AN EXPERIMENT TO DERIVE CLOUD MOTION VECTORS FROM SATELLITE IMAGES WITH 2-D FOURIER PHASE ANALYSIS TECHNIQUE[†]

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Abstract

A technique based on 2-D Fourier phase analysis is used to derive cloud motion vectors from satellite 1-minute interval IR imagery. Comparing the 2 wind fields derived from 3 adjacent images based on continuity analysis, unreasonable wind vectors in wind direction and speed would be eliminated.

Keywords: 2-D Fourier technique, cloud motion track, sub-pixel

1 INTRODUCTION

Derivation of cloud motion winds(CMW) from thirty-minutes interval geostationary satellite images by maximum correlation matching method has been performed operationally for about thirty years. It has been proved that the CMW products are helpful and valuable for weather forecasting especially in those areas lack of observation data[1]. As high temporal resolution images of 1 minute interval or even less can be obtained from new generation satellites such as GOES, Purdom[2] showed that it was valuable for deriving meso-scale fields of cloud motion but found that a problem called "sub-pixel" appeared when applying conventional maximum correlation matching method to extract cloud motion winds from these high temporal resolution images. Wang[3,4] suggested 1-D Fourier phase analysis technique to derive CMW vectors based on the assumption of 1-D displacement of cloud. Rather than traditional maximum correlation matching method, the Fourier phase analysis technique obtained *u*- and *v*- components of cloud motion independently with 1-D Fourier phase shift. In this article, 2-D Fourier phase analysis technique is introduced and the u- and v- components can be obtained simultaneously.

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2 THEORETICAL BASES FOR 2-D FOURIER PHASE ANALYSIS TECHNIQUE

Of the two adjacent images for cloud tracking, suppose that template 1 on the first image obtained at *t0* has N×N pixels, and *f(x,y)* is its grey function. The 2-D Fourier transformation $F(\mu,\nu)$ of template 1 can be expressed as

$$F_1(\mu,\nu)=\sum_{x=0}^{N-1}\sum_{y=0}^{N-1} f(x,y)\exp[-j2\pi(\mu x+\nu y)/N]=R_1(\mu,\nu)-jI_1(\mu,\nu)\,, \qquad (1)$$

in which both μ and ν are frequency variables, $R_1(\mu,\nu)$ and $I_1(\mu,\nu)$ are the real and imaginary parts of $F_1(\mu,\nu)$.

Therefore the amplitude spectrum $|F_1(\mu,\nu)|$ and phase spectrum $\phi_1(\mu,\nu)$ of $F_1(\mu,\nu)$ are

$$|F_1(\mu,\nu)|=\sqrt{R_1{}^2(\mu,\nu)+I_1{}^2(\mu,\nu)}$$ and

$$\phi_1(\mu,\nu)=\arctan\frac{I_1(\mu,\nu)}{R_1(\mu,\nu)}\,.$$

Suppose the cloud displacement are *x0* and *y0* in *x* and *y* direction respectively after a period of Δt, the 2-D Fourier transformation of template 2 in the second image which is at the same location as template 1 in the first image is

$$F_2(\mu,\nu)=\sum_{x=0}^{N-1}\sum_{y=0}^{N-1} f(x-x0,y-y0)\exp[-j2\pi(\mu x+\nu y)/N]=R_2(\mu,\nu)-jI_2(\mu,\nu) \qquad (2)$$

and the amplitude spectrum $|F_2(\mu,\nu)|$ and phase spectrum $\phi_2(\mu,\nu)$ are

$$|F_2(\mu,\nu)|=\sqrt{R_2{}^2(\mu,\nu)+I_2{}^2(\mu,\nu)}$$ and

$$\phi_2(\mu,\nu)=\arctan\frac{I_2(\mu,\nu)}{R_2(\mu,\nu)}\,.$$

According to the displacement theorem for Fourier transformation[5], the displacement in spatial domain corresponds to the phase shift in frequency domain as expressed by

$$F_2(\mu,\nu) = F_1(\mu,\nu)\exp[-j2\pi(\mu x_0 + \nu y_0)/N] \tag{3}$$

This implies that the amplitude spectrum of $F_1(\mu,\nu)$ is just the same as $F_2(\mu,\nu)$, and that the phase shift is determined by $2\pi(\mu x_0 + \nu y_0)/N$, i.e.

$$\begin{aligned} &|F_1(\mu,\nu)| = |F_2(\mu,\nu)| \\ &\Delta\phi(\mu,\nu) = \phi_2(\mu,\nu) - \phi_1(\mu,\nu) = 2\pi(\mu x_0 + \nu y_0)/N \end{aligned} \tag{4}$$

