A possible approach to extract the storm-relative typhoon asymmetric structures using GBVTD technique

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1. Introduction:

The Ground Based Velocity Tracking Display (GBVTD) technique, developed by Lee et al. (1999, 2000a), has demonstrated its capability in extracting the storm-relative typhoon structures using Doppler radar velocity data (Lee et al., 2000b). Nevertheless, the limitation of this method is that in its formulation, the asymmetric components of the typhoon radial flow are neglected in order to close the equations. Consequently, only the symmetric part of the radial flow can be retrieved. In this study, we propose that by applying GBVTD to two Doppler radars, it is possible to separate the typhoon circulation from the mean flow. This separation, however, cannot be accomplished by performing the traditional dual-Doppler syntheses. After obtaining the mean flow, the asymmetric components of the typhoon radial winds can be recovered up to its wave number 1 structure. In addition, depending on the number of points along each GBVTD analysis ing where an extra observation of the typhoon radial wind is available, the flow structures associated with higher wave numbers can be further resolved. This paper introduces the proposed algorithm, and reports some of our preliminary results.

2. The Original GBVTD Formulation:

In this section we adopt the equations used by Lee et al. (1999), and their Fig. 1 to define the geometry and all variables. The observed Doppler velocity ($\hat{V}_d$) at elevation angle ϕ can be expressed by:

$$\frac{\hat{V}_d}{\cos\phi} \approx V_M \begin{bmatrix} \cos(\theta_T-\theta_M)\begin{pmatrix} \frac{1-\cos\alpha_{max}}{2}\cos 2\psi \\ +\frac{1+\cos\alpha_{max}}{2} \end{pmatrix} \\ -\sin(\theta_T-\theta_M)\sin\alpha_{max}\sin\psi \end{bmatrix} - V_T\sin\psi + V_R\cos\psi \qquad (1)$$

where V_M and θ_M denote the mean flow speed and direction, respectively, and θ_T is the angle of the typhoon center viewing from the radar. The V_T stands for the typhoon tangential wind, while the typhoon radial wind is represented by V_R. The definitions of ψ and α_{max} can be found in Fig. 1. According to Lee et al. (1999), $\hat{V}_d$, V_T and V_R can be written with respect to angle ψ and a truncated Fourier series:

$$\frac{\hat{V}_d(\psi)}{\cos\phi} = \sum_{n=0}^{L}(A_n\cos n\psi + B_n\sin n\psi) \qquad (2)$$

$$V_T(\psi) = \sum_{n=0}^{M}(V_TC_n\cos n\psi + V_TS_n\sin n\psi) \qquad (3)$$

$$V_R(\psi) = \sum_{n=0}^{N}(V_RC_n\cos n\psi + V_RS_n\sin n\psi) \qquad (4)$$

Let L=4 and M=N=3, respectively, the Fourier coefficients V_TC_n, V_TS_n, V_RC_n and V_RS_n can be expressed by:

$$V_M\cos(\theta_T-\theta_M) = A_0 + A_2 + A_4 - V_RC_1 - V_RC_3 \qquad (5)$$

$$V_TC_0 = -B_1 - B_3 - V_M\sin(\theta_T-\theta_M)\times\sin\alpha_{max} + V_RS_2 \qquad (6)$$

$$V_RC_0 = A_1 + A_3 - V_RC_2 \qquad (7)$$

$$V_TS_1 = A_2 - A_0 + A_4 + \begin{pmatrix} A_0 + A_2 + A_4 \\ -V_RC_1 - V_RC_3 \end{pmatrix}\times\cos\alpha_{max} + V_RC_3 \qquad (8)$$

$$V_T C_1 = -2(B_2 + B_4) + V_R S_1 + V_R S_3 \quad (9)$$

$$V_T S_2 = 2A_3 - V_R C_2 \quad (10)$$

$$V_T C_2 = -2B_3 + V_R S_2 \quad (11)$$

$$V_T S_3 = 2A_4 - V_R C_3 \quad (12)$$

$$V_T C_3 = -2B_4 + V_R S_3 \quad (13)$$

In the original approach of Lee et al. (1999), the above equations are closed by neglecting $V_R C_n$ and $V_R S_n$ when $n \geq 1$. Then, by performing a least square fitting for the observed Doppler velocities along each analysis ing to estimate the coefficients A_n and B_n, one can retrieve the typhoon tangential winds up to its wave number 3 structures, and the symmetric part ($V_R C_0$) of the radial flow.

