Estimation of Sea Surface Wind Speed and Direction From RADARSAT Data

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Abstract

Wind vector information over the ocean is currently obtained using multiple beam scatterometer data. The scatterometers on ERS-1/2 generate wind vector information with a spatial resolution of 50Km and accuracies of ±2m/s in wind speed and ±20° in wind direction. Synthetic aperture radar (SAR) data over the ocean have the potential of providing wind vector information independent of weather conditions with finer resolution. Finer resolution wind vector information can often be useful particularly in coastal regions where the scatterometer wind information is often corrupted because of the lower resolution system characteristics which is often contaminated by the signal returns from the coastal areas or ice in the case of arctic environments.

In this paper we tested CMOD_4 and CMOD_IFR2 algorithms for extracting the wind vector from SAR data. These algorithms require precise estimation of normalized radar cross-section and wind direction from the SAR data and the local incidence angle. The CMOD series algorithms were developed for the C-band, VV-Polarized SAR data, typically for the ERS SAR data. Since RADARSAT operates at the same C-band but with HH-Polarization, the CMOD series algorithms should not be used directly. As a preliminary approach of resolving with this problem, we applied the polarization ratio between the HH and VV polarizations in the wind vectors estimation.

Two test areas, one in front of Inchon and several sites around Jeju island were selected and investigated for wind vector estimation. The new results were compared with the wind vectors obtained from CMOD algorithms. The wind vector results agree well with the observed wind speed data. However the estimation of wind direction agree with the observed wind direction only when the wind speed is greater than approximately 3.0m/s.

1. Introduction

Synthetic Aperture Radar(SAR) data have recently been used in various applications. Since the launching of ERS-1, there have been several attempts to estimate wind vectors from SAR data over water covered areas. Previously wind vector information over the ocean were usually obtained using scatterometer data or from in-situ measurements. Scatterometers on ERS-1/2 measure the wind vector over water covered regions with a spatial resolution of 50Km and accuracies of ±2m/s in wind speed and ±20° in wind direction [Wismann, 1992]. But because of the large scatterometer footprints, wind vector information in coastal regions or near coastal areas are difficult to estimate accurately using these sensors. Synthetic aperture radar data over the ocean, however, have the potential of providing wind vector information with finer resolution. A number of investigations on estimating wind vectors over oceans have recently been reported by various groups such as Korsbakken et al., 1997; Wackerman et al., 1994; Vachon et al., 1996, 1997; and Won et al., 1998.

In this paper we tested CMOD_4 [Stoffelen and Anderson, 1993] and CMOD_IFR2 algorithms for extracting the wind vector information from RADARSAT SAR data. The test areas include regions in front of Inchon and several sites around Jeju island, Korea.

2. Estimation of Wind Speed and Wind Direction

The CMOD_4 algorithm for extracting the wind vector from ERS-1 SAR data were first developed to estimate the wind vector over oceans using ERS-1 SAR data and CMOD_IFR2 is a revised version at the Ifremer, France. These algorithms are basically empirical methods of estimating sea surface wind speed and require precise estimation of normalized radar cross-section (σ^0), or sigma nought in certain literatures, and wind direction from the SAR data and the local incidence angle.

2.1 Model Description

2.1.1 CMOD4 model

The CMOD_4 model was developed with three types of information: the ERS-1 scatterometer data, the wind vectors from the European Centre for Medium Range Weather Forecasts (ECMWF) surface wind analysis, and the wind and wave information from the National Oceanic and Atmospheric Administration (NOAA) wind and wave buoys, respectively. The CMOD_4 model basically utilizes the potential to correlate sea surface scattering processes and the wind speed directly form the synthetic aperture radar image over the study area . The basic relationship between the SAR radar cross-section (or sigma-nought), the wind vector, and the local incidence angle is as follow:

$$\sigma^0 = b_0(1 + b1\cos\phi + b3\tanh(b2)\cos(2\phi))^{1.6}$$

where:, $b_0 = \delta \times 10^{\alpha + \gamma \cdot f(V + \beta)}$ and:,

$$f(y) = \begin{cases} 0 & \text{if}(y \le 0) \\ \log_{10}(y) & \text{if}(0 < y \le 5) \\ \frac{\sqrt{y}}{3.2} & \text{if}(y > 5) \end{cases}$$

