P4.11 SINGLE-DOPPLER RADAR WIND-FIELD RETRIEVAL EXPERIMENT ON A QUALIFIED VELOCITY-AZIMUTH PROCESSING TECHNIQUE

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ABSTRACT

Under the assumption that the horizontal wind vectors of two neighboring azimuths are uniform, the horizontal wind components can be derived in real time by single-Doppler radar velocity-azimuth processing (VAP) technique. Most applications, especially meteorological research for data assimilation, require quality-controlled wind field. Therefore, an extension of VAP, called qualified VAP, is presented in this study. Simulated data experiments are studied first to test the strengths and weaknesses of the method. An observed case of stratiform precipitation in a warm frontal system is used to further study the performance of the qualified VAP retrievals. The accuracy of the retrieval for this real case is examined against aircraft data and observations from a second radar. The verification shows that the qualified VAP technique can produce a reasonable description of the wind structure.

1. INTRODUCTION

As the resolution of numerical weather prediction models steadily increases, radar observations will play an important role in future convective- and mesoscale data assimilation systems. Doppler weather radar can provide wind observations with high temporal and spatial resolutions; but a main limitation of Doppler radar is that it measures only the radial component of the wind vector. Due to the distant spacing of the operational radars, considerable efforts have been made to develop single-Doppler velocity retrieval (SDVR) techniques.

The velocity-azimuth processing technique (hereafter VAP) estimates wind vectors based on the assumption of local uniformity of the wind field and the relation of the Doppler radial velocity to the horizontal wind vector (Zheng et al., 2003). The method is computationally efficient due to its simple assumptions. Furthermore, the wind vectors are derived at exactly the observation time on a polar coordinate system. The technique presented here is a modified version of VAP called qualified VAP. First, a new mathematical formula is derived, which is less sensitive to the noise in Doppler velocity measurements. Second, a two-dimensional running mean filter is introduced to remove the subscale 'noise' in Doppler velocities. Third, a VAP related quality control scheme is designed for the success of the retrieval.

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2. THE VAP TECHNIQUE

For low elevation scans, the contribution of the vertical component of the wind is very small in the measured Doppler velocity. Therefore, direct determination of the wind field is limited to the horizontal wind vector field. The Doppler radial velocity C can be related to the horizontal wind vector through the geometrical relation

$$C = u \times sin\theta + v \times cos\theta \quad (1)$$

where C is positive (negative) when the air is blowing away (toward) the radar. u and v are the westward and northward components of the horizontal wind vector, respectively. θ is the azimuth angle (clockwise from north).

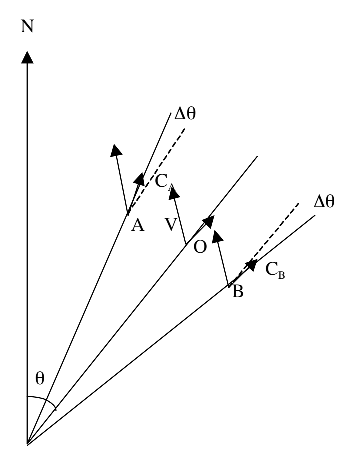

Figure 1: The representation of local uniformity assumption in the VAP method.

Given 3 points A, O and B at a specific range distance as in Fig. 1, denote θ as the azimuth angle of point O in the polar coordinate system, and Δθ as the azimuth resolution. Assume the horizontal wind vectors of two neighboring azimuths are uniform. Let C_A and C_B be the radial velocities at azimuth $\theta - \Delta\theta$ and $\theta + \Delta\theta$ measured by the radar at points A and B, respectively, which can be expressed as

$$C_A = u \times sin(\theta - \Delta\theta) + v \times cos(\theta - \Delta\theta) \quad (2)$$

$$C_B = u \times sin(\theta + \Delta\theta) + v \times cos(\theta + \Delta\theta) \quad (3)$$

Combining these two equations, one can derive the mathematical formula to get u and v simply by

$$u = \frac{C_B \times cos(\theta - \Delta\theta) - C_A \times cos(\theta + \Delta\theta)}{sin(2\Delta\theta)} \quad (4)$$

$$v = \frac{C_A \times sin(\theta + \Delta\theta) - C_B \times sin(\theta - \Delta\theta)}{sin(2\Delta\theta)} \quad (5)$$

The horizontal wind components u and v can be directly determined, given the distribution of Doppler velocities with azimuth. Therefore, this technique is called the velocity-azimuth processing (VAP).

