Abstract—Recently satellite SAR techniques have become essential observation tools for various ocean phenomena such as wind, wave and current. The CMOD4 and CMOD-IFR2 models are used to calculate the magnitude of wind at SAR resolution with no directional information. Combination of the wave-SAR spectrum analysis and the inter-look cross-spectra techniques provides amplitude and direction of the ocean wave over a square-km sized imagette. The Doppler shift measurement of SAR image yields surface speed of the ocean current along the radar looking direction at imagette resolution. In this paper we report the development of a SAR Ocean Processor (SOP) incorporating all of these techniques. We have applied the SOP to several RADARSAT-1 images along the coast of Korean peninsula and compared the results with oceanographic data, which showed reliability of space-borne SAR based oceanographic research.

Keywords - ocean wind; ocean wave; ocean current; CMOD4; CMOD-IFR2; wave-SAR transform; inter-look cross-spectra; Doppler shift

I. INTRODUCTION

Nowadays many researchers have been interested in oceanographic application of SAR systems that can acquire a high resolution images. The two-dimensional SAR image can observe spatial distribution of sea surface that arise from small gravity waves and capillary waves, the main sources of backscattered energy. Various ocean surface phenomena that affect the amplitude or spectral distribution of these waves will be visible on the radar images. These phenomena include surface swells, internal waves, currents, wind cells, eddies, ship wakes, and oil spills [1].

A good understanding of ocean surface state is important for any activity connected with the sea, e.g. fisheries, ship routing, coastal surveillance, offshore installations and exploration, etc. Space-borne SAR system is an efficient technique to monitor variations of dynamic ocean surface phenomena as well as to acquire high resolution surface images at any time and irrelevant of environmental conditions.

The objective of this study is the development of SAR processor for the analysis of oceanic parameters defined in the various ocean phenomena such as wind, wave, and current. We developed and tested a SAR processing tool for the extraction of the ocean wind speed, wavelength and propagation direction of the ocean wave, and the surface velocity and direction of the ocean current from SAR images. The results were compared with oceanographic data along the coast of Korean peninsula supplied by Korean Meteorological Administration (KMA) and National Oceanographic Research Institute (NORI).

II. SAR OCEAN PROCESSOR (SOP)

The processing flowchart for a SAR processor named SAR Ocean Processor (SOP), is shown in Fig. 1. The aim of SOP is the extracting of ocean wind, wave, and current parameters concerned with various oceanic phenomena using SAR images. The framework of SOP is composed of three categories which
can be processed individually to extract ocean wind, wave, and current parameters incorporating techniques as follows. The SOP uses CMOD4 and CMOD-IFR2 model for retrieval of wind speed, wave-SAR transforms and inter-look cross-spectra for extraction of wavelength and propagation direction, and the Doppler shift for estimation of surface velocity.

CMOD4 [2, 3] and CMOD-IFR2 [4] empirical models were used to calculate wind speed from backscattering coefficient of a SAR image. These methods determine wind vectors from vertically (VV) polarized images. For horizontal (HH) polarization, these model functions are modified by a polarization ratio conversion [5]. We applied the CMOD and CMOD-IFR2 model function and polarization ratio for Bragg, Kirchhoff, Thompson, and Elfouhaily models to RADARSAT-1 SAR images.

Wave information estimates from observed SAR spectra rely on the wave-SAR transform using 2D FFT method. This method has one problem; an inherent 180° directional ambiguity that exists in the derivation of wave propagation [6]. The image cross spectra technique [7] is used to remove the 180° ambiguity in the ocean wave propagation direction by using the cross spectrum of individual-look SAR images. The SAR image cross spectrum has a real and an imaginary part. The real part is symmetric and the imaginary part is anti-symmetric. The ocean wave propagation direction can be retrieved from the imaginary part of the SAR image cross spectrum. In this work the positive of imaginary part corresponds to the wave propagation direction.

The spectral density of the signals backscattered by time-varying target is called the Doppler spectrum. The frequency of a radar signal backscattered by a moving target occurs a Doppler shift proportional to the target’s line-of-sight velocity [8]. In this study we refer to [8] to calculate a surface velocity, \( U_s \), for a simple target of fixed shape moving along the surface as

\[
U_s = -\frac{f_d}{k} \sin \theta_i
\]

where \( f_d \) is the Doppler shift, \( k \) is the electromagnetic wave number, and \( \theta_i \) is the angle of incidence of the radar beam relative to the normal to the surface. The Doppler shift, \( f_d \), is calculated by multiplying \( \Delta f \) by \( \Delta \text{pixel} \), where \( \Delta f \) is the frequency sampling interval and \( \Delta \text{pixel} \) is the pixel distance between the nominal and the estimated Doppler centroid.

Table 1 lists the inputs and outputs of the SOP. The SOP works at cygwin environment. Output files of the SOP are produced separately for the wind, wave, and current information. Single-look complex header off images and multi-look images are extracted as well. These output files can be open and processed by using conventional RS and GIS tools. The SOP were tested to several RADARSAT-1 images of the coast of Korean peninsula and the results compared with the automatic weather system data which provide wind speed, direction, and duration time and the current simulation data for the magnitude of current velocity and propagation direction information.

