Wind direction retrieval of tropical cyclone from SAR imagery using improved local gradient method

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Abstract. Tropical cyclones (TCs) have caused heavy losses of human life and property. Hence, it is necessary to study TC. Additionally, the retrieval of wind direction is an important part among many researches of TC. Fortunately, Typhoon Iselle, Typhoon Nuri, and Tropical Storm Haima were captured by RADARSAT-2, Typhoon Hermine, Tropical Storm Harvey, and Super Typhoon Jose were captured by Sentinel-1A. In this paper, the wind directions of the six TCs are retrieved from SAR images by improved local gradient (ILG) method. The results show that the sea surface wind directions retrieved by ILG method have good correlation with the texture of the six TCs, respectively. This research is helpful for estimating wind speeds and constructing wind field of a TC.

1. Introduction
In recent years, synthetic aperture radar (SAR) plays a more and more important role in monitoring natural disasters in day-night conditions arising from high spatial resolution and the capacities of penetrating fog and cloud [1-5]. The development of SAR creates a good technological foundation for retrieving wind fields. The wind field is composed of wind direction and wind speed. However, one of the main disturbances for retrieving wind speeds from SAR images is the lack of the wind direction [6]. The roughness of sea surface is affected by the instability of the air-sea boundary layer which causes the light and dark distribution in an SAR image, and this phenomenon is called wind streak. Many actual observations and research results have shown that the directions of wind streaks in SAR images have good correlation with the sea surface wind directions [7]. Therefore, it is possible to retrieve wind directions from those SAR images containing wind streaks.

There are some methods to retrieve sea surface wind directions on the basis of wind streaks, including Fast Fourier transform (FFT) method, local gradient method, et al. The errors of different methods range from 15-40° [8]. As far as FFT method and local gradient method are concerned, many tests have indicated that the sea surface wind directions retrieved by the local gradient method are...
more accurate than those retrieved by the FFT method [6]. However, the local gradient method can be easily affected by speckle noise. Later, Zhou et al. developed an improved local gradient (ILG) method which is not easily disturbed by speckle noise [9].

A tropical cyclone (TC) is an extremely destructive storm system rotating around its low-pressure center [10]. In the last two centuries, TCs have resulted in the deaths of approximately 1.9 million people worldwide and damaged countless buildings, vehicles, bridges, et al. Sea surface wind field of TC is an critical parameter for studying some sea surface variables such as waves, atmospheric boundary layer and air-sea interactions [11-12]. What’s more, the wind field of TC can be utilized for estimating and forecasting the intensity and hazard of TC [13-14]. Consequently, it is necessary to study TCs. Among numerous researches of TC, the retrieval of wind directions is an important part. Fortunately, many TCs have been captured by SAR and this makes it impossible to retrieve wind directions of TCs.

In this study, the wind directions of six TCs are retrieved by the ILG method and have good correlation with the texture of each TC. Hence, the sea surface wind directions retrieved by the ILG method can serve as a data basis for constructing the sea surface wind fields of TCs. During the research of wind direction retrieval, it was found that the sea surface wind directions retrieved by ILG method are better than other methods including FFT method and local gradient method. Thus, only the results retrieved by ILG method are shown in this paper.

2. Data
In this paper, the wind directions of six TCs are retrieved by the ILG method from six SAR images. The specific parameters of the six SAR images and the six TCs are shown in Table 1 and Table 2, respectively.

| TC  | Imaging time (UTC) | Satellite   | Polari-zation | Swath (km) | Resolution (m) | Mode        |
|-----|-------------------|-------------|---------------|------------|----------------|-------------|
| Iselle | 03 Aug 2014 14:35 | RADARSAT-2 | VV            | 500        | 50             | SCW*b       |
| Nuri  | 01 Nov 2014 20:53 | RADARSAT-2 | VV            | 500        | 50             | SCW*b       |
| Haima | 15 Oct 2016 20:29 | RADARSAT-2 | VV            | 500        | 50             | SCW*b       |
| Hermine | 01 Sep 2016 23:45 | Sentinel-1A | VV         | 250        | 40             | IW*c        |
| Harvey | 29 Aug 2017 00:25 | Sentinel-1A | VV            | 250        | 40             | IW*c        |
| Jose  | 08 Sep 2017 22:03 | Sentinel-1A | VV            | 250        | 40             | IW*c        |