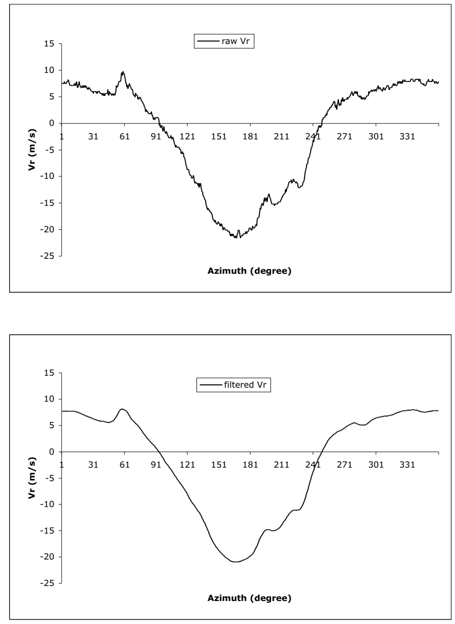

Figure 2: The distribution of Doppler velocity with azimuth.

3. SIMULATED DATA EXPERIMENTS

3.1 PERFORMANCE OF THE VAP METHOD

The VAP method described above is first tested on simulated data. Virtual 'observations' of radial velocity are created everywhere on a polar grid within a 112-km range. The range resolution is 500 m and azimuth resolution is 0.5°.

For a first case, uniform flow field is created. The wind speeds were equal and the wind directions were from southwest to northeast. To be more realistic, Gaussian random errors with zero mean and a standard deviation of 1 m/s are added to the gridded pseudo-observed radial velocities.

The VAP method is very sensitive to the 'noise' in Doppler velocities. This results in an inconsistent and noisy behavior in the VAP-derived vector fields (not shown). (Bai and Tao, 2000) proposed a two-dimensional, moving average filter to remove the 'noise' in the raw Doppler velocities. Mathematically, the filtered radial velocity V_r^f at point (r, θ) can be expressed as

$$V_r^f(r, \theta) = \sum_{(i,j) \in W} w_{ij} V_r(i, j) \quad (6)$$

where W represents the filter window, (r, θ) is the center point of W located by range r and azimuth θ, w is the weighting coefficient, and $V_r(i, j)$ is the raw Doppler velocity at point (i, j) within W. To account for the beam spreading nature related to radar observations, W is set to be range-dependent in the study. Fig. 2 gives an example of the distribution of Doppler velocity with azimuth before (upper panel) and after (lower panel) filtering for a specific range distance. The high-frequency signals are successfully removed. The fluctuations associated with the larger scales of interest have been preserved intact.

The VAP retrieved wind field (Fig. 3) based on filtered radial velocities shows good agreement with the true flow pattern. Wind vectors are oriented in the correct direction and the magnitudes are successfully recovered.

Figure 4 shows a simulated wind field rotating about a point. The center of rotation was 80 km to the west and south of the radar site. Wind speed decreased outward from the circulation center. The background wind blew from southwest. This crudely represents a mesoscale cyclonic circulation.

Figure 5 gives the retrieved wind fields and the related quality index (explain later) associated with this rotation case. The VAP generally recovered the signature of cyclonic rotation; however, the wind vectors are questionable in both direction and magnitude.