V : wind speed in m/s

ϕ : The relative radar look-wind in degree, i.e. this angle is zero when the wind is blowing towards the radar

δ : bias table defined between 17 and 58 degrees of incidence angle

α, β, γ and $b1$, $b2$, $b3$: combination coefficients of Legendre polynomials

2.1.2 CMOD_IFR2

A scatterometer wind field is usually estimated from three antenna measurements over open water. As the three possible measurements of sigma nought from the fore-, mid-, and aft-beam do not have direct relationships, the sigma nought or radar cross section is usually estimated through an indirect approach of inversion, known as

$$\sigma^0 = 10^{b_0}(1 + b_1 \cos\phi + \tanh(b_2)\cos(2\phi))$$

where:, $b_0 = \alpha + \beta\sqrt{V}$

V : wind speed in m/s

ϕ : wind direction relative to the antenna

α, β : combinations of Legendre polynomials

$b0$, $b1$, $b2$: function of wind speed

2.2 Backscattering coefficient or Normalized radar cross section(σ^0)

The Radar equation for distributed target is given by:

$$P_{rp}(\theta) = \int_A \int \frac{P_{tq} G^2(\theta_a, \phi_a)\lambda^2}{(4\pi)^3 R^4} \cdot \sigma^0_{pq} dA$$

where θ is the incidence angle, P_t is the transmitted power, λ is the wavelength, G is antenna gain, and σ^0 is the backscattering coefficient (or sigma nought), which is defined as the backscattering cross section of a distributed target of horizontal area A, normalized with respect to A such that $\sigma^0 = \sigma/A$. The polarization indices p and q are included in the above expression.

In the case of RADARSAT data, the relationship between Digital Number(DN) and radar cross section(σ) is as follow:

$$DN = INT[A_2 . \sqrt{\sigma} + A_3]$$

where A_2(function of range) is the output scaling gain, A_3 is the output scaling offset, which is normally zero. The backscattering coefficient is usually expressed in dB, which is given by:

$$\sigma^0_j = \beta^0_j + 10 * \log_{10}(\sin I_j) \ (dB)$$

where

$$\beta^0_j = 10 * \log_{10}[(DN^2_j + A3)/A2_j] \ (dB)$$

where I is incidence angle, and index j represents the order of pixel [Laur et al., 1998; Srivastava et al. 1998].

2.3 Estimation of wind direction

The precise wind direction information is necessary to estimate accurate wind speed using CMOD algorithms. Under certain circumstances, it is possible to extract the wind direction directly form the SAR image based upon the orientation of the km-scale image structure, under the assumption that such structure is caused by boundary-layer rolls or wind-driven Langmuir circulation in the upper ocean [Vachon et al., 1996]. Due to the periodicity of these features, we can estimate the wind direction utilizing a 2-D Fourier transform. The periods of the surface wave features are usually very long and the low-wavenumber energy of the wave features observed features will be very close to the origin and nearly perpendicular to the measured wind direction in the wave number space [Shuchman et al., 1994; Wackerman et al., 1994; Vachon et al, 1996]. This type of direction estimation using a 2-D Fourier transform is well known and will be repeated here.

2.4 Polarization ratio

The CMOD series algorithms were initially developed for the C-band, VV-Polarized microwave data such as ERS-1/2 scatterometers. In the case of RADARSAT, the SAR system operates at C-band and HH-Polarization, the CMOD series algorithms cannot be used as they are. As a preliminary way of dealing with this problem, the polarization ratio between the HH and VV polarizations is applied [Thompson et al., 1998], which is given by:

$$\sigma^H_0 = \frac{(1.6 - \sin^2\theta)^2}{(1.6 + \sin^2\theta)^2} \sigma^V_0(U, \theta, \phi)$$

where U is the wind speed, θ is the incidence angle, and ϕ is the azimuth angle of the radar with respect to the wind direction. This empirical and approximate relationship is applied for estimating the sea surface wind speed from the RADARSAT SAR data over the test areas.

3. Results

The four test areas were selected for estimating wind vectors from the RADARSAT SAR data, two of which were in front of Inchon, west coast of Korean peninsula, and other two were off Jeju island off south coast of Korea (Fig 1). Each test area was cut into a sub-image of size 1024× 1024 pixels(approximately 12.8Km×12.8Km), and date and beam type information is shown in Tabel 1. The time the table is expressed on UTC.

