Remote Sensing of Ocean Waves by Polarimetric SAR

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ABSTRACT

A new method to measure ocean wave slope spectra using fully polarimetric synthetic aperture radar (POLSAR) data was developed without the need for a complex hydrodynamic modulation transform function. There is no explicit use of a hydrodynamic modulation transfer function. This function is not clearly known and is based on hydrodynamic assumptions. The method is different from those developed by Schuler and colleagues or Pottier but complements their methods. The results estimated from NASA Jet Propulsion Laboratory (JPL) Airborne Synthetic Aperture Radar (AIRSAR) C-band polarimetric SAR data show that the ocean wavelength, wave direction, and significant wave height are in agreement with buoy measurements. The proposed method can be employed by future satellite missions such as *RADARSAT-2*.

1. Introduction

Ocean waves are an important component of upper ocean dynamics. The synthetic aperture radar (SAR) has been widely used to measure ocean surface wave spectra from space since the *Seasat* satellite was launched in 1978. Many papers have been published dealing with the wave imaging mechanism and slope retrieval method; for example, Alpers et al. (1981) reviewed the detectability of ocean waves by real and synthetic aperture radar, and Hasselmann et al. (1985) summarized the theory of SAR ocean imaging. Hasselmann and Hasselmann (1991) derived the nonlinear mapping of an ocean wave spectrum into a SAR image spectrum and presented an inversion method. Engen et al. (1994, 2000); and Engen and Johnsen (1995) presented the modified nonlinear inversion method and cross-spectrum method to retrieve ocean wave spectra from SAR images. In addition, ocean wave spectra can be measured by the phase or intensity images of an along-track interferometric SAR, which is a SAR employing two antennas displaced along the flight direction (Marom et al. 1990; Marom et al. 1991; He and Alpers 2003).

Schuler and Lee (1995) proposed a new method to improve the measurement of directional ocean wave spectra based on the identification of a new modulation process, polarization orientation modulation. He et al. (2004) derived the polarization orientation modulation transfer function and tilt modulation transfer function of a linear polarization SAR. In all of these research efforts, the ocean surface wave spectra are retrieved from SAR and polarimetric SAR (POLSAR) by using an image intensity-based algorithm. Recently, a new method, originally used in topographic measurements (Schuler et al. 1996), has been applied to the ocean (Schuler et al. 2003, 2004). The method estimates azimuth components of ocean wave slopes and wave spectra using the relationship between polarimetric orien-

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tation angle shift and the azimuth surface tilts, as derived by Lee et al. (1998) and Pottier (1998). The key to this method is the estimation of the orientation angles. A variety of techniques for the estimation of orientation angles were also proposed (Schuler et al. 1996, 1998, 2000, 2002; Lee et al. 2000). For example, Lee et al. (2002) analyzed different estimation methods for radar polarization orientation shifts and developed a unified analysis of estimation algorithms based on the circular polarization covariance matrix.

In addition, Pottier (1998) presented the eigenvector/eigenvalue decomposition average parameter alpha ($\overline{\alpha}$) method to measure wave slopes in the range direction. Note that the orientation angle parameter is largely insensitive to slopes in the range direction for ocean wave measurements. Therefore, an algorithm employing the orientation angle method and $\overline{\alpha}$ parameter method is capable of measuring slopes in any direction (Schuler et al. 2003, 2004).

In this paper, a new method to measure ocean wave slopes in any direction is presented using POLSAR image intensity. Comparisons are made between ocean wave spectra measured using National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) Airborne Synthetic Aperture Radar (AIRSAR) C-band backscatter data and in situ buoys maintained by the National Oceanic and Atmospheric Administration (NOAA)/National Data Buoy Center (NDBC).

2. Method

In the framework of linear modulation theory, the ocean surface elevation ξ and the variations of the local backscattering cross-section $\sigma(\mathbf{r}, t)$, remotely sensed by a real aperture radar, may be represented as a superposition of propagating wave components, whose wavenumber is $\mathbf{k}$ and frequency ω,

$$\xi(\mathrm{r}, t) = \sum_k \xi_k \exp[i(\mathbf{k}\cdot\mathbf{r} - \omega t)] + \mathrm{c.c.} \tag{1}$$