Thus the displace components, *x0* and *y0,* can be obtained by

$$\begin{cases} x_0 = \dfrac{N}{2\pi}\dfrac{\partial\Delta\phi(\mu,\nu)}{\partial\mu} \\ y_0 = \dfrac{N}{2\pi}\dfrac{\partial\Delta\phi(\mu,\nu)}{\partial\nu} \end{cases} \tag{5}$$

From Equation 5, (x_0, y_0) is independent of (μ,ν), but actually each harmonic component had its own displacement:

$$\begin{cases} x_{0(\mu,\nu)} = \dfrac{N}{2\pi}\dfrac{\partial\Delta\phi(\mu,\nu)}{\partial\mu} \\ y_{0(\mu,\nu)} = \dfrac{N}{2\pi}\dfrac{\partial\Delta\phi(\mu,\nu)}{\partial\nu} \end{cases}, \mu = 1,2 \ldots N-1, \nu = 1,2 \ldots N-1 \tag{6}$$

because of both the limited size *N* and the variability in phase speed. Thus, the (x_0, y_0) should be estimated based on an amplitude-weighted average as the following:

$$\begin{cases} \hat{x}_0 = \dfrac{\sum_{\mu=1}^{N-1}\sum_{\nu=1}^{N-1}|F_{\mu\nu}|^P \times x_{0(\mu\nu)}}{\sum_{\mu=1}^{N-1}\sum_{\nu=1}^{N-1}|F_{\mu\nu}|^P} \\ \hat{y}_0 = \dfrac{\sum_{\mu=1}^{N-1}\sum_{\nu=1}^{N-1}|F_{\mu\nu}|^P \times y_{0(\mu\nu)}}{\sum_{\mu=1}^{N-1}\sum_{\nu=1}^{N-1}|F_{\mu\nu}|^P} \end{cases} \tag{7}$$

in which P is weighting parameter. Though the parameter can be assigned with an arbitrary integer number, Let P=0 leads an arithmetic mean for (x_0, y_0). P=1 is for an amplitude-weighted average, and P=2 for a power-weighted average.

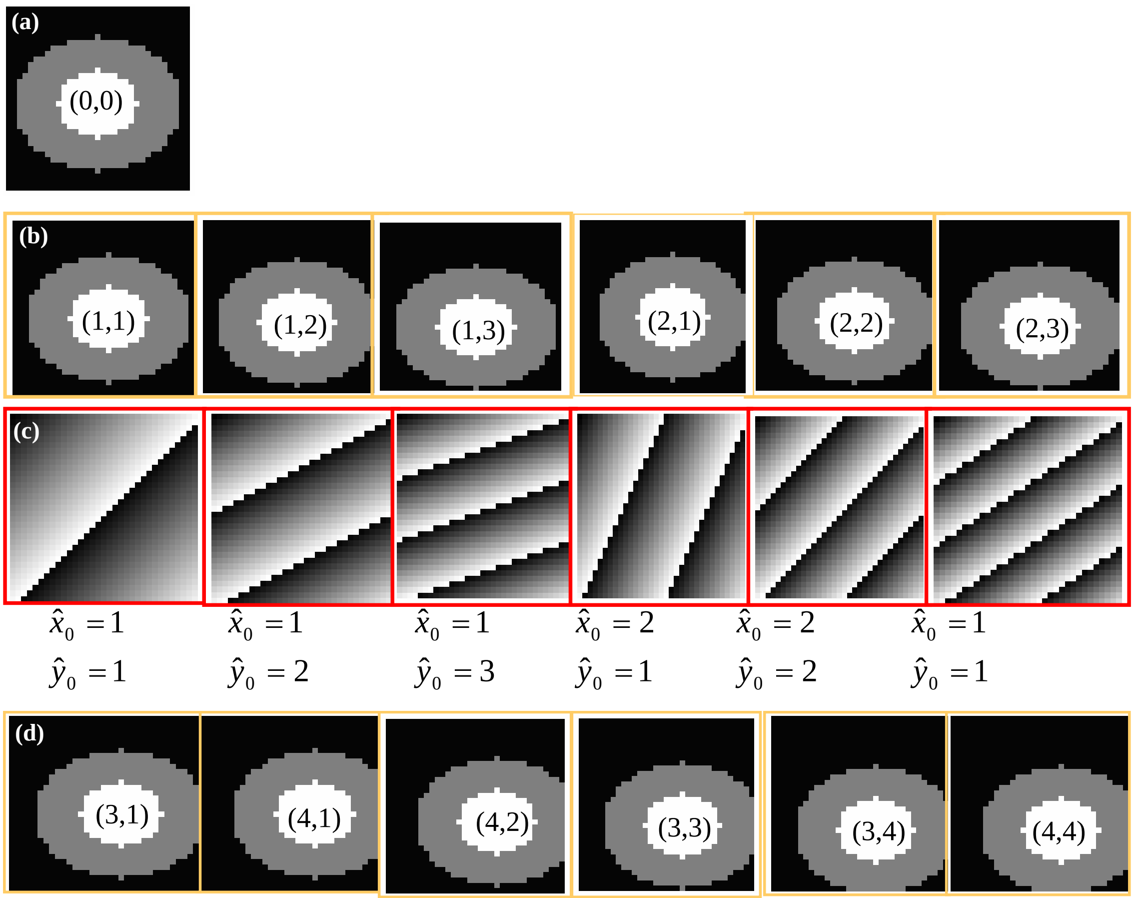
The u and v components of a motion vector are finally obtained with