Sigma-nought image, wind direction extracted from 2-D FFT, wind speed distribution obtained using the CMOD_4 algorithm, and from the CMOD_IFR2 algorithm over respective test areas shown in fig. 1 are shown in Figs. 2 to 5. The wind direction information required in the CMOD algorithms was estimated by adding or subtracting to the rotation values needed during the geo-rectification steps. The comparison between the wind vector results obtained from the SAR image data and the observed value at nearby meteorological stations is listed in Table 2, and in Fig. 6. Because the test areas are in the open ocean, there are no in-situ data available for the wind field during the specific date of observation. Therefore the comparison between the estimated and observed data study areas represents the comparison with the nearest station observation values. For example, the wind direction estimated for the test site in front of Inchon do not agree well with the observed wind direction data. But they do agree well with the observed data around Jeju island(Fig. 6(c)). The discrepancy between the calculated and the observed wind directions in front of Inchon and the good agreement between the two in Jeju island area may be explained as follow. The wind direction estimation is based upon the orientation of the km-scale sea surface features such as wind-driven Langmuir circulation, which are in turn closely related to the low wave number sea surface wave features. It becomes therefore very difficult to extract precise wind direction if the wind speed is very low. If the wind speed increases on the other hand, the sea surface features related to the low-wavenumber space becomes apparent in the processed SAR data and the estimation of the wind vector estimation becomes more accurate. We can thus infer that the estimation of wind directions agrees well with the observed wind directions usually when the wind speed is greater than approximately 3.0m/s. As mentioned above, estimation of the wind speed using the CMOD algorithms require a priori information on wind directions. Subsequently, one input this wind direction information to the respective CMOD_4 or CMOD_IFR2 algorithms. In order to compare the estimated wind speed with the observed wind speed, we use observed wind direction at the nearest station for CMOD algorithms, instead of estimating wind direction. In this approach, the SAR data driven wind speed agrees well with observed wind speed for the Inchon test sites, but the results show certain level of disagreement in Jeju island test sites(Fig 6(a),(b)). In general, the CMOD_4 algorithm approximates more accurate wind speed when the wind speed is large, whereas the CMOD_IFR2 algorithm performs better when the wind speed is lower.

We made a further comparison of the wind vector estimated from SAR data with the buoy data recorded at meteorological station in duckjeok island. Both the SAR data acquisition time, associated wind speed and wind direction values are listed in Table 3. Sigma-nought image [2048×2048pixels or 25.6Km×25.6Km] (Fig. 7(a)), and distribution of wind speed from two algorithms (Fig. 7(b,c)) are displayed in Fig. 7. Since there are many islands around Duckjeok island, the estimation of wind direction directly from SAR image data was judged inappropriate and was not applied two algorithms. The wind direction data of duckjeok island buoy was input instead. The results obtained from both two algorithms agree well with the buoy data in the 3.0m/s～4.0m/s range.

4. Conclusion and Discussion

The estimation of wind vector using CMOD_4 and CMOD_IFR2 algorithms requires precise information on sigma-nought image, accurate wind direction, and antenna geometry. In physical oceanographic terms, the extraction of wind direction directly from SAR image is based on the orientation of the km-scale image structures such as wind-driven Langmuir circulation, to which the wind direction is nearly perpendicular. However, the estimation of wind direction agrees well with the observed wind direction only when the wind speed is greater than approximately 3.0m/s. It is thus possible to accurately estimate the wind speed, only when the wind direction information is available for both algorithms. The CMOD_IFR2 algorithm appears to be more suitable for weak or slow wind speed situation, whereas the CMOD_4 algorithm appears to work better for fast wind speed environment.

