Application of an Interferometric Phase Unwrapping Technique To Dealiasing of Weather Radar Velocity Fields

Stephen L. Durden and Charles L. Werner

Jet Propulsion Laboratory

California Institute of Technology

Submitted to: J. *Atmos. Oceanic Technol.*

Date: August *31, 1995*

Abstract

We point out, that dealiasing of Doppler weather radar velocity measurements is identical to the problem of phase unwrapping encountered in radar and optical interferometry. A technique developed for phase unwrapping in interferometric synthetic aperture radar is described and successfully applied to weather radar velocity dealiasing.

1 Introduction

In pulsed Doppler weather radar systems, the maximum velocity which can be unambiguously measured v_a is limited by the pulse repetition frequency (PRF). Velocities greater than v_a are aliased into the range $(-v_a, v_a)$. The true velocity v is related to the measured velocity v_m, by $v = v_m + 2nv_a$, where n, the Nyquist number, specifies the aliasing interval. To recover the true wind field, the measured wind field must be dealiased. This can be thought of as a two step process. The first, which we call the relative velocity step, produces a velocity field that is correct in the sense that the velocities in each connected, or spatially continuous, region differ from each other by the correct amount. Once complete, the velocities in each region are either correct or are incorrect by the same multiple of $2v_a$. The second step in dealiasing is determination of the correct multiple of $2v_a$ for each connected region. This step attempts to produce the correct absolute velocity. Recent, algorithms for the velocity dealiasing problem include Bergen and Albers (1988), Eilts and Smith (1990), and Jing and Wiener (1993).

The dealiasing problem has also been considered in field of interferometry in both radar and optical settings. (Goldstein et al. 1988, Huntley 1989, Ghilia and Romero 1990, Cusack et al. 1995). In the interferometric measurement process, the true phase is aliased into the interval $(-\pi, \pi)$. The true phase ϕ is related to the measured phase ϕ_m by $\phi = \phi_m + 2n\pi$, where n, the Nyquist number, specifies the alias interval. Recovery of the true phase requires dealiasing the measured phase and is identical to the weather radar velocity dealiasing problem, As in velocity dealiasing, the phase dealiasing problem often requires two steps. The first, called phase unwrapping, creates a consistent, phase field in each connected region. The second, absolute phase determination, finds the correct multiple of 2π to add to each region.

Although dealiasing is common to both Doppler weather radar and interferometry, the methods that have been developed in the two areas are different. It is the purpose of this note to show how a technique from interferometry phase unwrapping can be applied to weather. radar velocity dealiasing. We first discuss the algorithm itself and then show examples of its application to weather radar measurements. We consider only the problem of relative velocity determination within a connected region. Tbc absolute velocity determination problem often requires environmental wind information and is not considered here.

2 Description of Technique

In both the weather radar and interferometry problems, it is assumed that the true field is continuous. Hence, when a sharp jump in the measured field is encountered, it is assumed that aliasing has occured, and the field is adjusted to remove (or minimize) the discontinuity. This procedure can be thought of as forming the gradient of the measured field, adjusting the derivative field so that the derivatives are witbin desired limits, and then integrating the result. This simple procedure works well in high SNR cases. However, when SNR is low, errors which propagate throughout, large areas can occur. In Goldstein et al (1 988) it was noted that these problem areas can be identified by a dependence of the result on the direction of dealiasing. Dealiasing along range and then azimuth produced different results from dealiasing along azimuth and then range. These results can be understood by considering the gradient of the measured field. A vector field which is the gradient of a scalar field has a line integral which is independent of the integration path, and the line integral around any closed path is zero. A problem may occur, however, when the gradient is adjusted to remove a discontinuity. When noise is present, the adjusted gradient may no longer be the gradient of a scalar field. in this case the line integral becomes path dependent, explaining the finding by Goldstein et al (1 988).

Several possible approaches to the noise problem have been suggested. In Bergen and Albers (1988) median filtering is applied to the velocity field before dealiasing to remove noise. In Eilts and Smith

(1 990) various heuristically derived checks and comparisons are used to detect problem areas during dealiasing. The algorithm is fast, generally works well, and is the basis of the WSR-88D operational algorithm. In Jing and Wiener (1993) the noise problem is handled by using a least squares technique rather than an integration of the corrected gradient. Their approach is somewhat similar to the least squares method of Ghiglia and Romero (1989) in the phase unwrapping literature. An improved least squares phase unwrapping technique was presented in Song et al. (1 995) in the context of magnetic resonance imaging.

