnitudes of the correlation coefficient and the right column is real part of the logarithm of the cross-correlation ratio that used to retrieve transverse velocity. In the 1st level, we also compare the current method with the auto/cross ratio method. The slope is twice as that of auto/cross ratio, the retrieved velocities are very close. We see higher SNR in the 2nd and 3rd correlation coefficient plots and consistent results of retrieved transverse velocity. Although the slope is different from that of first-level processing in the 3rd level processing because of the different effective separation, the retrieved velocities are almost the same.

Fig. 4 shows comparisons of the results with that using full correlation analysis and that of in-situ anemometer measurement. Compared with the FCA method, the current method gives the result with less fluctuation and agrees better with the anemometer measurement.

5. ACKNOWLEDGEMENTS

Authors would like to appreciate Drs. Larry Cornman, Steve A. Cohn, and William Brown for their great helps in providing data and helpful discussions. We sincerely appreciate the support provided by NCAR Research Application Program.

6. REFERENCES

Briggs, B. H., G. J. Phillips, and D. H. Shinn, 1950: The analysis of observation on spaced receiver of the fading radio signals, *Proc. Phys. Soc. London*, 63, 106-121.

Cohn, S. A., C. L. Holloway, S. P. Oncley, R. J. Doviak, and R. J. Lataitis, 1997: Validation of a UHF spaced antenna wind profiler for high-resolution boundary layer observations. *Radio Science,* 32, 1279-1296.

Doviak, R. J. and D. S. Zrnic, 1993: Doppler radar and weather observations. Academic Press. Inc., San Diego, California.

Doviak, R. J., R. J. Lataitis, and C. L. Holloway, 1996: Cross correlation and cross spectra for spaced antenna wind profilers: 1. Theoretical analysis, *Radio Science*, 31, 157-180

Holloway, C. L., R. J. Doviak, S. A. Cohn, R. J. Lataitis, and J.S. Van Baelen, 1997: Cross correlation and cross spectra for spaced antenna wind profilers: 2. Algorithms to estimate wind and turbulence, *Radio Science*, 32, 967-982

Liu, C. H., J. Rottger, C. J. Pan, and S. J. Franke, 1990: A model for spaced antenna observational mode for MST radars, *Radio Science*, 25, 551-563

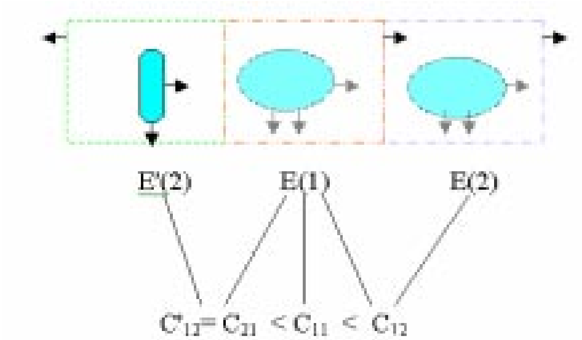
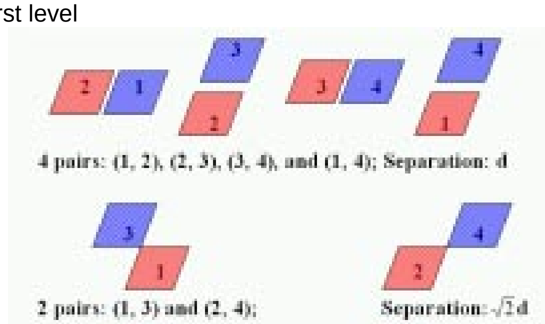
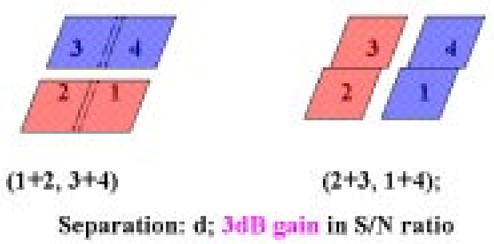


Figure 1. Understanding of interferometry technique based on the change in correlation.

First level



Second level



Third level

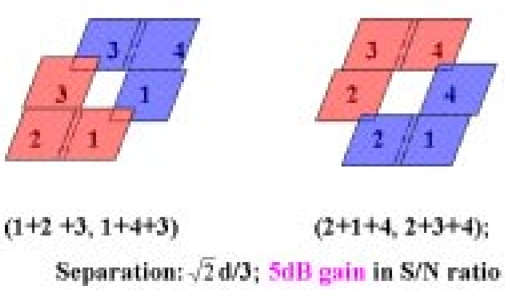
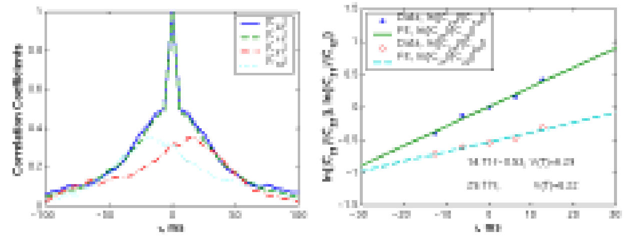
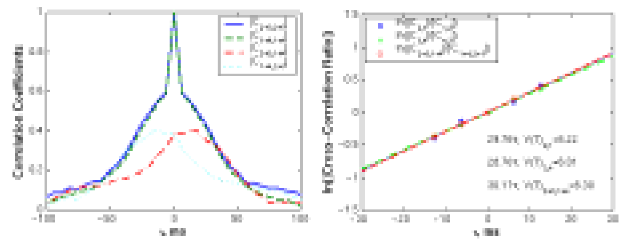


Figure 2: Spatial multi-level processing for MAPR configurations

First Level



Second level



Third level

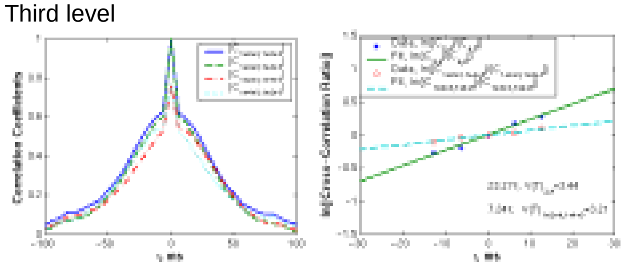


Figure 3: An example of velocity retrieval for MAPR measurement using cross-correlation ratio and multi-level processing

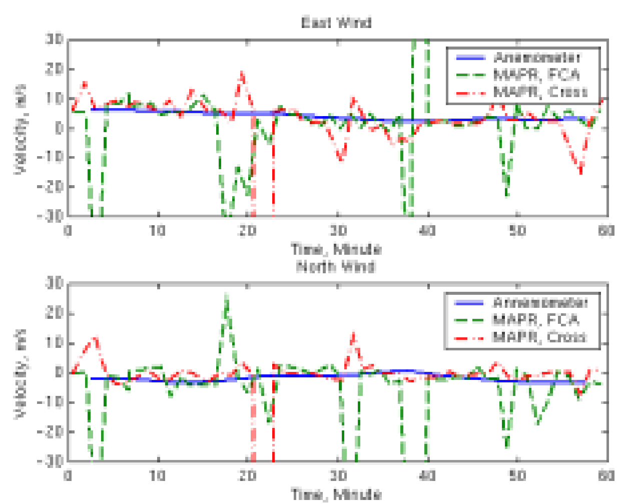


Figure 4: Results and comparisons with that using FCA method and in-situ measurements.