References

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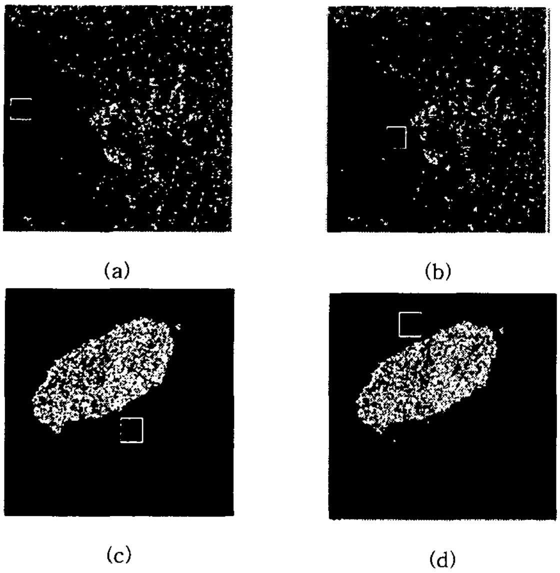


Fig. 1. Test areas (a) Inchon1, (b) Inchon2, (c) Seoguipo, (d) Jeju.

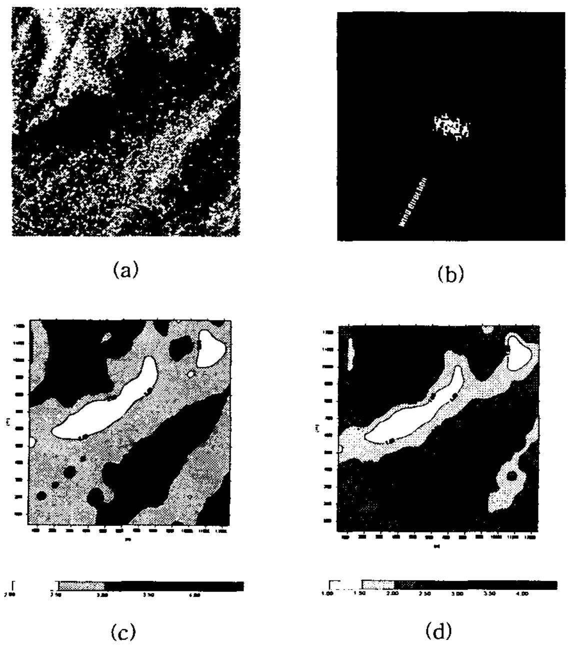


Fig. 2. Wind vector calculation for Inchon1 test area. (a) Sigma-nought(σ^0) image (1024 × 1024), (b)Wind direction estimated using FFT (252°), (c) Wind speed estimated using CMOD_4 (average wind speed: 2.9m/s), and (d) Wind speed estimated using CMOD_IFR2 (average wind speed: 2.4m/s).

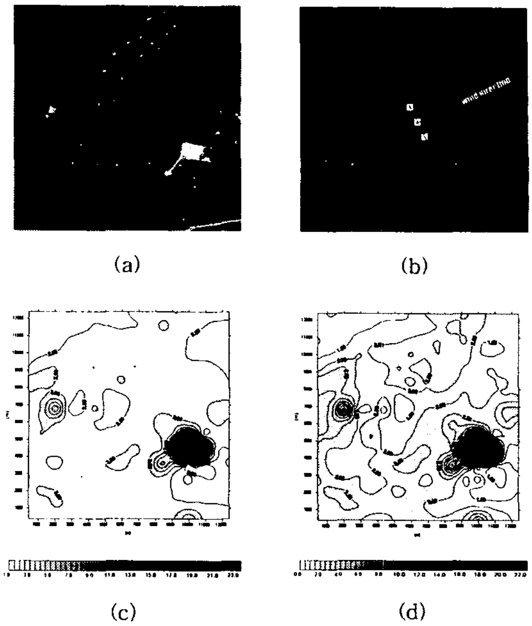


Fig. 3. Wind vector calculation for Inchon2 test area. (a) Sigma-nought(σ^0) image (1024 × 1024), (b) Wind direction estimated using FFT (236°), (c) Wind speed estimated using CMOD_4 (average wind speed: 2.9m/s), and (d) Wind speed estimated using CMOD_IFR2 (average wind speed: 2.2m/s).