Here, we use the technique of Goldstein et al. (1988), hereafter referred to as GZW. The method was developed for interferometric synthetic aperture radar and was independently proposed by Huntley (1 989) and further developed in Cusack et al. (1 995). As mentioned previously, the line integral around a closed loop should be zero if the integral of the field is to be path inpendendent. Thus, problem areas can be identified by examining the line integral around each of the smallest possible units of the field, namely, a 4 point square. This quantity can be conveniently calculated directly from the measured field velocity using:

$$s(m,n) = [(v(m+1,n) - v(m,n))/2v_a] + [(v(m+1,n+1) - v(m+1,n))/2v_a] + [(v(m,n+1) - v(m+1,n+1))/2v_a] + [(v(m,n) - v(m,n+1))/2v_a] \tag{1}$$

where [ ] denotes the operation of finding the closest integer. Figure 1 shows velocity data that appeared as an example in Eilts and Smith (1 990). The first set of data is the true velocity field. The next set of data is the aliased measurement of the true field, with v_a equal to 20 m/s. The last column is the result of applying (1) to the aliased data and is non-zero only for the box shown. This same problem area was found by a heuristic check in the Eilts and Smith (1 990) algorithm. Here it is identified by a rigorous mathematical test.

The GZW technique precedes by evaluating (1) for each point in the field. Points with non-zero s are called residues, and their locations are saved. Next, branch cuts are created, connecting residues with opposite sign. These branch cuts are analogous to the branch cuts in complex analysis, and integration across thcm is forbidden. The adjusted gradient is then integrated, taking care to avoid branch cuts. Any integration path which avoids crossing a branch cut may be used; the results are independent of the chosen path. It should be noted that the choice of branch cuts is not unique and is still the subject of research. The optimum choice appears to be that which minimizes the total cut length. Unfortunately, an exhaustive search is not practical, so other methods arc used. GZW uses a nearest neighbor algorithm, and the problem is discussed in detail in Cusack et al. (1 995).

3 Results

We initially applied the algorithm to data acquired by the NASA/J P], ARMA R airborne radar (Durden et al. 1994). This system operates on the NASA I) C-8 aircraft,. Because ARMAR looks downward and usually has v_a of 22 m/s, aliasing is rare. However, we were able to find cases where aliasing occured in measurements of the eyewall in Cyclone Oliver during 10GA COARE in the Western Pacific Ocean in early 1993. The algorithm successfully dealiased the data, although, because of the high signal-to-noise ratio (SNR), few residues were found. In this case even a simple algorithm would have worked properly. A more challenging data set was acquired try the WSR-88D radar in Melbourne, FL on March 13, 1993, as a squall line was approaching from the northwest. The radar was operated with a 1020 Hz PRF, giving a v_a of 26.5 m/s. Because of the nearly 200 km distance of the squall line from the radar, the SNR was rather low. Figure 2a shows a portion of the squall line in range- angle coordinates. These data have been range dealiased but not velocity dealiased. Regions with sudden velocity changes can be noted in various portions of the image. Because of the low SNR, Figure 2a has 113 residues scattered throughout. Figure 2b shows the same area after dealiasing with the GZW algorithm. Agreement of Figure 2b with independent velocity measurements and with the output, of the WSR-88D operational algorithm is generally good, although several small areas appear to be incorrect, including isolated range bins not connected to the main region.

4 Conclusions

We have noted that the phase unwrapping and velocity dealiasing problems are identical and that techniques developed for one problem are applicable to the ot her. We described one phase unwrapping technique developed for interferometric synthetic aperture radar. The technique is able to locate and handle inconsistencies in the velocity field in a mathematically rigorous manner. The technique was used to successfully dealias both ARMAR and NEX I{ Al) data in connected regions.

Acknowledgments

We would like to thank W. D. Zittel for supplying the WSR-88D data. The work described here was performed by the Jet Propulsion Laboratory, California Institute of ‘J’ethnology, under contract with the National Aeronautics and Space Administration.

References

Bergen, T. A., and S. C. Albers, 1988: Two-- and three-dimensional dealiasing of Doppler radar velocities. *J. Atmos. Oceanic Technol.*, 5, 305-319.

Cusack, R., J. M. Huntley, and H. T. Goldrein, 1995: Improved noise-ilnmunc phase-unwrapping algorithm. *Appl. Optics*, 34, 781-789.

Durden, S. L., E. Im, F. K. Li, W. Ricketts, A. Tanner, and W. Wilson, 1994: ARMAR: An airborne rain mapping radar. *J. Atmos. Oceanic Technol.*, 11, *727-737*.

Eilts, M. D., and S. D. Smith, 1990: Efficient deal iasing of Doppler velocities using local environmental constraints. *J. Atmos. Oceanic Technol.*, *7*, 118-128.

