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SWIMSAT: A Real-Aperture Radar to Measure Directional Spectra of Ocean Waves from Space-Main Characteristics and Performance Simulation

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TABLE 4. Sea-state spectra and wind–wave conditions used in the surface simulation.

	Nondirectional spectrum	Angular distribution	Wind–wave conditions
Fully developed wind sea	Pierson and Moskowitz (1964) $F(k) = \frac{0.008}{2} k^{-4} \exp\left[-\frac{5}{4} \left(\frac{k_{\text{peak}}}{k}\right)^2\right]$ $k_{\text{peak}} = 0.7 \text{ g}/U^2$	Jackson (1987) $G(\phi) = \frac{4}{3\pi} \cos^4(\phi - \phi_0)$	$U = 13 \text{ m s}^{-1}$ Corresponding H_s : 3.6 m, Corresponding k_{peak} : $2\pi/155 \text{ m}$
Swell	Durden and Vesecky (1985) $F(k) = \frac{H_s^2}{16\sqrt{2}\pi\sigma_r} \exp\left[-\frac{1}{2} \left(\frac{k - k_{\text{peak}}}{\sigma_r}\right)^2\right]$	$G(\phi) = \frac{\cos^{14}(\phi - \phi_0)}{\int \cos^{14}(\phi - \phi_0) d\phi}$	$k_{\text{peak}} = 2\pi/200 \text{ m}$ $\sigma_r = 0.006 \text{ rad m}^{-1}$ $H_s = 4 \text{ m}$ or $H_s = 1 \text{ m}$

level. This dispersion is probably due to the signal modulation being calculated for a radar footprint restricted to 3 dB and to numerical uncertainties in the simulation (particularly those generated by geometric projections and sampling necessary to translate from the radial to the horizontal plane).

b. Speckle effects

In accordance with Jackson et al. (1985) and Jackson and Walton (1985) and as detailed in the appendix, we can show that the spectrum of the received signal for each pulse is related to the signal’s modulation spectrum by the following equation:

$$P_i(k) = \delta(k) + R(k)P_m(k) + P_s(k) + h(k), \quad (20)$$

where $\delta(k)$ is the continuous component of the signal; $R(k)$ is the radar’s impulse response; $P_m(k)$ is the signal modulation spectrum, as expressed by Eq. (6); $P_s(k)$ is the speckle spectrum; and $h(k)$ is a second-order term due to the speckle effect on the signal modulation. Assuming that the transmitted waveform is Gaussian, one obtains the following expressions for $R(k)$ and $P_s(k)$:

$$R(k) = \exp\left(-\frac{k^2}{2k_p^2}\right), \quad (21)$$

where $k_p = 2\sqrt{2 \ln 2} / \Delta x$ and Δx is the system’s inherent horizontal resolution, and

$$P_s(k) = \frac{1}{\sqrt{2\pi}k_p} \exp\left(-\frac{k^2}{2k_p^2}\right). \quad (22)$$

Concerning $h(k)$, we obtain (see appendix)

$$h(k) = \frac{\sqrt{2}}{\sqrt{\pi}k_p} \left[\int R(k')R(k' - k)^2 P_m(k' - k) dk' \right] P_s(k). \quad (23)$$

For SWIMSAT, $R(k)$ varies between 0.97 and 0.99 for wavelengths from 20 m to 1 km. Hereafter, we adopt an impulse response of unity. We also assume that the continuous part of the signal is prefiltered. Consequently, for a given pulse and look direction ϕ , the modulation spectrum of the signal affected by speckle noise is written as

$$P(k) \approx P_m(k) + P_s(k) + h(k). \quad (24)$$

For a signal estimated from N_{int} independent samples, the speckle spectral density $P_s(k)$ is given by

$$P_s(k) = \frac{1}{N_{\text{int}} \sqrt{2\pi}} \frac{\Delta x}{2\sqrt{2 \ln 2}}. \quad (25)$$

