Adjoint-Method Retrievals of Microburst Winds From TDWR Data*

Qin Xu, Chong-Jian Qiu, Jin-Xiang Yu, Hong-Dao Gu
CIMMS/CAPS, University of Oklahoma
Marilyn Wolfson
Lincoln Laboratory, MIT

1. Introduction
The simple adjoint (SA) method of Qiu and Xu (1992, henceforth referred to as QX92) was recently upgraded and tested with the Phoenix-II data for retrieving the low-altitude winds from single-Doppler scans (Xu et al. 1993a,b,h, henceforth referred to as XQY93a,b). The major results can be briefly reviewed as follows: (i) Using multiple time-level data with the adjoint formulation makes the retrieval more accurate and less sensitive to the observational error. (ii) Imposing a weak nondivergence constraint can suppress the spurious divergence caused by the data noise and improve the retrieval. (iii) Retrieving the eddy coefficients improves the wind retrieval. (iv) Retrieving the time-mean residual term improves the wind retrieval.

Although the results in XQY93a,b were encouraging, the Phoenix-II data used in XQY93a,b were collected on non-storm days with chaff dispersed from an aircraft. The real challenge is to test the SA method with storm data. A microburst case is selected for the test in this paper.

2. 11 July 1988 Microburst case
On 11 July, a very strong microburst (> 35 m/s differential velocity) occurred at the Denver Airport during the 1988 TDWR (Terminal Doppler Weather Radar) operational test and evaluation (Elmore et al. 1990, Proctor and Bowles 1992). Dual Doppler coverage was provided by the TDWR testbed radar (FL2, operated by MIT Lincoln Laboratory) and the UND (University of North Dakota) radar (see Fig. 1). The operational scan strategy executed by FL2 included a surface sector scan over the airport every minute. This surface scan was matched nearly simultaneously (avg. within 3.5 sec) by UND. The polar data from each radar were thresholded at 5 dB SNR and median smoothed with a 5 gate x 3 degree filter (at least 8 good values out of 15 required). The data were then sampled to a 250 m resolution Cartesian grid (at the level of z = 190 m above the FL2 radar site).

Surface anemometer data from the 12 station Low Level Wind Shear Alert System (LLWAS) were also collected during the experiment (see Fig. 1). Several of the stations in 1988 suffered from wind sheltering problems (Lieuins et al. 1990) that have since been remedied by raising the sensor height.

3. Method description
As in XQY93b, the radial-component wind $v_r$ is used as a "tracer" field and is governed by the following approximate radial-component momentum equation:

$$\partial_t v_r + \mathbf{v}_m \cdot \nabla v_r - v_{cm}^2 / r - k \nabla h^2 v_r = f_m.$$  (1)

where $v_{cm}$ is the cross-beam wind, $\mathbf{v}$ the horizontal vector wind, $\nabla h$ the time-mean operator, $f_m$ the unknown residual forcing (mainly the pressure gradient and vertical advection). The boundary and initial values are given by the observed $v_r$.

The objective is to find the best estimate of $(v_m, k, f_m)$ in (1) that gives the best "prediction" of the radial wind $v_r$ in terms of minimizing the following cost-function

$$J = \{(P_1 \Delta^2 + P_2 \Delta m^2 + P_3 \mathbf{d}_m^2 + P_4 \zeta_m^2)\}_{m}.$$  (2)

Here $\{(\cdot)\} = (1/\Omega) \int (\cdot) d\Omega$ is the area-mean operator over the retrieval domain $\Omega$; $P_1$ and $P_2$ are nondimensional weights, $\Delta = v_r - v_{cm}, \Delta m = v_m - v_{cm}$, and $\Omega$ is the observed value of $(\cdot); P_3$ and $P_4$ are dimensional weights (in unit m²), $\mathbf{d}_m = \nabla h v_m$ the divergence, and $\zeta_m = \mathbf{k} \cdot \nabla h^2 v_m$ the vorticity. The minimum of $J$ can be approached by numerical iteration along the gradient of $J$ with respect to $(v_m, k, f_m)$. The gradient is computed at each step of iteration by an explicit expression derived from the adjoint formulation similar to (2.7) of XQY93b.