$$\sigma_{\mathrm{pp}}(\mathrm{r}, t) = \overline{\sigma}_{\mathrm{pp}}(1 + \{\sum_k T^R_{\mathrm{ppk}}\xi_k \exp[i(\mathbf{k}\cdot\mathbf{r} - \omega t)] + \mathrm{c.c.}\}), \tag{2}$$

where $\mathbf{r} = (x, y)$, x, y are component vectors in the radar look direction and platform flight direction, respectively; c.c. is complex conjugate of the series; $\overline{\sigma}$ denotes the spatially averaged specific cross section; $T^R_{\mathrm{pp}k}$ is the real aperture radar (RAR) modulation transfer function, including tilt modulation $T^t_{\mathrm{pp}k}$, hydrodynamic modulation T^h_k, polarization orientation angle modulation $T^p_{\mathrm{pp}k}$, (Lee et al. 2000) the range and azimuthal direction shift modulation (T^s_x, T^s_y), subscript "pp" indicates the radar transmission and receiving polarizations, where p = h, v, φ denote the horizontal polarization, vertical polarization, and linear polarization, with polarization orientation angle given by φ, respectively. For SAR, a velocity bunching modulation T^v_k must be included. For all modulations, as only tilt and polarization orientation angle modulation transfer functions depend on the radar polarization, Eq. (1) can be rewritten as

$$\frac{\Delta\sigma_{\mathrm{pp}}(\mathbf{r}, t)}{\sigma_{\mathrm{pp}}} = \sum_k (T^t_{\mathrm{pp}k} + T^p_{\mathrm{pp}k})\xi_k \exp[i(\mathbf{k}\cdot\mathbf{r} - \omega t)] + c_1 + R, \tag{3}$$

where the polarization orientation angle modulation $T^p_{\mathrm{pp}k}$ is produced by sea surface tilt (He et al. 2004). This term vanishes when the polarization p is the horizontal polarization (h) or vertical polarization (v), and so it is usually not accounted for in the well-known formulations on this subject (e.g., Hasselmann and Hasselmann 1991). Note that a Bragg scattering model and Phillips wave spectrum are assumed in order to derive polarization orientation angle modulation and tilt modulation in He et al. (2004). Also, in He et al. (2004) the wave slopes in the ground range direction are neglected for getting the polarization orientation angle modulation function. In fact, because the sea surface slopes are small, the above assumption is acceptable. The complex conjugate of the series is indicated by c_1, and R is given by

$$R = \sum_k (T^h_k + ik_xT_x + ik_yT_y + T^v_k)\xi_k \times \exp[i(\mathbf{k}\cdot\mathbf{r} - \omega t)] + c_2, \tag{4}$$

where c_2 is complex conjugate of the series; R includes hydrodynamic modulation, velocity bunching modulation, and the range and azimuthal directional shift modulation. There are no polarization sensitive terms. Therefore, we can get

$$\frac{\Delta\sigma_{\mathrm{vv}}(\mathrm{r}, t)}{\sigma_{\mathrm{vv}}} - \frac{\Delta\sigma_{\mathrm{hh}}(\mathrm{r}, t)}{\sigma_{\mathrm{hh}}} = \sum_k (T^t_{\mathrm{vv}k} - T^t_{\mathrm{hh}k})\xi_k \times \exp[i(\mathbf{k}\cdot\mathbf{r} - \omega t)] + c_3, \tag{5a}$$

$$\frac{\Delta\sigma_{\varphi\varphi}(\mathrm{r}, t)}{\sigma_{\varphi\varphi}} - \frac{\Delta\sigma_{\mathrm{vv}}(\mathrm{r}, t)}{\sigma_{\mathrm{vv}}} = \sum_k (T^t_{\varphi\varphi k} - T^t_{\mathrm{vv}k} + T^p_{\varphi\varphi k})\xi_k \times \exp[i(\mathbf{k}\cdot\mathbf{r} - \omega t)] + c_4, \tag{5b}$$

where c_3, c_4 are the complex conjugate of the series, respectively; $T^t_{\varphi\varphi k}$, $T^p_{\varphi\varphi k}$ are given by Eq. (15) in He et al. (2004); and

$$T^t_{\mathrm{hh}k} = ik_x \frac{4 - 0.5(1 + \sin^2\theta)}{\tan\theta(1 + \sin^2\theta)}, \tag{6a}$$

$$T^{t}_{\mathrm{vv}k} = ik_x \frac{4 - 0.5(1 - \sin^2\theta)}{\tan\theta(1 - \sin^2\theta)}, \tag{6b}$$

where θ is the radar incident angle. This is the local angle between the radar illumination direction and the vertical sea surface.