3.2 DEFINITION OF QUALITY INDEX

The results from simulated data experiments suggest that the accuracy of the VAP retrievals depends on the complexity of the flow pattern. To assimilate wind vectors into numerical weather prediction (NWP) models, high-quality wind vector fields are required (Friedrich

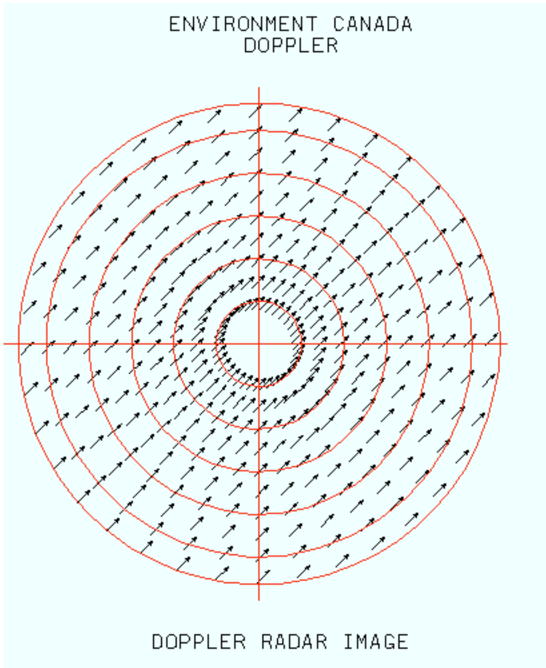

Figure 3: The VAP-derived wind field associated with uniform flow.

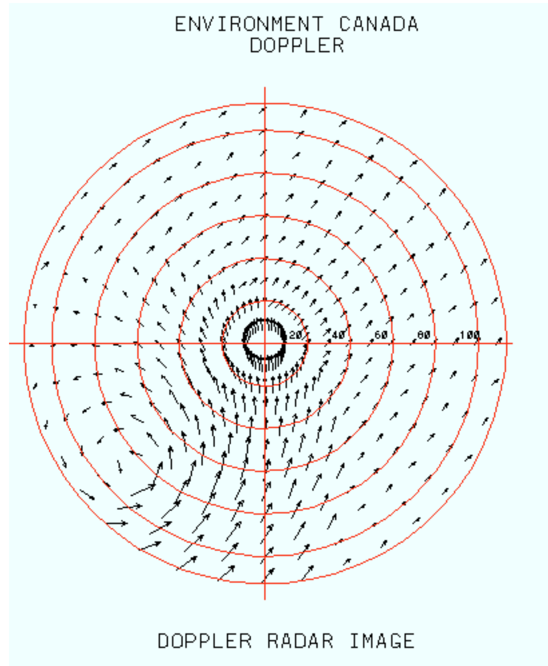

Figure 4: The simulated rotating flow field.

and Hagen, 2004). Thus, creating a quality index field that represents the confidence of the VAP retrievals is highly needed. In this study, a quality index with values range from 0 to 1 is generated for each retrieval. A 1 corresponds to measurements with high quality, while low-quality retrievals are flagged with 0 values.

For the simulated data experiments, two quality factors are considered to take account 1) the radar position, denoted as F_1; and 2) the gradient of the observed radial velocity, denoted as F_2.

1) *Quality factor* F_1

The quality of the retrieval is sensitive to radar position (Liou and Luo, 2001). When the flow is nearly parallel(perpendicular) to the beam, the quality of the retrieved winds is more(less) reliable. This view is supported by Fig. 5. The apparently wrong flow occurs in regions where the retrieved wind vectors are nearly perpendicular to the radar beam. To describe the importance of radial components (observed) relative to the azimuthal portion (unknown), a quality factor F_1 is defined as

$$F_1 = \frac{|V_{rad}|}{\sqrt{V_{rad}^2 + V_{azi}^2}} \tag{7}$$

where V_{rad} and V_{azi} are the retrieved radial and azimuthal winds, respectively.