The optimal retrieving time period $\tau$ should cover 4 sequential scans, i.e., $\tau = 3 \Delta \tau$. The weights are given by

$$P_1 = \tau / (T \Delta t)^2,$$

$$P_2 = 0.02 P_1 \text{ with } P_1 \equiv (P_1)_{m},$$

$$P_3 = k_3 \sigma_v \mathbf{d}_m \text{ with } k_3 = 30 \sim 200 \text{ m}^2,$$

$$P_4 = k_4 \sigma_v \zeta_m \mathbf{d}_m \text{ with } k_4 = 100 \sim 600 \text{ m}^2,$$  (3)

where $\sigma_v$ is the root mean square amplitude of $v_r$. The choice of the time-dependent form for $P_1$ was explained in QX92. With the above specified value for $P_2$, the weak form of the constraint $\Delta m = 0$ can reduce the error in the estimated cross-beam wind. The relative strength of the weak divergence (or vorticity) constraint is controlled by $k_3$ (or $k_4$). As long as $k_3$ (or $k_4$) is in the optimal range shown in (3), the retrieval is not very sensitive to $k_3$ (or $k_4$). The weights in (3) are consistent with those in XQY93a,b, but $k_4$ and the last term in (2) are new here.

4. Results
The SA method is tested with the microburst data for a continuous period (22:04-22:33). The averaged (over 25 time-levels) RMS errors and correlation coefficients between the retrieved and observed variables are listed

* A portion of this work was sponsored by the Federal Aviation Administration. The views expressed are those of the authors and do not reflect the official policy or position of the U.S. Government.
in Table 1. When the observed radial winds are used in
the final results, the vector RMS errors for \( \mathbf{V}_m \) reduce to
those for \( \mathbf{V}_{\text{ext}} \) in Table 1. The retrieved wind field is com-
pared with the observed in Fig. 2a-b. The correlation di-
agram is shown in Fig. 3, where the RMS error and corre-
lation coefficient between the retrieved and observed
wind components are also listed. The retrievals from FL2
radar data are better than those from UND radar data.

The accuracy of the retrievals are affected mainly by
three factors: the data noise, the temporal fluctuation of
the residual forcing (i.e., the equation error), and the wind
direction relative to the radar beam.

Using the wind field retrieved at the previous time level
as an initial guess can reduce the CPU cost, but may not
always improve the accuracy. Extrapolating the LLWAS
data to the grid level of \( z = 190 \text{ m} \) and using it as a weak
constraint may (or may not) improve the retrieval, if the
surface winds are well (not well) correlated to the
Doppler radial winds at the grid level.

\begin{table}[h]
\centering
\begin{tabular}{c|cccc}
\hline
 & \( \mathbf{V}_m \) & \( \mathbf{V}_{\text{ext}} \) & \( \mathbf{C}_m \) & \( \mathbf{F}_m \) \\
 & m/s & m/s & \( 10^{-3} \text{ s}^{-1} \) & \( 10^{-2} \text{ m/s}^2 \) \\
FL2 radar: & & & & \\
RMS error & 3.30 & 2.99 & 4.75 & 3.16 & 1.25 \\
Correlation & 0.92 & 0.83 & 0.60 & 0.22 & 0.77 \\
UND radar: & & & & \\
RMS error & 4.53 & 4.37 & 5.34 & 3.32 & 1.41 \\
Correlation & 0.84 & 0.65 & 0.48 & 0.17 & 0.68 \\
\hline
\end{tabular}
\caption{Statistics of the retrievals (with FL2 radar).}
\end{table}

5. Conclusion

In addition to the earlier findings reviewed in section 1,
it is found in this paper that using the weak vorticity
constraint also improves the retrieval, especially for
microburst cases. Using the previous time-level retrieval
as an initial guess can reduce the CPU cost. Optimal
uses of the surface wind data need further investigations.

Acknowledgment

This work is supported by the NOAA contract NA90-
RAN00078 and NSF Grants ATM-9113906 at CIMMS
and ATM-8809862 at CAPS, University of Oklahoma.

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