$$u = \hat{x}_0 / \Delta t \quad \text{and}$$

$$v = \hat{y}_0 / \Delta t \, .$$

3 SIMULATION EXPERIMENTS

A two-layer cloud cell is simulated for tracking experiment. As shown in Figure 1a, template 1 is at the reference position *(0,0)* with 32×32 pixels. Figure 1b is template 2 for several cases in which the cell has moved to a new position, as shown with the numbers inside each of the template, in both *x* and *y* directions under the condition that all pixels of the cell are inside the template. Phase shift between template 1 and 2 can be computed for each case based on the 2-D Fourier analysis(see equation 4) and as shown in Figure 1c as a function of both μ and ν. The regular, spotless pattern means that each harmonic has moved at the same speed. Thus the displacement of the cell computed with equation 7 is completely equal to its true value.



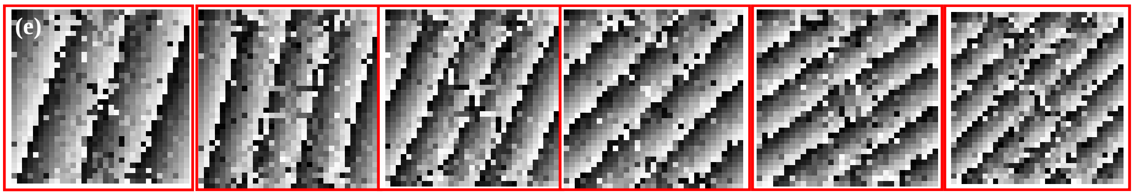


Figure 1 **Simulation study on cloud tracking with 2-D Fourier phase analysis. (a) Template 1 in experiment, (b) template 2 with different displacement relative to template 1 under condition that cloud pixels moves inside the template, (c) phase shift computed with 2-D Fourier analysis between (a) and (b), (d) the same as (b) but some of the cloud pixels has moved out of the template, (e) phase shift between (a) and (d)**

If some pixels of the cell in template 2 have moved out of the template as shown in Figure 1d, noise would appear in phase shift distribution as shown in Figure 1e. Under this condition, harmonic displacement is different for each (μ, ν) and the estimated displacement is not equal to the true (*x0* , *y0*).

4 CLOUD TRACK EXPERIMENTS WITH SATELLITE-OBSERVED IMAGES

Two cases have been performed with the Fourier technique on satellite-observed images. In each case, three IR images are selected to derive cloud motion wind. From three images, two fields of cloud motion wind can be obtained so that one of them can be used to check another through temporal consistency analysis before they are combined to form a final wind field.

Three images in Case 1 are taken at 13 04 14, 13 05 18 and 13 06 22, and 13 09 34, 13 10 38 and 13 11 42 on 5 February 1997 in Case 2 in the area of 40-55^{o}N and 23-50^{o}W. They are a sequence of GOES-8 rapid scan images obtained during one of the Intensive Observing Periods during the Fronts and Atlantic Storm Track Experiment (FASTEX) and had been remapped onto Mercator with 512×512 pixels. The spatial resolution of these images are about 5390m/pixel in latitudinal direction and 3610m/pixel in longitudinal direction.

In Figure 2a, observed at 13 04 14, cellular clouds covered the two quadrants on the left, though the cloud in the top-left quadrant is generally higher than that in the bottom-left quadrant. In the top-right quadrant high clouds with low and middle clouds underneath are dominant. In the bottom-right, the multi-layer cloud structure is more easily seen because the high cloud in this area is broken into a few long, narrow bands on the right running from southwest to northeast and massive lumps constituting a long, wide band on the left. The sub-areas in the top-left and bottom-right corners are blank because of the limited area over which the rapid scan sequence is made.

Figures 2b and 2c show the cloud motion vectors derived with 2-D Fourier phase analysis technique. Temporal and spatial consistence analyses for quality control has been performed in both cases.

