EM Bias at Off-Nadir Incidence Angles

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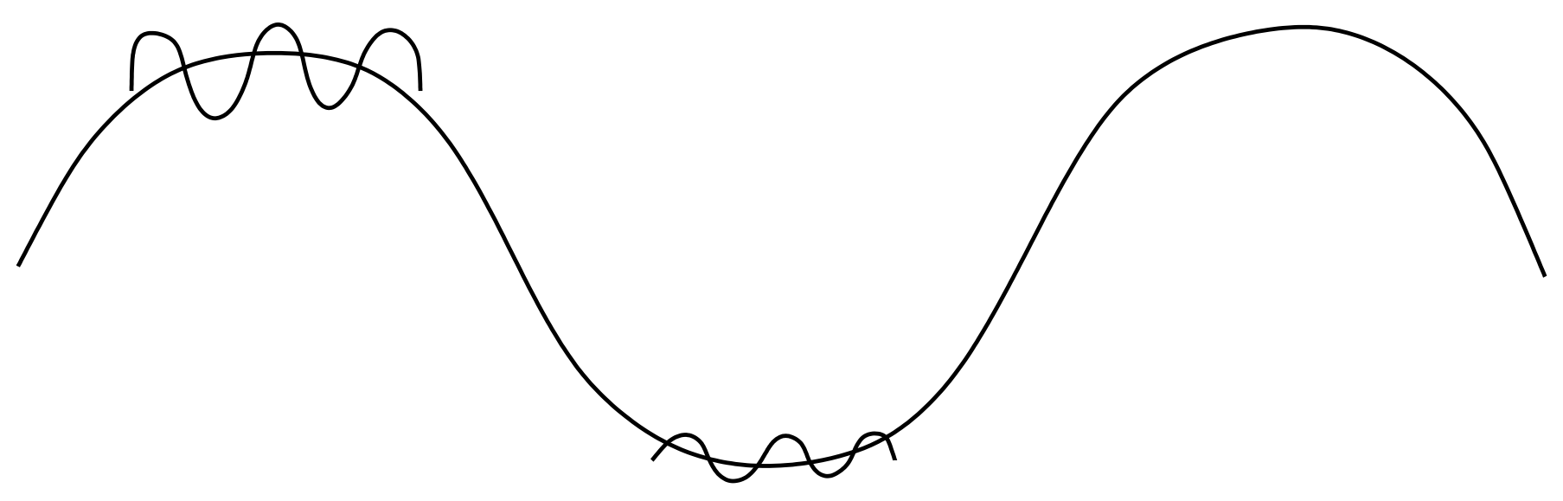
ABSTRACT

Recent theoretical and experimental results indicate that the dominant sea state bias (SSB) component is due to hydrodynamic modulation of small surface waves on the order of the electromagnetic wavelength in size. Since scattering from small-scale surface roughness is incident-angle dependent, the EM bias should behave differently at off-nadir incidence angles than at nadir incidence. In this study, we develop a theoretical model for off-nadir EM bias and consider some of the practical implications of the possibility of incidence angle dependence.

EM BIAS

Hydrodynamic modulation causes short waves on the order of the EM wavelength riding on long wave components (wavelength $>$ 1 meter) to increase in amplitude near wave peaks and decrease in the troughs.



At nadir incidence, less energy is backscattered from the rougher long wave peaks than from the troughs, leading to a negative SSB. Off-nadir, the situation reverses. Increased roughness leads to more energy in the backscattered direction from the long wave peaks, possibly causing a positive EM bias. In this study, we ignore tilt modulation and the SSB component due to skewness of the long-wave surface slope distribution.

HYDRODYNAMIC MODEL

For a sea surface consisting of small amplitude short waves riding on long waves, a simple first order hydrodynamic model [Melville and Felizardo, preprint, 1999] provides a linear model for hydrodynamic modulation of the form

$$h_s(\eta) = h_s(0)\left[1 + S\eta/h_l\right]$$

where h_l and h_s are surface height standard deviations of the long waves and short waves respectively and S is RMS long wave surface slope.