* Spatial resolution.  
*b ScanSAR Wide Swath.  
*c Interferometric Wide Swath

Table 2. The information of TCs at SAR imaging time.

| TC  | Classificationa | PRESb (hPa) | Wind Speedc (km/h) | TC center (lat, lon) |
|-----|----------------|-------------|---------------------|---------------------|
| Iselle | Typhoon     | 965         | 185                 | (15.52°N, 132.58°W) |
| Nuri  | Typhoon     | 955         | 155                 | (15.13°N, 132.97°E) |
| Haima | Tropical Storm | 985       | 97                  | (9.91°N, 139.94°E)  |
| Hermine | Typhoon | 983         | 129                 | (29.13°N, 84.73°W)  |
| Harvey | Tropical Storm | 996       | 74                  | (28.10°N, 95.34°W)  |
| Jose  | Super Typhoon | 938        | 249                 | (16.59°N, 58.53°W)  |

*a Standardized by the Joint Typhoon Warning Center (JTWC).  
b Minimum pressure near the TC center.  
c Maximum sustained surface wind speed.
3. The ILG method

3.1. Data processing in the spectral domain

The Gaussian function is used in the paper due to that it can be expressed analytically in both spatial and spectrum domains. The Gaussian function is expressed as

$$f(i, j) = \frac{1}{2\pi\sigma^2} e^{-\frac{i^2 + j^2}{2\sigma^2}}$$

(1)

where \(\sigma\) determines the width of smoothing window in the ILG method and its value is empirical, in this study \(\sigma\) is set to 15 for the six SAR images. Furthermore, smoothing is expressed as

$$s'(i', j') = \int s(i, j) f(i - i', j - j') \, didi$$

(2)

where \(s\) is original image and \(s'\) is the image after smoothing. The Eq.3 is the gradients of an image,

$$\nabla s'(i', j') = \frac{\partial}{\partial i} s'(i', j') \hat{e}_i + \frac{\partial}{\partial j} s'(i', j') \hat{e}_j$$

(3)

where \(\hat{e}_i\) and \(\hat{e}_j\) are the unit vectors in the \(i\) and \(j\) directions, respectively.

Here, let \(g_i = \frac{\partial}{\partial i} s'(i', j')\) and it represents the \(i\) component of gradients in spatial domain which can be expressed as

$$g_i = \frac{\partial}{\partial i} s'(i', j') = -s(i, j) * h_i(i, j)$$

(4)

$$F[g_i] = -F[s(i, j)] \cdot F[h_i(i, j)]$$

(5)

similarly,

$$g_j = \frac{\partial}{\partial j} s'(i', j') = -s(i, j) * h_j(i, j)$$

(6)

$$F[g_j] = -F[s(i, j)] \cdot F[h_j(i, j)]$$

(7)

where \(*\) represents convolution, and \(F\) represents 2D Fourier transform. \(h_i(i, j) = \frac{\partial}{\partial i} f(i, j)\) and \(h_j(i, j) = \frac{\partial}{\partial j} f(i, j)\). \(F[s(i, j)]\) can be calculated by Fourier transform directly, and let \(G_i = F[h_i(i, j)], G_j = F[h_j(i, j)]\). Combining with Eq.1, it can be deduced that

$$G_i = F[h_i(i, j)] = -\frac{I k_i}{\sigma^2} e^{-2\sigma^2 k_i^2(i_1^2 + i_2^2)}$$

(8)

$$G_j = F[h_j(i, j)] = -\frac{I k_j}{\sigma^2} e^{-2\sigma^2 k_j^2(j_1^2 + j_2^2)}$$