Inserting Eqs. (6a) and (6b) and He et al.'s (2004) Eq. (15) into our Eq. (5), and performing straightforward algebraic calculations, we obtain

$$\frac{\Delta\sigma_{\mathrm{hh}}}{\sigma^0_{\mathrm{hh}}} - \frac{\Delta\sigma_{\mathrm{vv}}}{\sigma^0_{\mathrm{vv}}} = -\frac{8\tan\theta}{1 + \sin^2\theta}\frac{\partial\xi}{\partial x}, \tag{7a}$$

$$\frac{\Delta\sigma_{\varphi\varphi}}{\sigma^0_{\varphi\varphi}} - \frac{\Delta\sigma_{\mathrm{vv}}}{\sigma^0_{\mathrm{vv}}} = A\frac{\partial\xi}{\partial x} + B\frac{\partial\xi}{\partial y}, \tag{7b}$$

where,

$$A = \frac{a_2}{a_0} - a_3,\ B = \frac{a_1}{a_0}, \tag{8a}$$

$$a_0 = \frac{1}{4}\left\{1 + \left[\frac{(1 + \sin^2\theta)}{(1 - \sin^2\theta)}\right]^2\right\}[1 + \cos^2(2\varphi)] - \frac{2\sin^2\theta}{1 - 8\sin^2\theta + 8\sin^4\theta}\cos(2\varphi) + \frac{1 + 2\tan^2\theta}{2}\sin^2(2\varphi), \tag{8b}$$

$$a_1 = -\left[\left\{1 + \left[\frac{(1 + \sin^2\theta)}{(1 - \sin^2\theta)}\right]^2\right\}\cos(2\varphi) + \left\{1 - \left[\frac{(1 + \sin^2\theta)}{(1 - \sin^2\theta)}\right]^2\right\} - 2\left[\frac{(1 + \sin^2\theta)}{(1 - \sin^2\theta)}\right]\cos(2\varphi)\right]\frac{\sin(2\varphi)}{\sin\theta}, \tag{8c}$$

$$a_2 = \left[2\frac{\tan\theta}{\sin^2\theta\cos^2\theta}[1 + \cos^2(2\varphi)] - 4\frac{\tan^3\theta}{\sin^2\theta}\cos(2\varphi) + 2\frac{\tan^3\theta}{\sin^2\theta}\sin^2(2\varphi)\right], \tag{8d}$$

$$a_3 = \frac{4 - 0.5(1 - \sin^2\theta)}{\tan\theta(1 - \sin^2\theta)}, \tag{8e}$$

where φ is the polarization orientation angle. Subscript $\varphi\varphi$ indicates a copolar channel of linear polarization at $\varphi°$. It indicates HH polarization when $\varphi = 0$ and VV polarization when $\varphi = (\pi/2)$. Therefore, the polarization subscript p can be neither "h" nor "v" in Eq. (7) in order to allow solution for the range and azimuth slopes in this relation. Note that Eq. (7b) degenerates into Eq. (7a) if $\varphi = \mathrm{h}$, and when $\varphi = \mathrm{v}$, Eq. (7b) vanishes.

Finally, we note that cross-polarization (HV) was considered by Valenzuela (1968) for a slightly rough surface. It is produced by tilting, multiple scattering, and volume scattering. Nevertheless, the dielectric constant of the ocean, even at microwave frequencies, is relatively large, and surface scattering should be dominant, except in high sea state conditions. In the approach of Lee et al. (2002), a single-scattering process is assumed, and different estimation methods for radar polarization orientation shifts by surface slope were analyzed. One of these is the circular polarization covariance matrix method, and a unified analysis of estimation algorithms based on this method was developed. The surface slope is estimated by using HV/HH–VV information in the circular polarization covariance matrix method. In our approach, cross-polarization information is not used directly, but it is included implicitly in the linear polarization pp. Therefore, the wave surface slopes $\partial\xi/\partial x$, $\partial\xi/\partial y$ can be obtained from Eqs. (7a)–(7b) only when φ is appropriately chosen. The steps needed to estimate sea surface slopes are as follows:

1) Choose a 256 × 256 size image and transfer the slant range image into ground range images using linear interpolation in the range direction.
2) Calculate sea surface slopes using Eqs. (7a)–(7b), which is the linear polarization p, when $\varphi = 45°$, and smooth the slopes using a 4 × 4 Gaussian filter.
3) Calculate slope spectrum, wave height, wave direction, and wavelength using slope images.