Figure 6 presents results obtained under the same conditions as in Fig. 5 but simulating speckle for a signal integrated over 147 successive echoes and six radial range gates. The simulated modulation spectral density (thick lines) is systematically overestimated with respect to the reference level (thin line). This shows that we need to correct the speckle modulation spectrum. On the basis of these results, we calculated that the difference between the simulated spectrum ignoring speckle (square symbols) and the simulated spectrum allowing for speckle (thick line) is very close to the level of the speckle spectrum computed analytically from Eq. (25) (dashed line). We thus verify that to apply a speckle correction, we simply need to apply Eqs. (24)–(25), ignoring $h(k)$. We were able to calculate

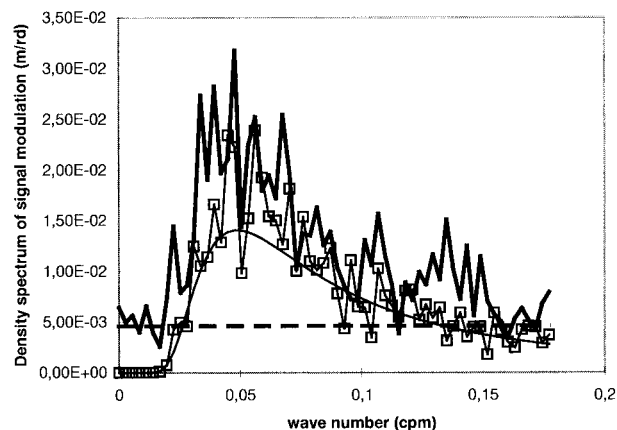


FIG. 6. Effect of speckle on simulated modulation spectrum. Bold line: simulation includes speckle but without correction of this effect in the inversion; squares: simulation does not include speckle; thin line: analytical modulation spectrum; (dotted line): speckle spectrum level according to Eq. (25).