(9)

where \(I\) represents the imaginary part. Hence,

$$g_i = -F^{-1}\{F[s(i, j)] \cdot G_i\}$$

(10)

$$g_j = -F^{-1}\{F[s(i, j)] \cdot G_j\}$$

(11)

where \(F^{-1}\) represents the inverse Fast Fourier transform (IFFT). Therefore, the gradient matrix in spatial domain of an SAR image is obtained and expressed as

$$g = g_i + Ig_j$$

(12)

3.2. Data processing in the spatial domain

The following steps are the same as the local gradient method [6] and that can be summarized as follows.
1) The unusable points in gradient matrix are discarded.
2) The gradient matrix is cropped into submatrices with the same size. In the six cases, the size of each submatrix is 400×400 pixels.
3) The main direction of each submatrix is extracted, and wind directions are obtained due to that the sea surface wind direction is perpendicular to the direction of the gradient. Furthermore, the 180° ambiguity of sea surface wind directions can be removed because TCs rotate counter clockwise in the northern hemisphere.

The flowchart of retrieving sea surface wind directions of TC from SAR images by ILG method is shown in Figure 1.

![Flowchart of the ILG method for retrieving wind directions of TCs.](image)

**Figure 1.** Flowchart of the ILG method for retrieving wind directions of TCs.

4. Results and discussion

4.1. Results

4.1.1. Iselle, Nuri, and Haima

![Figure 2.](image)

**Figure 2.** (a) The retrieved wind directions of Typhoon Iselle (RADARSAT-2, 03 Aug, 2014, 14:35 UTC) are displayed by downsampling (1200×1200 pixels). (b) The enlargement of the red box in (a), and the retrieved wind directions are not displayed by downsampling (400×400 pixels).

![Figure 3.](image)

**Figure 3.** (a) The retrieved wind directions of Typhoon Nuri (RADARSAT-2, 01 Nov, 2014, 20:53 UTC) are displayed by downsampling (1200×1200 pixels). (b) The enlargement of the red box in (a), and the retrieved wind directions are not displayed by downsampling (400×400 pixels).
Figure 4. (a) The retrieved wind directions of Tropical Storm Haima (RADARSAT-2, 15 Oct, 2016, 20:29 UTC) are displayed by downsampling (1200*1200 pixels). (b) The enlargement of the red box in (a), and the retrieved wind directions are not displayed by downsampling (400*400 pixels).

4.1.2. Hermine, Harvey, and Jose

Figure 5. (a) The retrieved wind directions of Typhoon Hermine captured by Sentinel-1A at 01 Sep, 2016, 23:45 UTC. (b) The enlargement of the red box in (a).

Figure 6. (a) The retrieved wind directions of Tropical Storm Harvey captured by Sentinel-1A at 29 Aug, 2017, 00:25 UTC. (b) The enlargement of the red box in (a).
4.2. Discussion
The wind directions of the six TCs retrieved by ILG method are shown in Figure 2 - Figure 7. From the six figures, it can be seen that the wind blows counterclockwise generally, and the retrieved wind directions near the TC centers change rapidly and far away from the TC centers change gently. As a whole, the retrieved wind directions of six TCs from SAR images agree well with the texture of the six TCs in the six figures. Thus, this study is very helpful for constructing wind field of TC and other researches of TC.

The retrieved wind directions of the three TCs captured by RADARSAT-2, shown in Figure 2 - Figure 4, are not very well compared to the other three TCs captured by Sentinel-1A. It may result from three aspects. The first one is owing to the differences between the sensors of RADARSAT-2 and Sentinel-1A. The second reason is that the rain bands are widely spread in the SAR image of Tropical Storm Haima. The rain bands can disorder the directions of gradients and then reduce the accuracy of the retrieved results. The third reason is that there are few wind streaks far from TC centers in the SAR images of Typhoon Iselle and Nuri. Hence, the wind directions where far from the TC centers are not retrieved accurately.

5. Conclusion
In this paper, the wind directions of TCs are retrieved by ILG method from wind streaks in RADARSAT-2 and Sentinel-1A SAR images. It can be found that the retrieved sea surface wind directions have good correlation with the texture in SAR images. To conclude, the ILG method can be utilized for retrieving wind directions of TCs and it will benefit other researches of TC such as storm surges and air-sea interaction.

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