3. Results and analysis

In this paper, the fully polarimetric SAR data from the NASA JPL AIRSAR are used to estimate ocean wave slopes. The five acquired AIRSAR images and corresponding buoy information are shown in Table 1. Figure 1 shows the C-band SAR image in the VV polarization of this area in test image 1. The wave slopes estimated from the study area box are shown in Fig. 2. Figure 2a is the azimuthal direction wave slope, and Fig. 2b is the range direction wave slope. Note that we have applied a 4 × 4 Gauss filter to the wave slopes in order to eliminate noise. The slope spectrum is shown in Fig. 3.

Waves traveling at arbitrary propagation angles can be handled by an algorithm by which measurement pairs in orthogonal directions are determined by the aircraft flight path. The slope spectrum is $F(\mathbf{k})$, where

$$F(\mathbf{k}) = F_a(\mathbf{k}) + F_r(\mathbf{k}), \tag{9}$$

TABLE 1. AIRSAR data acquired and buoy information.

Image code	Acquired time (UTC)	Buoy time	Image central site	Buoy site	Average radar incidence angle
1	2059:58 11 May 1993	2100:00 11 May 1993	37°45.3′N, 122°22.5′W	37°45′32″N, 122°50′W	58°
2	2103:38 10 May 2000	2100:00 10 May 2000	37°46.8′N, 122°28.8′W	37°45′32″N, 122°50′W	33°
3	2219:05 7 Apr 2002	2200:00 7 Apr 2002	33°6′N, 118°28.2′W	33°44′42″N, 119°05′02″W	37°
4	2204:42 7 Apr 2002	2200:00 7 Apr 2002	32°48.6′ N, 118°30.6′ W	32°26′00″N, 119°31′59”W	42°
5	2026:49 16 Apr 2003	2000:00 16 Apr 2003	33°27.6′ N, 118°31.8′ W	33°44′42″N, 119°05′02″W	55°

and $F_a(\mathbf{k})$ and $F_r(\mathbf{k})$ are the estimates of the slope spectra in the azimuthal and range directions, respectively. The dominant wavelength λ_d and direction given in Table 2 are obtained from the wave slope spectra. In estimating significant wave height $H_{1/3}$, we apply the expression

$$H_{1/3} = 2\sqrt{2}S_{\text{rms}} \tag{10}$$

in terms of the rms wave elevation S_{rms} calculated from wave slope. The significant wave height, wavelength, and wave direction are compared with corresponding quantities provided by the National Data Buoy Center (NDBC) buoy in Table 2. For all five SAR images, the results retrieved from AIRSAR polarimetric SAR are in very good agreement with those provided by NDBC buoys.

Finally, although we attempted to use relatively low frequency P-band and L-band AIRSAR polarimetric SAR images to retrieve ocean slope spectra, results were poor. The orientation angle methods presented by Schuler et al. (2003, 2004) at P band and L band are better than at C band. Our approach is based on a two-scale Bragg scattering model that generates an intensity modulation due to large-scale tilting. For C band, the image intensity depends on capillary gravity waves and long waves. But for L and P bands, the pri-