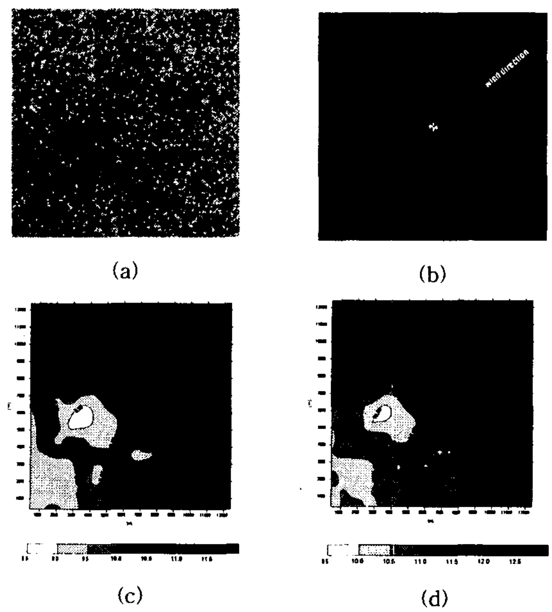


Fig. 4. Wind vector calculation for Seoguipo. (a) Sigma-nought(σ^0) image (1024 × 1024), (b) Wind direction estimated using FFT (239°), (c) Wind speed estimated using CMOD_4 (average wind speed: 10.1m/s), and (d) Wind speed estimated using CMOD_IFR2 (average wind speed: 11.2m/s).

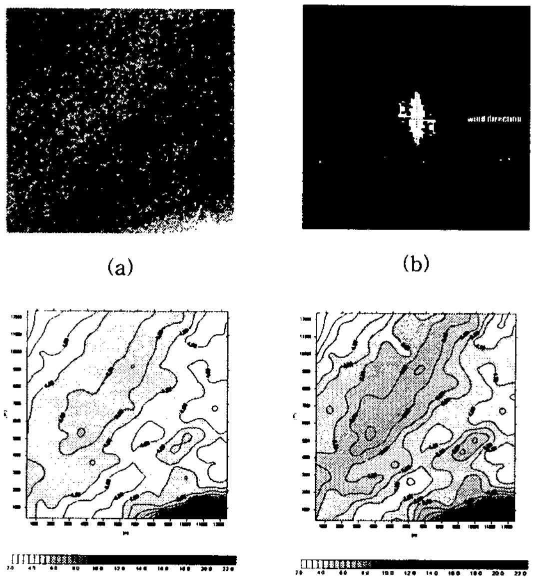


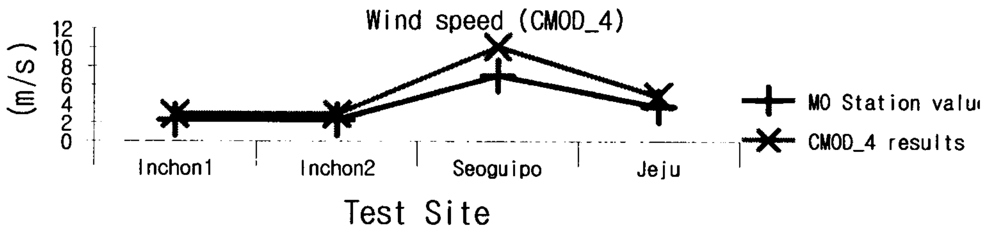
Fig. 5. Wind vector calculation for Jeju test area. (a) Sigma-nought(σ^0) image (1024×1024), (b) Wind direction estimated using FFT (279°), (c) Wind speed estimated using CMOD_4 (average wind speed: 4.8m/s), and (d) Wind speed estimated using CMOD_IFR2 (average wind speed: 5.5m/s).

Satellite	Test Site	Date & Time (UTC)	Beam Type	Configuration /Orientation	Product Type
RADARSAT (Standard)	Inchon1	Date: 1997/11/4 Time: 09:30.41	S4	ASCENDING /NORMAL	SGF
	Inchon2	Date: 1997/11/4 Time: 09:30.41	S4	ASCENDING /NORMAL	SGF
	Seoguipo	Date: 1998/02/19 Time: 21:31.58	S7	DESCENDING /NORMAL	SGF
	Jeju	Date: 1998/02/19 Time: 21:31.58	S7	DESCENDING /NORMAL	SGF

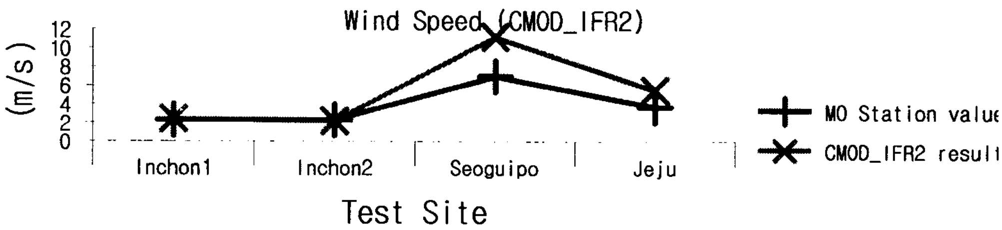
Table 1. Data acquisition date and beam type.