SCATTERING MODEL

The physical optics approximation (PO) for a 1D surface with Gaussian surface height distribution leads to the near-nadir backscattering coefficient

$$\sigma^0(\theta_{inc}) \simeq \frac{k_{EM}^2 L^2}{\pi} \int_{-1}^{1} du\,(1-|u|)e^{ik_b L u} e^{-\lambda[1-C(Lu)]}$$

where $C(x)$ is the sea surface height correlation function, k_b is the Bragg wavenumber $2k_{EM}\sin(\theta_{inc})$, and $\lambda = 4k_{EM}^2 h_s^2 \cos^2(\theta_{inc})$.

BIAS MODEL

The variation of the PO backscattering coefficient with displacement η leads to the EM bias model

$$\epsilon(\theta_{inc}) = -\gamma(\theta_{inc}) S h_l$$

where

$$\gamma(\theta_{inc}) = \frac{2\lambda \int_{-1}^{1} du\,(1-|u|)[1-C(Lu)]e^{ik_b L u} e^{-\lambda[1-C(Lu)]}}{\int_{-1}^{1} du\,(1-|u|)e^{ik_b L u} e^{-\lambda[1-C(Lu)]}}.$$

The EM bias can also be written as

$$\epsilon(\theta_{inc}) = -(\gamma/4) S H$$

where H is significant wave height.

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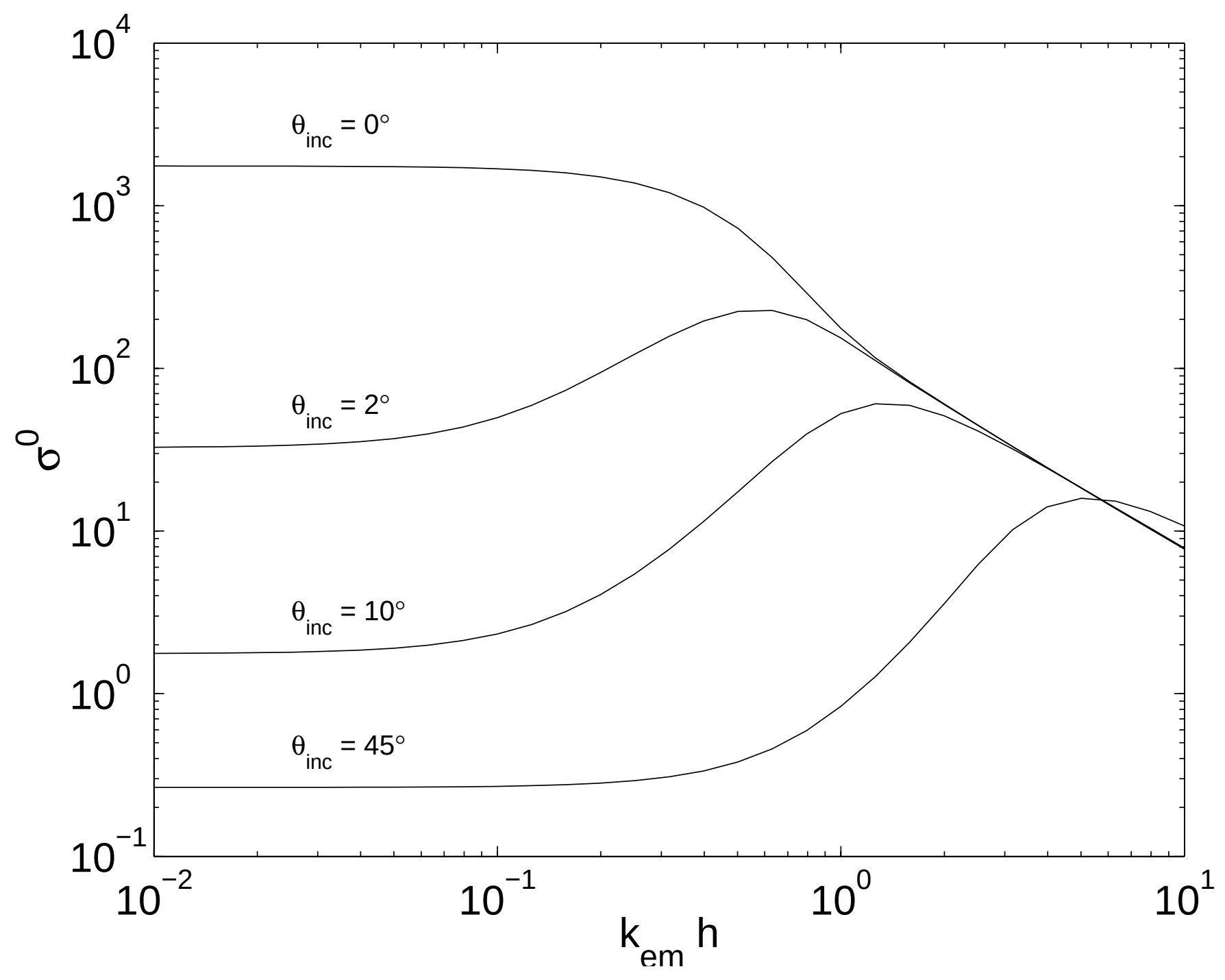
NADIR AND OFF-NADIR BACKSCATTERING