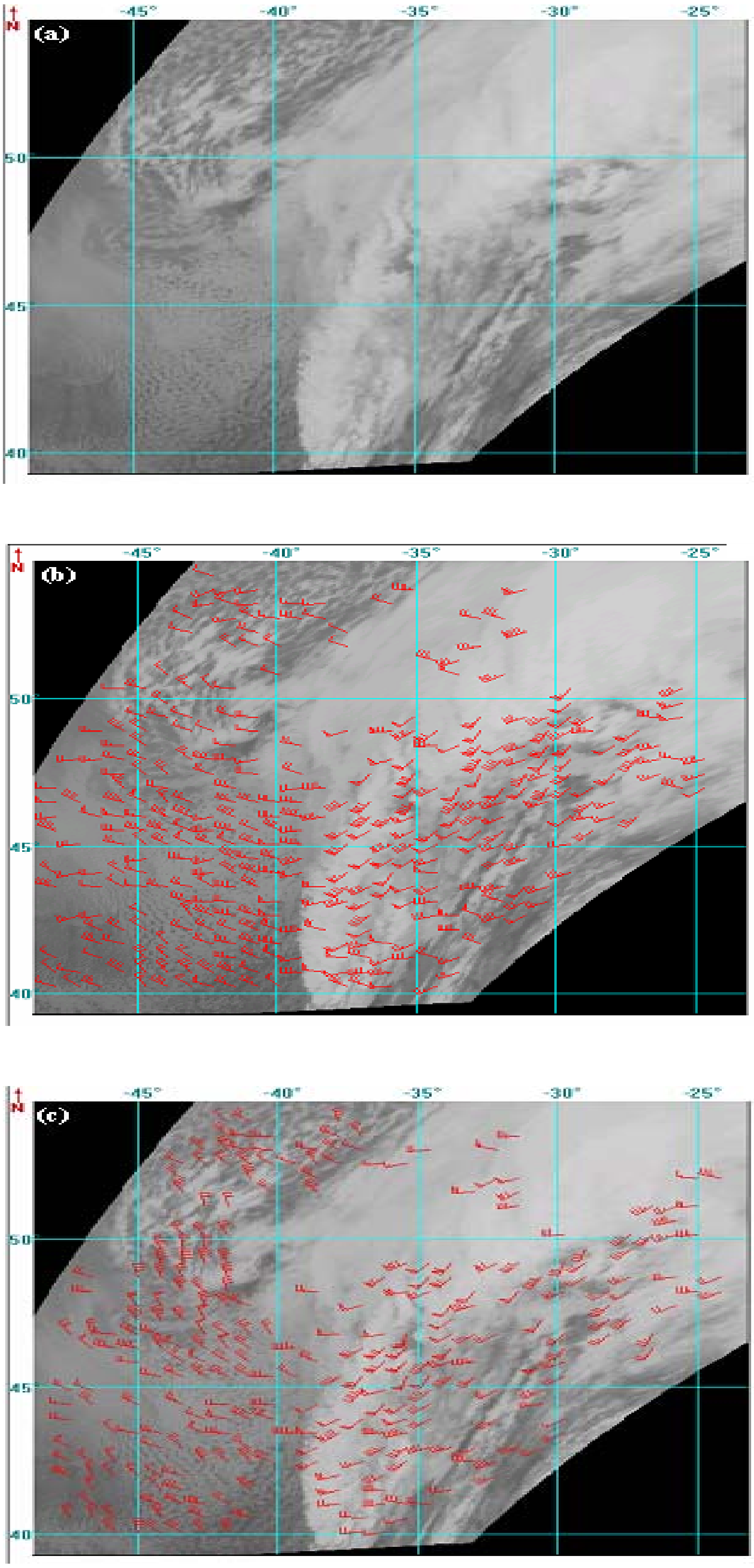


Figure 2 **Case study on cloud tracking with 2-D Fourier phase analysis technique**

(a) IR image obtained by GOES-8 at 13 04 14 GMT on Feb.5, 1997;

(b) Cloud motion wind derived from three images at 13 04 14, 13 05 18 and 13 06 22 GMT on Feb 5, 1997 ;

(c) Cloud motion wind derived from three images at 13 09 34, 13 10 38 and 13 11 42 GMT on Feb 5, 1997

Though the accuracy needs to be further studied because truth is not available for verification, the two wind fields show similar weather system and the general flow pattern associated has been reflected.

5 CONCLUSIONS

Tracking cloud with 2-D Fourier phase analysis has been discussed. The results from both the simulated and the practical images show that the 2-D Fourier phase analysis technique is efficient and significant in deriving cloud motion vectors from high temporal satellite images and can effectively address the "sub-pixel" problem when traditional maximum correlation matching method is used.

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