3. The Proposed New Approach:

3.1 The recovery of mean flow

In the original GBVTD formulation, the information of the mean flow (V_M and θ_M) is unknown. It is aliased into $V_T C_0$ (see Equation 6). Now, assuming the typhoon can be observed by a second Doppler radar, as illustrated by radar B in Fig. 2, then one can also perform the GBVTD analysis using this second set of radar data. Since $V_T C_0$ is the symmetric part of the tangential wind, its value should not depend on the viewing angle of the radar. However, considering the factors such as the approximations used during the derivations of GBVTD, or the radar observational errors etc., it is only expected that the $V_T C_0$ retrieved by two radars should exhibit similarity. Based on this concept, Equation (6) is employed to seek a set of optimized V_M and θ_M which, in the least square sense, minimizes the difference between these two $V_T C_0$. In other words, we have:

$$(V_T C_0)_i = [-B_1 - B_3 - V_M \sin(\theta_T - \theta_M) \times \sin\alpha_{\max}]_i \quad (14)$$

and

$$(V_T C_0)'_i = [-B'_1 - B'_3 - V_M \sin(\theta'_T - \theta_M) \times \sin\alpha'_{\max}]_i \quad (15)$$

where the subscript i denotes the index of the analysis ing surrounding the typhoon center, and the prime stands for the results of the GBVTD analysis using Radar B data. The best estimated V_M and θ_M become the solutions which minimize the following expression:

$$\sum_{i=1}^{NR} [(V_T C_0)_i - (V_T C_0)'_i]^2 \quad (16)$$

NR is the total number of rings involved in the analysis. Note that $V_R S_2$ in Equation (6) is assumed to be small, and can be neglected.

3.2 The recovery of wave number 1 typhoon radial flow:

After obtaining V_M and θ_M, and assuming $V_R C_3$ is negligible, the $V_R C_1$ can be estimated from Equation (5). Then, as depicted in Fig. 2, Equation (1) is applied at points P1 and P2. Since at these two points, the ψ angle (ψ_B) viewed from radar B equals 0 and π, respectively, Equation (1) is simplified to (assuming $\phi = 0$):

$$\hat{V}_d(radarB;P1) = V_M \cos(\theta'_T - \theta_M) + V_R(P1) \quad (17)$$

$$\hat{V}_d(radarB;P2) = V_M \cos(\theta'_T - \theta_M) - V_R(P2) \quad (18)$$

Since radar B measures the Doppler winds at these two points, the left-hand-side of the above equations becomes known. Thus, the typhoon radial flow (V_R) can be computed at these two locations. The next step is to decompose the typhoon radial flow at, say, P2 to wave number 1:

$$V_R(P2) = V_R C_0 + V_R C_1 \cos(\psi_{A2}) + V_R S_1 \sin(\psi_{A2}) \quad (19)$$

in which ψ_{A2} is the value of ψ angle at P2 viewing from radar A. Finally, since Equation (19) contains only one unknown variable $V_R S_1$, it can be solved. The derived $V_R C_1$ and $V_R S_1$ can also be utilized in Equations (8) and (9) to improve the estimation of $V_T C_1$ and $V_T S_1$. The above procedures demonstrate the newly proposed algorithm to retrieve the wave number 1 structure of the storm-relative typhoon radial winds.

4. Results:

A series of theoretic studies using idealized typhoon circulation model has demonstrated the feasibility of this approach. For brevity, these results are not shown here. Instead, we present some of our preliminary results obtained from a test in which the newly designed method is applied to typhoon Nari (2001). Our calculation indicates that the mean flow speed is about 9 m/s, and its direction is around 312^o (note that 0^o means the wind is blowing toward due east). By separating this mean flow from the typhoon circulation, Fig. 3 displays the retrieved storm-relative tangential winds, ranging from 35 to 45 km from the center, using the traditional dual-Doppler syntheses and our improved GBVTD, while the retrieved storm-relative radial winds are plotted in Fig. 4. The agreements are rather satisfactory. In Fig. 3, the strongest tangential winds appear in the northern part of the typhoon. In Fig. 4, the eastern (western) portion of the typhoon turns out to be occupied by inflow (outflow). Figure 5 shows the retrieved results at one selected analysis ring with a radius of 30 km. It is apparent that both the phase and magnitude of the curves extracted by the improved GBVTD are consistent very well with their counterparts computed by the dual-Doppler syntheses.