2) *Quality factor* F_2

The quality of the QVAP retrieval is closely related to the azimuthal gradient of the 'observed' radial wind. The illegality of the local uniformity assumption might be responsible for the poor retrievals. Therefore, a quality factor F_2 is introduced by

$$F_2 = 1 - \frac{|\frac{C_B - C_A}{2\Delta\theta}|}{1m/s} \quad for \quad |\frac{C_B - C_A}{2\Delta\theta}| < 1 \tag{8}$$

where C_B, C_A and $\Delta\theta$ are as defined in section 2.; $\frac{C_B - C_A}{2\Delta\theta}$ is the radial wind gradient along the azimuth direction. $1m/s$ is the threshold that is chosen empirically. F_2 is set to be zero when $\frac{C_B - C_A}{2\Delta\theta} \geq 1$.

3) *Quality factor* F_3

To apply the QVAP technique to real Doppler observations, an additional quality factor F_3 is introduced to represent the signal uncertainties in the measurements.

$$F_3 = 1 - \frac{\sigma}{8m/s} \quad for \quad \sigma < 8 \tag{9}$$

where σ is the value of spectral width in m/s, and $8m/s$ is a somewhat arbitrary threshold value. F_3 is set to zero when $\sigma \geq 8$.

4) *Quality index QI*

The quality factors can be averaged to get a single quality index by defining

$$QI = \frac{w_1 F_1 + w_2 F_2 + w_3 F_3}{w_1 + w_2 + w_3} \tag{10}$$

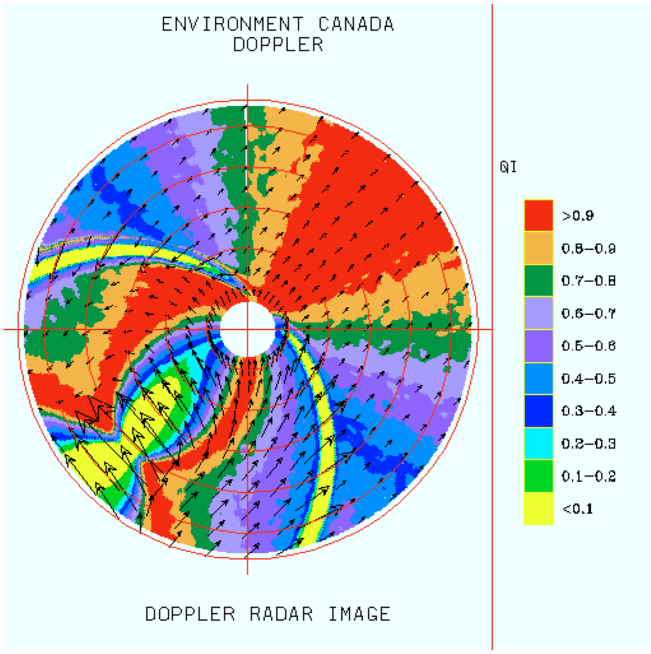

Figure 5: The distribution of quality index *QI* associated with Fig. 4.

The influence of each quality factor on the overall quality index *QI* is weighted by w_1, w_2 and w_3, respectively. Figure 5 exhibits the average quality index field *QI* calculated for the simulated flow (rotation case). The good retrievals are indeed given high confidence with values from 0.5 and up; the poor retrievals are flagged with values below 0.3. This method, the modified version of that first described by (Tao, 1992), is called qualified velocity-azimuth processing technique (QVAP hereafter).

4. REAL DATA EXPERIMENTS

To apply the QVAP method to real radar observations, the following retrieval steps are proposed.

1) Remove the signals contaminated by nearby ground clutter.

2) Modify the filter defined in (6) to account for data voids in the real observations.

3) Perform QVAP retrieval based on the filtered radial velocity field. The same filter is applied to the derived u and v to get a smooth wind field.

4) Calculate the quality index *QI* in (10) to represent the accuracy of the retrieval.