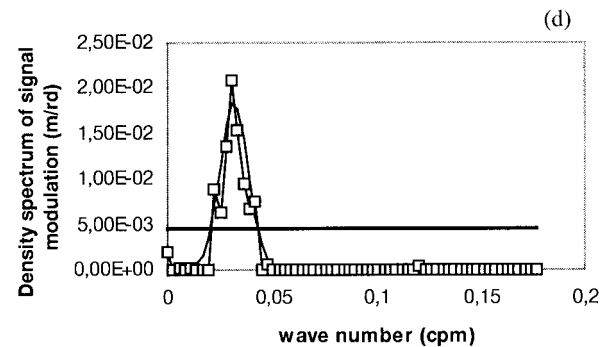
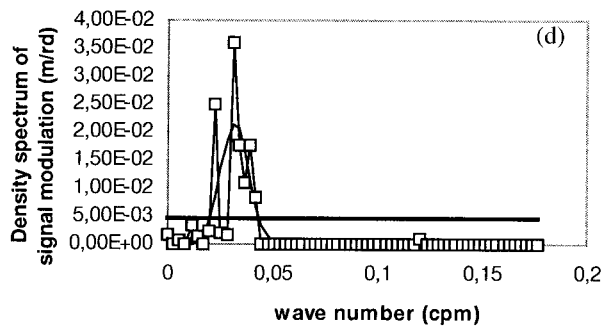
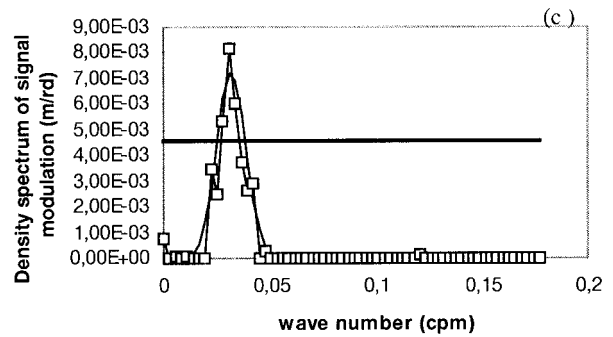
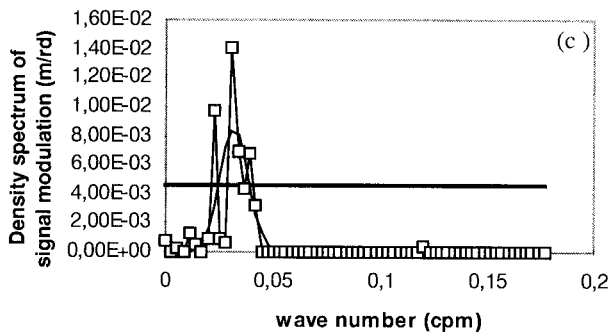
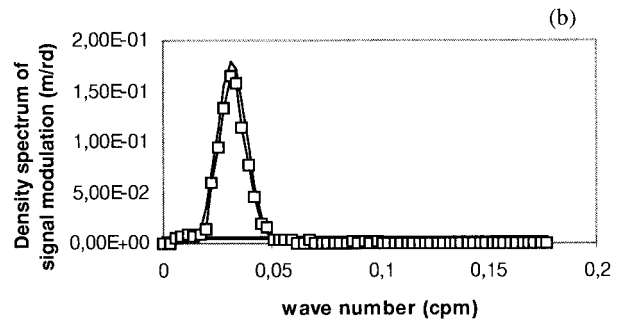
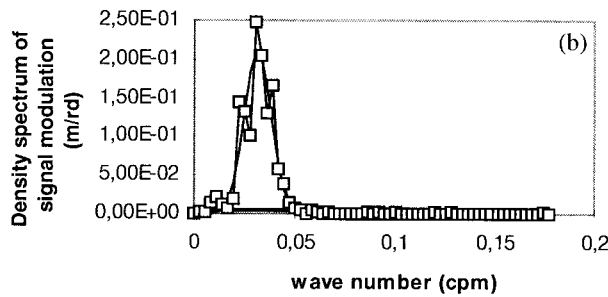
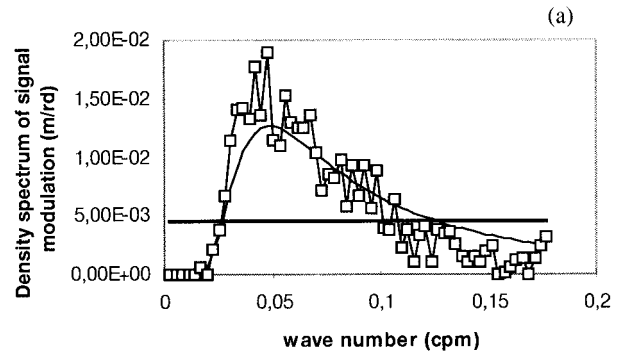
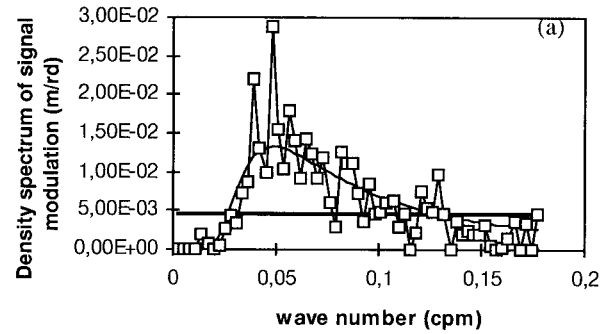


FIG. 10. Fully simulated modulation spectra for a given look direction ϕ (lines with square symbols). Thin line without symbols: analytical reference spectrum. (a), (b), (c), (d): sea-state conditions for cases A, B, C, and D, respectively.

FIG. 11. Same as Fig. 10 but for results obtained from averaging over 16 samples, covering 15° azimuth.