5. Combination with other instruments, and extension to higher wave numbers:

It is realized that the purposes of having the second Doppler radar are: (1) Estimate the mean flow; (2) Provide an extra point of independent wind observation over each ing However, there are other possible methods to achieve the above purposes. For estimating the mean flow, the scheme commonly used in typhoon bogussing (e.g. Davis and Low-Nam, 2001) provides an algorithm whereby a vortex can be smoothly removed from the flow field. The wind residue (maybe after an area average), can be considered the mean flow. In addition, the so-called Hurricane-Customized Extension of the VAD (HEVAD) technique developed by Harasti and List (2001) also offer a possible alternative to estimate the mean flow.

As illustrated in Fig. 2, if at any location along the ring, except the points where $\psi_A = 0$ or π, the true ground-relative winds are measured not by a second Doppler radar, but by instruments such as releasing a dropsonde or a wind profiler (hereafter, ds/wp data). Then, the procedures introduced in Section 3 can also be extended to resolve higher wave number structures of the radial flow. Here we propose two possible scenarios:

Scenario I: Dual-Doppler GBVTD + ds/wp observations:

As described in section 3 that by applying the GBVTD to two Doppler radars, the mean flow can be separated from the typhoon circulation, and the coefficient $V_R C_1$ can be recovered from Equation (5). Under this condition, if there are extra ds/wp observations along the analysis ring, then we can identify two cases:

CASE 1: If radar B only measures the radial winds at P2, then only $V_R S_1$ can be completely recovered. Thus, N (N is an even number) points of additional ds/wp observations would enable us to recover the radial flow up to wave number $N/2 + 1$ structures. Note that the number of unknown coefficients (that is, $V_R C_n$ and $V_R S_n$) are counted by extending equation (19) to higher wave numbers.

CASE 2: If radar B can measure the radial winds at P1 and P2, then one more point of ds/wp data is sufficient to yield the coefficients $V_R S_1$, $V_R C_2$ and $V_R S_2$. A general rule is that N (N is an odd number) points of extra ds/wp data can help to recover the asymmetric radial flow to wave number $(N+3)/2$.

Scenario II: Single-Doppler GBVTD + known mean flow + ds/wp observations:

If the mean flow information is known through methods described above, then $V_R C_1$ and $V_R S_2$ can be computed from Equations (5) and (6). In this situation, one more ds/wp data point is needed to estimate the $V_R S_1$ so that the recovery of wave number 1 structure is completed. With two ds/wp data points, we can compute both $V_R S_1$ and $V_R C_2$, or the wave number 2 structure. A general rule for this scenario is that N (N is an even number) points of ds/wp data can help to recover the radial winds to wave number $(N/2 + 1)$.

6. Discussion:

This paper uses the GBVTD technique, and presents a new approach to retrieve the asymmetric structure of the typhoon circulation, especially along the radial components. Although a second Doppler radar may be needed, there are several advantages over the traditional dual-Doppler synthesis:

(1)The new approach is capable of separating the typhoon circulation from the mean flow. This separation, however, cannot be accomplished with the traditional dual-Doppler analysis. The wind field products of the latter are always ground-relative.

(2)One can also remove the mean flow directly from the dual-Doppler synthesized results to obtain the pure typhoon circulation.

(3) The GBVTD method does not require a full data coverage over each analysis ring, but the dual-Doppler synthesis does. Therefore, even though the data coverage on each ring is not complete, our method is still useful.

Finally, the discussion presented in section 5 demonstrates the procedures to rebuild the storm-relative typhoon asymmetric structures using a combination of dual- and single-Doppler GBVTD and extra wind measurements independently taken at a finite number of points over each ring.