Ghiglia, D. C. and L. A. Romero, 1989: Direct phase estimation from phase differences using fast elliptic partial differential equation solvers. *Optics Lett.*, 14, 1107-1109.

Goldstein, R. M., H. A. Zebker, and C. L. Werner, 1988: Satellite radar interferometry: Two-dimensional phase unwrapping. *Radio Sci.*, *23*, 713-720.

Huntley, J. M., 1989: Noise-immune phase unwrapping algorithm. *Appl. Optics*, 28, 3268-3270

Jing, Z., and G. Wiener, 1993: 'Two-dimensional dealiasing of Doppler veloctics. *J. Atmos. Oceanic Technol.*, 10, 798-808.

Song, S. M. H., S. Napel, N. J. Pelc, and G. H. Glover, 1995: Phase unwrapping of MR phase images using Poisson equation. *IEEE Trans. Image Proc.*, *4*, 667-676.

Figure Captions

Figure 1. Example velocity data from Eilts and Smith (1990) showing; true and slimed velocity fields (m/s) and the results of applying Equation (1) to the aliased field.

Figure 2. illustration of algorithm performance for WSR-88D data. a) Raw (aliased) velocities. b) Dealiased velocities using GZW algorithm. The velocity scale is from -40 m/s (black) to +40 m/s (light gray). Bad or non-existing data is white. The horizontal axis is range, varying from 1 55 km at left to 230 km at right . lhe vertical axis is azimuth angle, varying from 240° at the top of the images to 360° at the bottom.

RANGE

True		Aliased		S
-19	**-17**	-19	-17	0
-24	-20	16	-20	0
-23	-23	17	17	0
-22	-22	18	18	0
-19	-22	-19	18	0
-20	-21	-20	19	1
-5	2	-5	2	0
-1	0	-1	0	0
0	-3	0	-3	0
3	4	3	4	0
3	3	3	3	

AZIMUTH

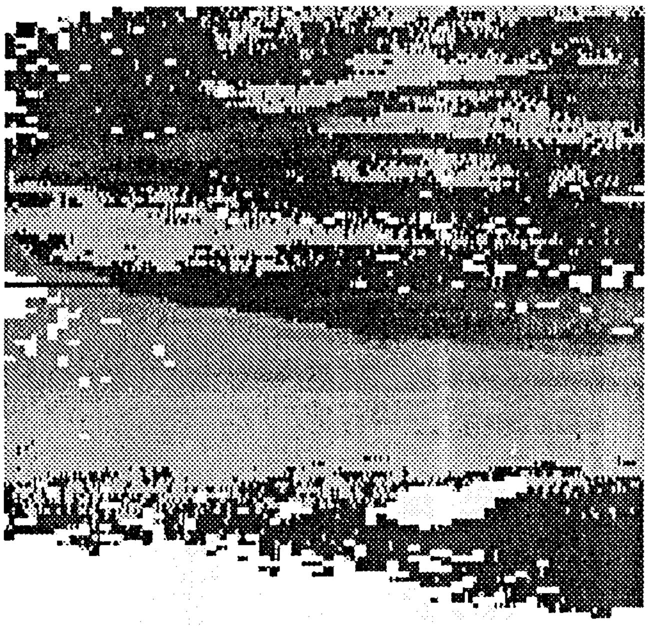

Figure 2a

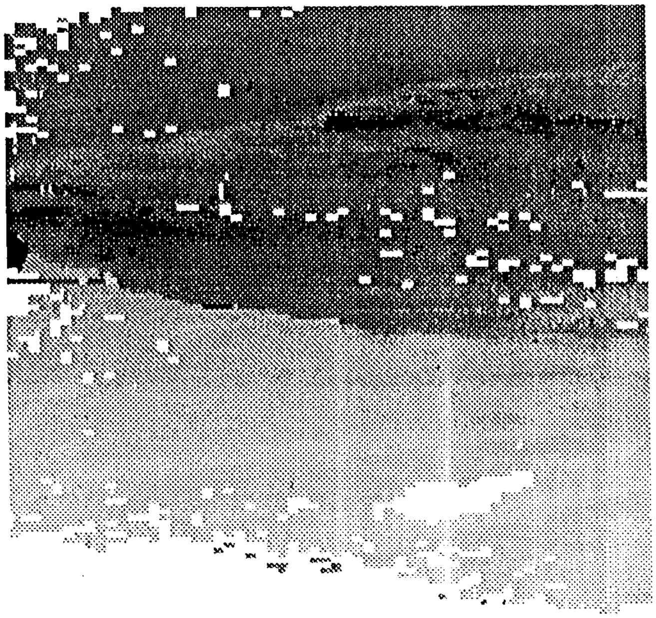

Figure 2 b