4.1 DESCRIPTION OF RADAR DATA

Figure 6 shows the locations and surrounding topography of the Aldergrove and Victoria radars located in British Columbia, Canada. The Aldergrove radar (Latitude 49.0161°N, Longitude 122.4878°W, Altitude 114 m MSL) is located just southeast of Vancouver. It measures reflectivity, radial velocity and velocity-spectral width data at 0.5°, 1.5° and 3.5° elevation angles. Mountains cause significant blockage of scans near the radar site. The Victoria radar (Latitude 48.8606°N, Longitude 123.7555°W, Altitude 748 m MSL) is about 100 km to the west of the Aldergrove radar. This radar is blocked by mountains mainly to its west. The operational cycle includes Doppler scans taken at -0.3°, 0.5° and 3.5°. The negative (-0.3°) scan angle is useful because this radar is located atop a mountain. The Doppler scans for both radars are performed with a 10-min cycle. The range resolution is 500 m and azimuth resolution is 0.5°.

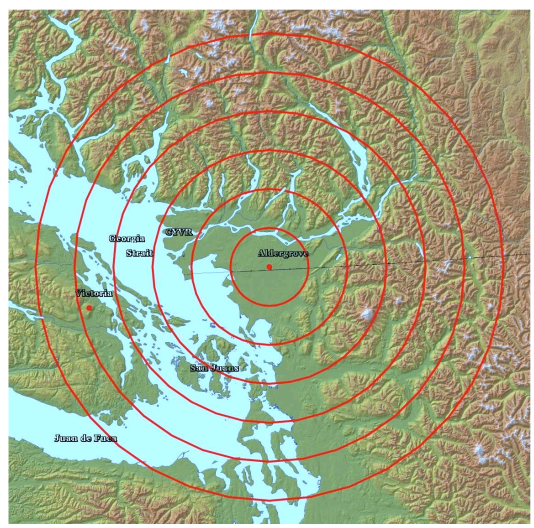

Figure 6: The background topography near the Aldergrove radar site. The dots mark the radar locations. The range rings are at 20 km interval.

On November 15, 2001, an intensifying low pressure system and the associated warm front passed over the radar viewing area and spread stratiform rainfall over the region. Synoptic observations (not shown) revealed light easterly flow at low-levels. The wind speed increased, and direction veered with height gradually, resulted in a strong southwesterly upper-level flow.

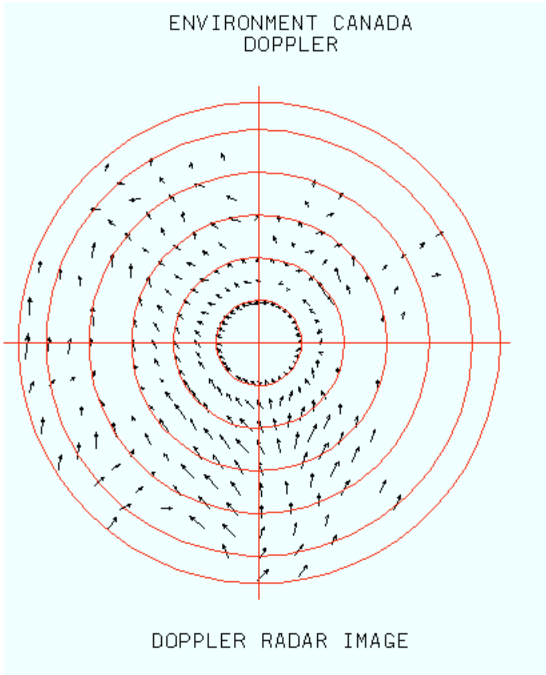

Figure 7: The QVAP retrieved horizontal wind field from the Aldergrove radar (0.5° elevation scan).