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7. Reference:

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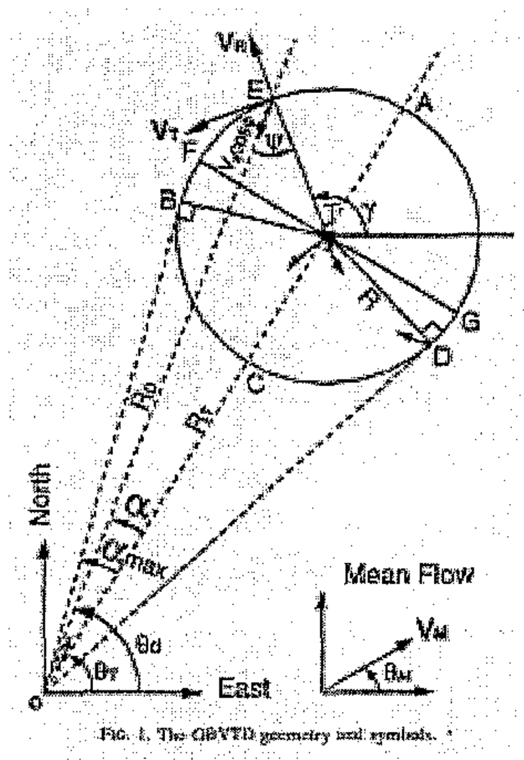

Fig 1 The geometry of GBVTD and the definitions of all variables (Courtesy of Lee et al. (1999))