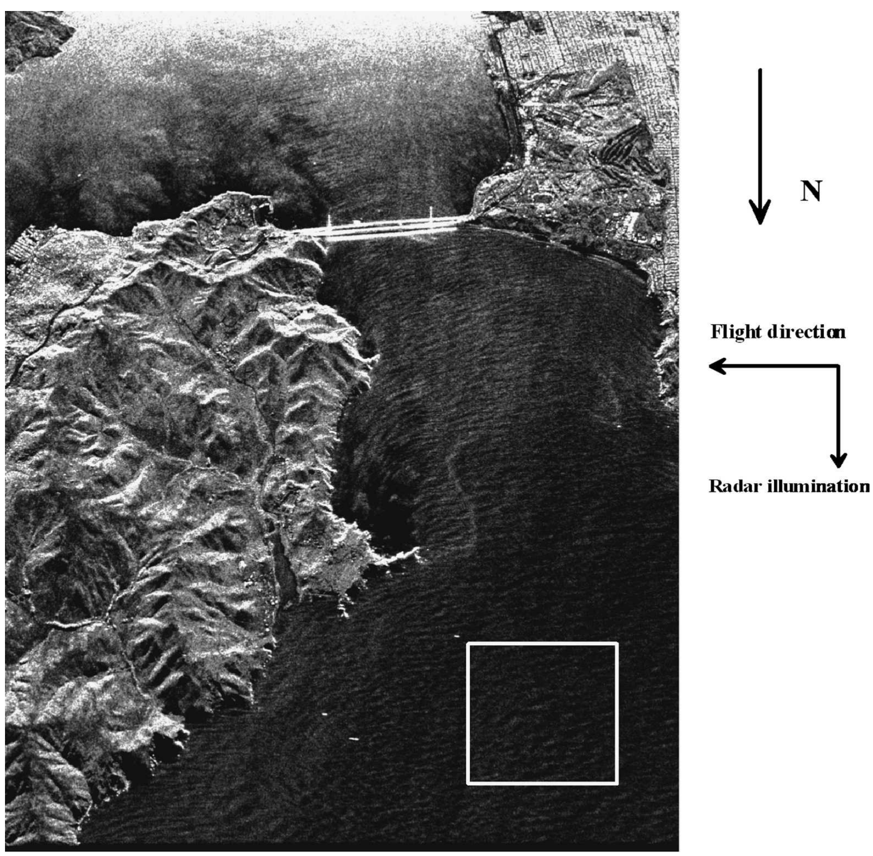

FIG. 1. A C-band, VV polarization, AIRSAR image of San Francisco, CA, coastal waters.

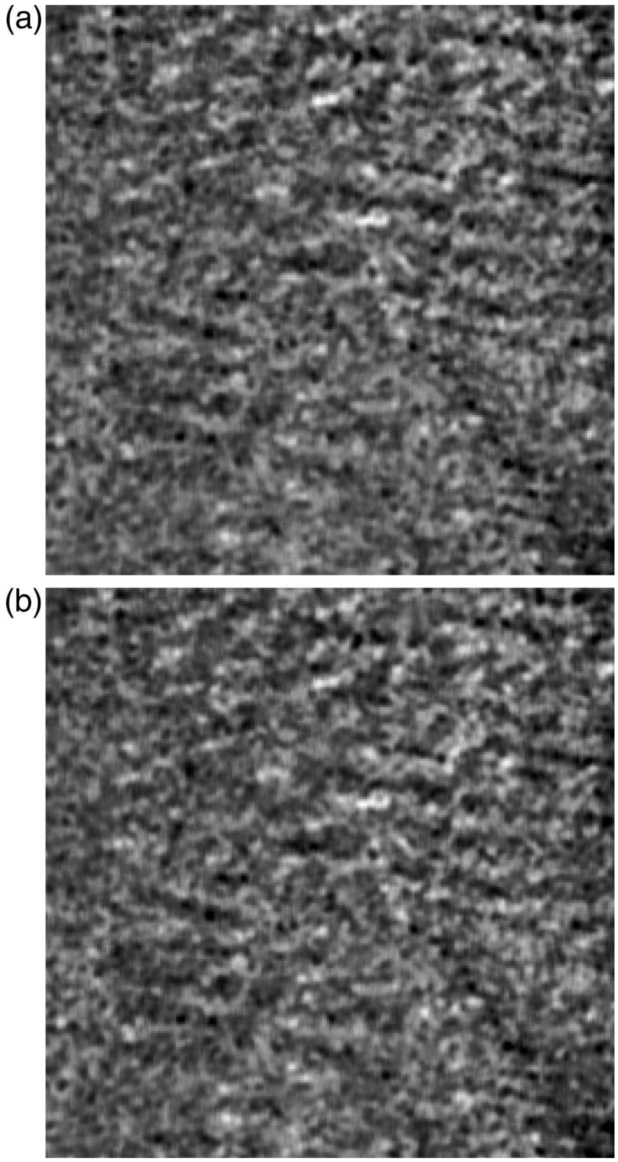

FIG. 2. Images of wave slope in (a) the azimuthal direction and (b) the range direction.

mary scattering mechanism is Kirchhoff scattering, and the image intensity primarily depends on the long waves. Thus, our approach is more appropriate at high frequencies than at low frequencies. Meanwhile, it is also suitable only for incidence angles greater than 20° and medium sea state conditions because the Bragg scattering is not the primary scattering mechanism for high and very low sea states. Moreover, the Schuler et al. method (using the polarization orientation angle approach) is a low-frequency tilt-Bragg approximation, which is expected to fail at high frequencies. Therefore, their approach complements our method, in this sense.