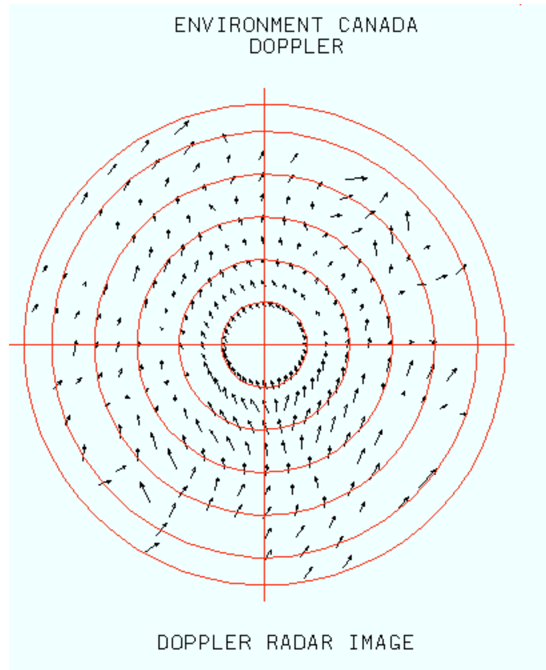

Figure 8: The QVAP retrieved horizontal wind field from the Aldergrove radar (1.5° elevation scan).

4.2 WIND RETRIEVALS FOR THE ALDERGROVE RADAR

For this case, volume scan data taken by the Aldergrove radar around 00:40 UTC 15 November 2001 was utilized for the retrieval. The QVAP retrieval is performed directly on a polar grid; therefore, it reveals the wind structure at different levels.

Figs. 7, 8 and 9 give the retrieved flow field from the Aldergrove radar data for 0.5°, 1.5° and 3.5° elevation scans, respectively. Visual inspection reveals the slowly increasing wind speed and correspondingly veering wind direction over an extensive transition region. No distinct discontinuity is observed for this warm frontal system as anticipated.

The plot of in situ ACARS data collected by a flight taking off from CYVR around 00:45 UTC is shown in Fig. 10. The resulting profile indicates veering wind directions from southeast to southwest (left panel) and increasing wind speeds from 10 m/s to 30 m/s (right panel) with increasing height. Fig. 11 shows the QVAP retrieved wind speed and direction at heights nearest to the ACARS altitudes. Note the close agreement between the ACARS-observed and QVAP-derived winds for most layers. This favorable comparison supports the accuracy of the flow fields constructed from the Aldergrove data. A major discrepancy occurred between 1-3 km, which is likely due to fluctuation within the front zone.

4.3 WIND RETRIEVALS FOR THE VICTORIA RADAR

In this part, volume scan data obtained from the Victoria radar around 00:40 UTC 15 November 2001 is used for the QVAP retrieval. The flow field derived from the Victoria radar (not shown) recovered the light southeast wind near surface and strong southwest wind aloft successfully. The clockwise turning wind direction and slowly increasing wind speed provide persuasive evidence of the warm air advection. Similarly, the plot of the QVAP-derived wind speed and direction from the Victoria radar (not shown) indicates good agreement for most layers and a mismatch around 2.5-km layer.

4.4 VALIDATION WITH A SECOND RADAR

This precipitation event was acquired by both the Aldergrove and Victoria radars. Therefore, the QVAP-derived 2-D wind field can be used to derive 'analysis' radial winds that can be further verified against the raw Aldergrove/Victoria radar-observed ones. As an example, Fig. 12a depicts the raw radial wind V_{rad}^{O} observed by Aldergrove radar for 0.5° elevation angle. Fig. 12b indicates the equivalent QVAP-derived radial winds V_{rad}^{P}, retrieved and projected from the Victoria radar scans taken at -0.3°, 0.5° and 3.5°, over the intersection re-