Satellite	Test Site	Observed Data [wind speed] [wind direction]	Estimated Data [wind speed, wind direction]	
			CMOD_4	CMOD_IFR2
RADARSAT	Inchon1	2.3m/s	2.9m/s	2.4m/s
		340°	252°	
	Inchon2	2.3m/s	2.9m/s	2.2m/s
		340°	236°	
	Seoguipo	7.0m/s	10.1m/s	11.2m/s
		200°	239°	
	Jeju	3.7m/s	4.8m/s	5.5m/s
		270°	279°	

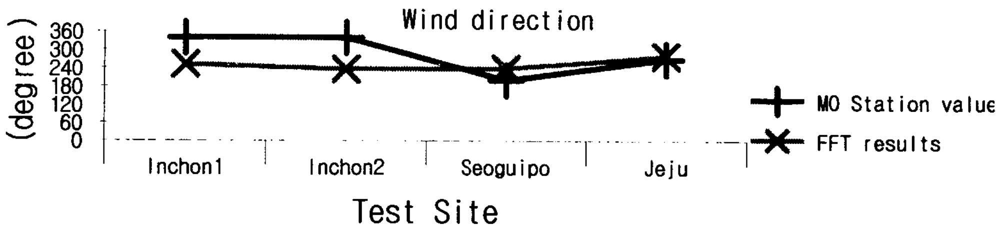
Table 2. Wind vector calculation results obtained from the RADARSAT data and the observed value at nearby meteorological office stations corresponding to each test areas.



(a)



(b)

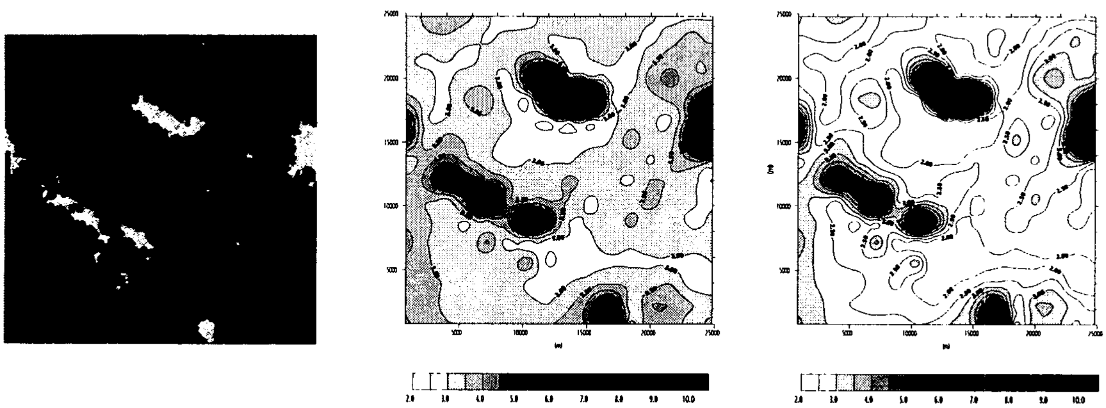


(c)

Fig. 6. Wind speed calculation results using CMOD_4 (a), and CMOD_IFR2 (b). Wind direciton results from FFT (c).

	Site	Date & Time (UTC)	wind speed(m/s) /wind direction(°)
Buoy	**Duckjeok island**	Date : 1997/11/4 Time : 08:59.36	4.0(m/s)/282(°)
		Date : 1997/11/4 Time : 09:59.36	3.7(m/s)/278(°)

Table 3. Buoy data in duckjeok island.



(a) (b) (c)

Fig. 7. (a) Sigma-nought(σ^0) image (2048×2048) computed RADARSAT image, (b) Wind speed results obtained using CMOD_4, and (c) Wind speed results obtained using CMOD_IFR2.