Moreover, other image intensity approaches, for example, the nonlinear inversion method, the cross-spectrum method, or the parameter method, need a hydrodynamic modulation transfer function. However, the modulation transfer function is not clearly known.

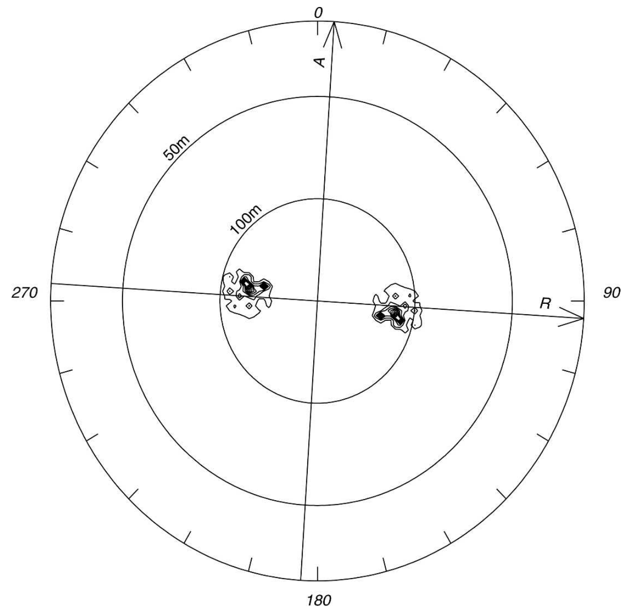

FIG. 3. Wave slope spectrum retrieved from a C-band fully polarimetric SAR image, where waves are coming from 281.1°.

TABLE 2. Estimated wave parameters from SAR for the five images in Table 1, compared to corresponding wave parameters provided by in situ buoy measurements.

Parameter	Image	Retrieval	Buoy	Error
Wave period (s)	1	8.77	7.3	1.44
	2	5.72	5.72	0.0
	3	4.94	5.76	−0.82
	4	5.72	5.35	0.37
	5	9.64	10.24	−0.6
Average error				0.65
Wavelength (m)	1	120	83.1	36.9
	2	51	51.0	0.0
	3	38	51.7	−13.7
	4	51	44.6	6.4
	5	145	163.5	−18.5
Average error				15.0
Wave direction (°)	1	281.1	273.0	8.1
	2	277.4	315	−37.6
	3	301.5	280	21.5
	4	286.5	299	−12.5
	5	278.7	273	5.7
Average error				15.1
Significant wave height (m)	1	1.6	1.8	−0.2
	2	2.6	1.56	1.04
	3	1.3	0.87	0.43
	4	1.2	1.82	−0.62
	5	1.1	1.07	0.03
Average error				0.46

Our approach does not depend on the modulation function. Moreover, the hydrodynamic modulation transfer function may be neglected when the incidence angle is about 20° for SAR wave mode data [i.e., for the European Remote Sensing Satellites (ERS) and *ENVISAT*], because it is weak compared to the tilt modulation function.

4. Conclusions

A new method to measure ocean wave slope spectrum using polarimetric SAR data was developed without the need for a complex hydrodynamics modulation transform function. A comparison with in situ measurements was made. The ocean wavelength, wave direction, and significant wave height are in very good agreement with those measured by the buoy. The method can be used to invert data collected from a polarimetric SAR satellite, such *RADARSAT-2*. Thus, a methodology is presented to monitor ocean waves on the global ocean.

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REFERENCES

Alpers, W., D. B. Ross, and C. L. Rufenach, 1981: On the detectability of ocean surface waves by real and synthetic aperture radar. *J. Geophys. Res.,* **86,** 6481–6498.

Engen, G., and H. Johnsen, 1995: SAR–ocean wave inversion using image cross spectra. *IEEE Trans. Geosci. Remote Sens.,* **33,** 1047–1056.

——, ——, H. E. Krogstad, and S. F. Barstow, 1994: Directional wave spectra by inversion of ERS-1 synthetic aperture radar ocean imagery. *IEEE Trans. Geosci. Remote Sens.,* **32,** 340–352.