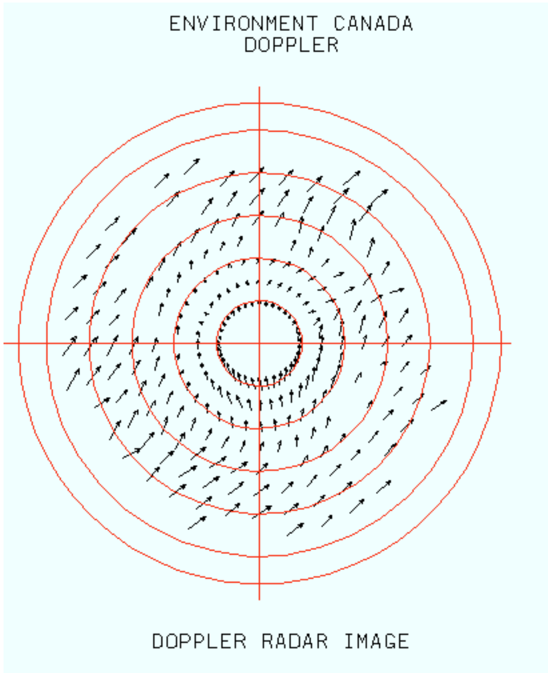

Figure 9: The QVAP retrieved horizontal wind field from the Aldergrove radar (3.5° elevation scan).

gions. Index R plotted in Fig. 12c is defined by

$$R = \frac{|V_{rad}^P|}{\sqrt{(V_{rad}^P)^2 + (V_{rad}^O)^2}} \times sgn(V_{rad}^P \times V_{rad}^O) \qquad (11)$$

The expression $sgn()$ on the rhs of (11) is used to determine the correctness of the retrieved radial wind direction. For cases where the radial wind field is completely recovered, the value of R is approximately $1/\sqrt{2}$ ($\sim$0.7). Therefore, the 'good' retrievals are represented by R ranges from 0.6 to 0.8. The quality index field is given in Fig. 12d. It is evident that the retrieved radial wind agrees reasonably well with the observed one over high QI regions.

The statistics related to a second radar verification are listed in Table 1. *Radar* represents the radar from which the QVAP-retrieval is performed. The variable QI indicates the critical index values above which the statistics is executed. *Ratio* gives the percentage of grid points that had a reasonably accurate retrieval. MAE is the mean absolute error, estimated by

$$MAE = \frac{1}{N} \sum \sqrt{(V_{rad}^O - V_{rad}^P)^2} \qquad (12)$$

where N is the number of total retrievals over the common area; and V_{rad}^O and V_{rad}^P are as defined earlier.

When QI increased, the *Ratio* increased and MAE decreased correspondingly, which indicates that the quality index reflects the retrieval accuracy quite well.

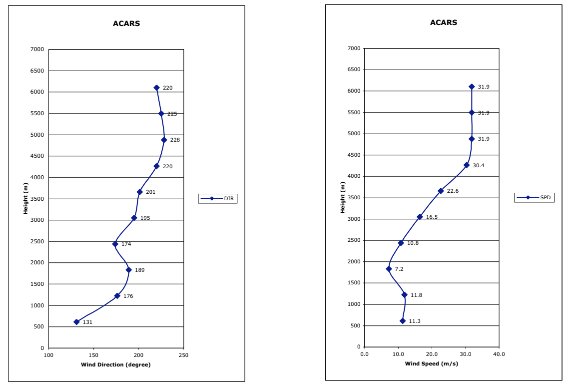

Figure 10: Vertical profiles of wind speed in m/s (right panel) and wind direction in degree (left panel) measured from a flight taking off from CYVR around 00:45 UTC, 15 November 2001.

Table 1: Statistical results - November 15, 2001

Radar	QI	$Ratio(\%)$	$MAE(m/s)$
	0.1	0.32	4.96
	0.2	0.33	4.92
Aldergrove	0.3	0.35	4.80
	0.4	0.38	4.24
	0.5	0.41	3.62
	0.1	0.54	4.50
	0.2	0.57	4.05
Victoria	0.3	0.58	3.66
	0.4	0.60	3.33
	0.5	0.59	2.95

5. Summary and future work

Assume the horizontal wind vectors of two neighboring azimuths are uniform, a method for obtaining the horizontal wind vectors is presented. This method, called qualified velocity-azimuth processing (QVAP), is an extension of VAP. The modifications include 1) a new mathematical formula is derived to calculate the wind vectors directly; 2) a two-dimensional filter is modified to take account data voids in real applications; and the filter is applied before and after the retrieval to get a smoothed wind field; 3) a QVAP-related quality index field, based on the geometric location of radar, the spatial gradient of the observed radial wind and signal quality of the radar measurements, is defined to indicate the retrieval accuracy .