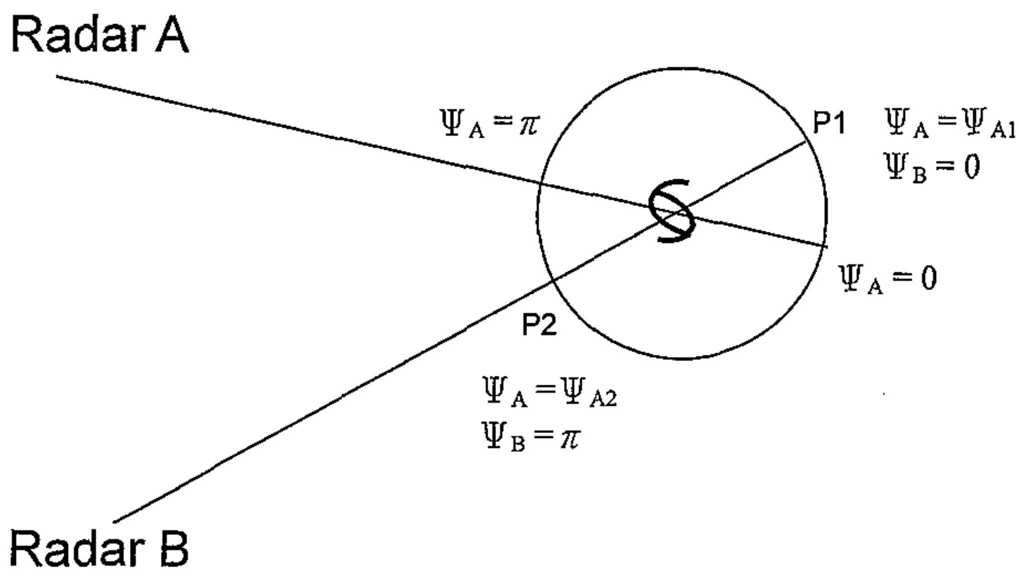

Fig. 2 The concept of applying GBVTD to two Doppler radars

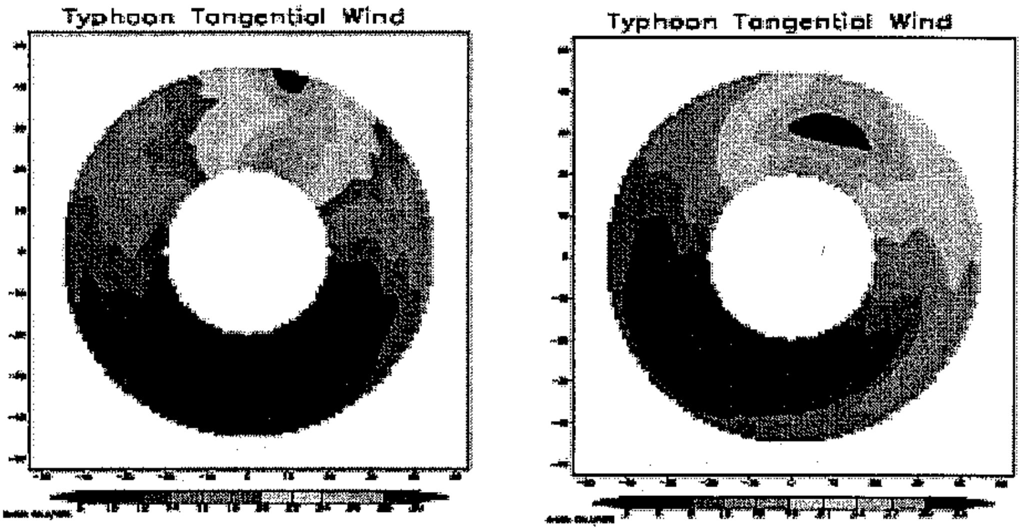

Fig. 3 The storm-relative tangential flow structure of typhoon Nari (2001) retrieved by Dual-Doppler synthesis (left panel) and GBVTD (right panel)

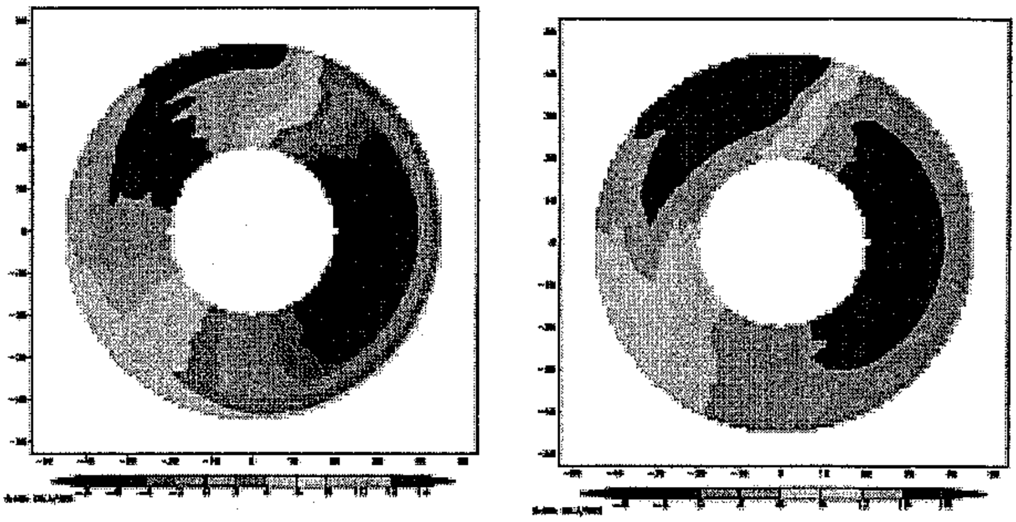

Fig. 4 The storm-relative radial flow structure of typhoon Nari (2001) retrieved by Dual-Doppler synthesis (left panel) and GBVTD (right panel)

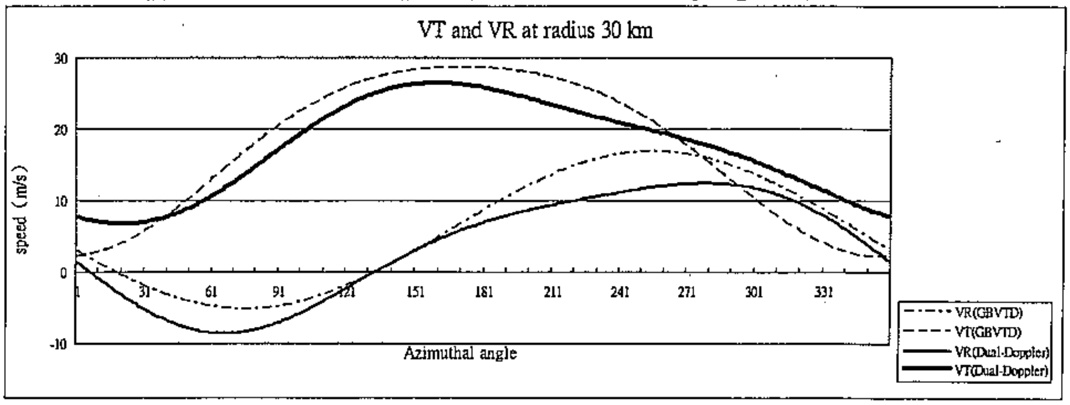

Fig. 5 The GBVTD and dual-Doppler retrieved storm-relative typhoon tangential and radial flows at the ring with a radius of 30 km.