![Figure 1. Flowchart of the SAR ocean processor.](Imagette)

### Table 1. Input and output of SOP processor

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
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<tr>
<td>SLC</td>
<td>Wind</td>
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<td>ML</td>
<td>Wave</td>
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<td>Current</td>
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#### III. RESULTS

The RADARSAT-1 SAR images were processed according to the SOP procedure. The extracted results of ocean wind, wave, and current from SOP were compared with the oceanographic data supplied by KMA and NORI.

#### A. Wind

Fig. 2 shows the wind retrieval results using CMOD4 and CMOD-IFR2 models combined with polarization conversion for Bragg model. The test site (color image area) is covered near the sea of Woo-island near Jeju, Korea. The color images are the extracted CMOD4 (a) and CMOD-IFR2 (b) results with the color scale of wind speed at an interval of 2 m/s. CMOD-IFR2 results shown more complicated and higher value of wind speed than CMOD4.

Fig. 3 represents the plot of the retrieved wind speed versus the backscattering coefficient. The values of the extracted wind speed from CMOD4 model range from 1 to 8 m/s while the results from CMOD-IFR2 model appear from 1 and 16 m/s. Polarization ratio conversion step were calculated using Bragg, Thompson, Kirchhoff, and Elfouhaily models. The automatic weather system (AWS) data near Woo-island supplied by KMA showed that the wind speed was about 10 m/s at the time of the RADARSAT-1 SAR image acquisition.
models with the backscattering coefficient ($\sigma_0$). The information of the ocean wave propagation direction resides in positive (red color) in the imaginary part of inter-look cross spectrum result shown in Fig. 7.

Fig. 2. Example of graphical map of wind retrieval results (color region) using (a) CMOD4 and (b) CMOD-IFR2. Test area covers Woo-island located near Jeju-island, Korea (1999/11/15, descending orbit).

Fig. 3. Plot of wind speed estimated using CMOD4 and CMOD-IFR2 models with the backscattering coefficient ($\sigma_0$).

### B. Wave

Fig. 4-6 represent the SAR wave spectrums at several square-km sized imagettes and the corresponding multi-look images. The three RADARSAT-1 images to retrieve the SAR wave spectrum were acquired on 11 November, 25 November, and 19 December in 1999, respectively. The wavelength of the SAR wave spectrum applied to 2D FFT method is calculated from (2),

$$\lambda = \frac{2\pi}{k}$$

where $\lambda$ is a wavelength and $k$ is a wave number.

The value of ocean wavelength calculated from SAR wave spectrum ranges from 90 to 160 m in these images. The wavelength and the propagation direction of ocean wave were compared with the data from an automatic weather station data supplied by KMA near Woo-island, Korea, which showed good correlation. As the AWS data do not provide the information about ocean wave directly, we could only infer the environment and state of ocean wave by wind speed, direction, and duration time. The multi-look image at Fig. 6 shows the directional wave texture of the fully developed wave (swell) better than other case of Fig. 4 and 5.

Fig. 7 shows the examples of image cross spectra computed from the individual look images that are separated in time by typically a fraction of the dominant wave period, and thus provides information about the ocean wave propagation direction [6].

Fig. 4. SAR wave spectrum results and the corresponding multi-look image (1999/11/15). The measured wavelength and propagation direction and AWS data acquired at near Woo-island are written in the lower box.

Fig. 5. SAR wave spectrum results and the corresponding multi-look image (1999/11/25). The measured wavelength and propagation direction and AWS data acquired at near Woo-island are written in the lower box.

Fig. 6. SAR wave spectrum results and the corresponding multi-look image (1999/12/19). The measured wavelength and propagation direction and AWS data acquired at near Woo-island are written in the lower box.
C. Current

Fig. 8 shows the results of current parameters extracted from the Doppler shift method. The output files from the current procedure of SOP are the Doppler image, Doppler shift estimation (vector) image, and velocity estimation (text file). The Doppler shift vector provides only the surface velocity direction in the line-of-sight. The current direction at a test site (red box) near Deokjeok-island, Korea shows mainly in the left direction. The magnitude of surface velocity ranged from -0.5 to 1.5 m/s. From the current simulation data (Fig. 8c) supplied by NORI, the current direction appeared toward west and northwest direction with magnitude between 0.05 and 1.5 m/s.

IV. CONCLUSION

We developed the SAR Ocean Processor (SOP) for the analysis of ocean parameters such as wind speed, wave direction and wavelength, and current velocity. We incorporated the existing algorithms such as CMOD4 and CMOD-IFR2 models to retrieve ocean wind speed, the combination of the SAR wave spectrum and inter-look cross-spectra algorithms to extract wavelength and propagation direction of ocean wave, and Doppler shift method for the estimation of the surface velocity in line-of-sight direction. Tests of SOP to several RADARSAT-1 images of the coast of Korean peninsula showed good agreement with other oceanographic data. More detailed study on the evaluation and improvement of the SOP will follow this initial implementation effort.

ACKNOWLEDGMENT

This work was supported by the Maritime and Ocean Engineering Research Institute/Korea Ocean Research & Development Institute (MOERI/KORDI).

REFERENCES