——, P. W. Vachon, H. Johnsen, and F. W. Dobson, 2000: Retrieval of ocean wave spectra and RAR MTF's from dual-polarization SAR data. *IEEE Trans. Geosci. Remote Sens.,* **38,** 391–403.

Hasselmann, K., and S. Hasselmann, 1991: On the nonlinear mapping of an ocean wave spectrum into a synthetic aperture radar image spectrum and its inversion. *J. Geophys. Res.,* **96,** 10 713–10 729.

——, R. K. Raney, W. J. Plant, W. Alpers, R. A. Shuchman, D. R. Lyzenga, C. L. Rufenach, and M. J. Tucker, 1985: Theory of synthetic aperture radar ocean imaging: A MARSEN view. *J. Geophys. Res.,* **90,** 4659–4686.

He, Y., and W. Alpers, 2003: On the nonlinear integral transform of an ocean wave spectrum into an along-track interferometric synthetic aperture radar image spectrum. *J. Geophys. Res.,* **108** (C6), 3205, doi:10.1029/2002JC001560.

——, W. Perrie, T. Xie, and Q. Zou, 2004: Ocean wave spectra from a linear polarimetric SAR. *IEEE Trans. Geosci. Remote Sens.,* **42,** 2623–2631.

Lee, J. S., R. Jansen, D. L. Schuler, T. Ainsworth, G. Marmorino, and S. Chubb, 1998: Polarimetric analysis and modeling of multifrequency SAR signatures from Gulf Stream fronts. *IEEE J. Oceanic Eng.,* **23,** 322–332.

——, ——, and T. L. Ainsworth, 2000: Polarimetric SAR data compensation for terrain azimuth slope variation. *IEEE Trans. Geosci. Remote Sens.,* **38,** 2153–2163.

——, ——, ——, E. Krogager, D. Kasilingam, and W. M. Boerner, 2002: On the estimation of radar polarization orientation shifts induced by terrain slopes. *IEEE Trans. Geosci. Remote Sens.,* **40,** 30–41.

Marom, M., R. M. Goldstein, E. B. Thornton, and L. Shemer, 1990: Remote sensing of ocean wave spectra by interferometric synthetic aperture radar. *Nature,* **345,** 793–795.

——, L. Shemer, and E. B. Thornton, 1991: Energy density directional spectra of a near-shore wave field measured by interferometric synthetic aperture radar. *J. Geophys. Res.,* **96,** 22 125–22 134.

Pottier, E., 1998: Unsupervised classification scheme and topography derivation of POLSAR data on the H/A/a polarimetric decomposition theorem. *Proc. Fourth Int. Workshop on Radar Polarimetry,* Nantes, France, IRESTE, 535–548.

Schuler, D. L., and J. S. Lee, 1995: A microwave technique to improve the measurement of directional ocean wave spectra. *Int. J. Remote Sens.,* **16,** 199–215.

——, ——, and D. De Grandi, 1996: Measurement of topography using polarimetric SAR images. *IEEE Trans. Geosci. Remote Sens.,* **34,** 1266–1277.

——, T. L. Ainsworth, J. S. Lee, and G. De Grandi, 1998: Topographic mapping using polarimetric SAR. *Int. J. Remote Sens.,* **19,** 141–160.

——, J. S. Lee, T. L. Ainsworth, and M. R. Grunes, 2000: Terrain topography measurement using multipass polarimetric synthetic aperture radar. *Radio Sci.,* **35,** 813–832.

——, ——, D. Kasilingam, and G. Nesti, 2002: Surface roughness and slope measurements using polarimetric SAR data. *IEEE Trans. Geosci. Remote Sens.,* **40,** 687–698.

——, ——, ——, and E. Pottier, 2003: Measurements of ocean wave spectra using polarimetric SAR data. *Proc. IGARSS 2003,* Vol. 2 Toulouse, France, IEEE and ECSU, 708–710.

——, ——, ——, and ——, 2004: Measurement of ocean surface slopes and wave spectra using polarimetric SAR image data. *Remote Sens. Environ.,* **91,** 198–211.

Valenzuela, G. R., 1968: Scattering of electromagnetic waves from a tilted slightly rough surface. *Radio Sci.,* **3,** 1057–1066.