The QVAP method is attractive because: 1) it can produce a reasonable description of the wind structure with a reasonable computational cost for routine operation; 2) the retrieval is performed directly on a polar coordinate

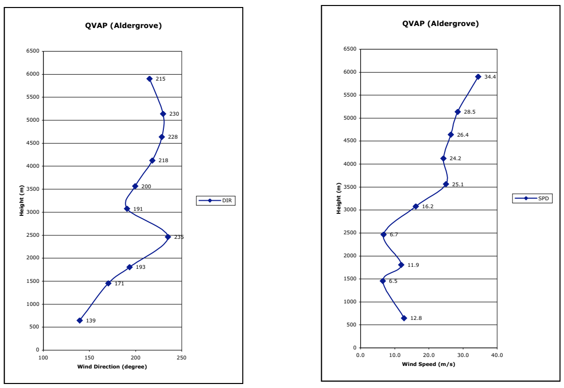

Figure 11: Vertical profiles of wind speed in m/s (right panel) and wind direction in degree (left panel) derived from volume-scan data for the Aldergrove radar around 00:40 UTC, 15 November 2001.

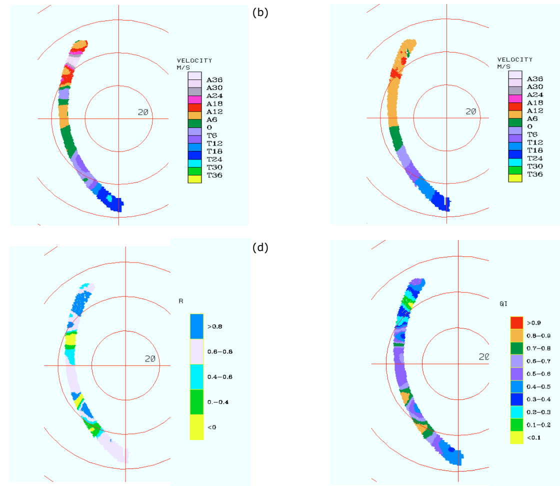

Figure 12: (a) Radial wind observed by the Aldergrove radar. (b) The Aldergrove radial wind retrieved from the Victoria radar. (c) The distribution of the R index. (d) The distribution of QI. All fields are over intersections between the Aldergrove 0.5° elevation scan and the Victoria -0.3°, 0.5° and 3.5° scans.

system and at exactly the observation time; 3) it can be used to visualize and analyze the wind field in real time; 4) the retrieved wind vectors and the associated quality index field provide a new data set for data assimilation research.

The behavior of this method has been investigated with both simulated wind fields and an observed stratiform event. To validate the retrievals, the retrieved winds are projected into the beam direction of a second Doppler radar and a direct comparison is made with the observed radial winds of that second radar. The accuracy is also verified against automated weather reports from commercial aircraft (ACARS) data. The key results of this study are:

1. The QVAP retrieval is sensitive to the 'noise' in Doppler velocities. A two-dimensional, moving average filter can be applied to remove the subscale noise and resolve presumed important scales of motion simultaneously.

2. The accuracy of the QVAP retrieval depends on the complexity of the flow pattern. The quality index can be used to represent the confidence in the retrievals.

3. The formula used in the method is designed for low elevation scans. As a result, only horizontal wind vectors can be retrieved by the QVAP method.

4. The real data case is mainly evaluated by visual inspection. Objective verifications by a second radar and ACARS observations are performed over limited point/region. Numerical model simulations could be a candidate for wide area validation in the future.

In future work, more real case studies, involving various kinds of weather phenomena are planned. The qualified retrievals will be further applied to high-resolution numerical weather forecasts in data assimilation research.

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