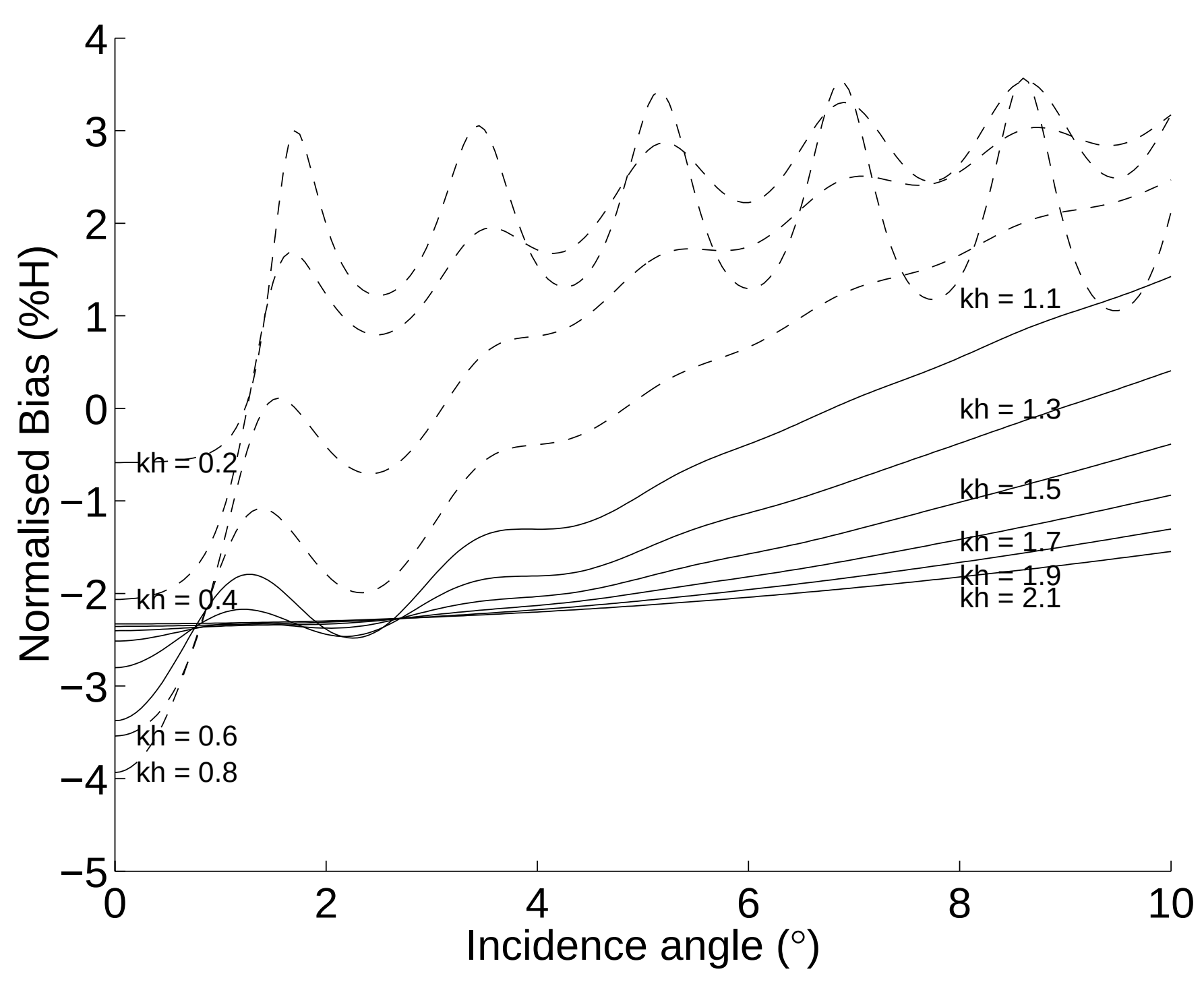
At nadir incidence, the backscattering coefficient of a flat surface with small-scale roughness monotonically decreases as the roughness increases. Off-nadir, the PO scattering model predicts a region of increasing backscatter for small roughness values. As the incidence angle increases, the positive slope region moves to larger roughness values. Ignoring the effects of long wave tilting, this region of increasing backscatter with roughness leads to a positive EM bias.



In this figure, the horizontal axis is the small scale surface roughness.

INCIDENCE ANGLE DEPENDENCE OF EM BIAS

The EM bias obtained using the PO scattering model and the simple first order hydrodynamic model described previously is shown in the figure below. Each curve corresponds to a different value for the small-scale surface roughness, as annotated on the plot. As incidence angle increases, the bias becomes positive. We expect that the magnitude of the variation would be decreased if surface tilting were taken into account.



Note in the previous figure that at nadir incidence, the bias increases with small-scale roughness until a peak value is reached, then begins to decrease with roughness. Since small-scale roughness is due to local wind speed, this leads to a roll-off of the bias at high wind speeds, which has been observed in a number of experimental studies.

For these results, the surface height power spectral density of the small-scale roughness is of the power law form k^{-p}, where $p = 2.7$. The surface illumination length length is chosen to be 1 m, and the lower cutoff of the surface spectrum is 2π rad/m. The oscillation of the curves is due to variation in the number of Bragg lengths which fit in the illumination length with incidence angle. This effect is presumably averaged out by long wave tilting.

IMPLICATIONS

This predicted incidence angle variation of the EM bias has two practical consequences:

- Bias correction models for the proposed wide swath altimeter design [Rodriguez and Pollard, Tech. Rep. 2001-4, High-Resolution Topography Science Working Group, 2001.] would need to be incidence angle dependent. Although the range of incidence angles is small, the theoretical results presented here indicate that an appreciable effect may still be manifested.
- Multiple along-track measurements of the same surface pixel at different incidence angles could be used in a manner similar to crossover differences to predict surface parameters such as RMS long wave slope and more accurately estimate SSB. If a theoretical or empirical model for $\gamma(\theta, U)$ could be obtained, then multiple height measurements would allow RMS slope S to be found using $h_1 - h_2 = [\gamma(\theta_1, U_1) - \gamma(\theta_2, U_2)]SH/4$.