Friction velocity estimation using dual-frequency altimeter data

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FRICTION VELOCITY ESTIMATION USING DUAL-FREQUENCY ALTIMETER DATA

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Abstract. Global estimation of wind speeds near the sea-surface can be obtained using normalized radar cross sections σ_0 from satellite-borne single-frequency altimeters. Indeed recent validation studies of Geosat altimeter-derived wind speeds show that several often cited semi-empirical algorithms yield linear trends between wind-speeds from altimeter data and wind speeds from (a) ships of opportunity (Etcheto 1992), (b) buoys (Carter 1992) and (c) atmospheric models (Guillaume 1992). Although the linear trends are striking, there is considerable scatter since the range of standard deviations is from 1.5 to 3 m s^{-1}. In fact, the scatter of some particular measurements about the regressions is striking because they depart from the 'standard' by as much as $\pm$ 5 m s^{-1}, which is large - even for full gale winds of 20 m s^{-1}. These anomalies can cause serious problems for gas exchange, heat, and aerosol estimates. They can also induce considerable errors in wind-driven oceanic circulation models and sea-surface wave models. This paper explores the possibility of improving the accuracy of wind speed estimation using dual-frequency altimeters.

1 Introduction

Undoubtedly sea-surface morphology depends upon not only local wind conditions but also upon winds that have acted previously – both locally and faraway. Short waves rapidly adjust to the local wind and because their wavelengths are small, they damp out quickly. On the other hand, long-waves require considerable distance and/or duration to develop and because their relaxation time is large, they can last for hours after their initial cause has disappeared. They even propagate great distances from their source region. Therefore long-wave characteristics are not well correlated to the local wind. Because sea-surface morphology is not uniquely determined by the local wind, it is unlikely that a robust one-to-one relationship exists between σ_0 and local wind speed.

Considering these factors, we assessed the effects of long-wave variability on an altimeter wind algorithm by using a multiple-parameter spectral model to represent the sea-surface. This analysis assumes normal wind-generated seas, *i.e.*, that winds are from the direction of the long-waves. The simulations of a K_u-band altimeter show that σ_0 is predominantly a function of short-waves, which are coupled to the local wind friction velocity u_*; however, long-wave steepness also affects σ_0 levels. Therefore we examine a dual-frequency altimeter and the analysis of $\sigma_0(C)$ and $\sigma_0(K_u)$ data reveals a technique to derive long-wave steepness. Consequently for suitable conditions, it may be possible to account for long-wave steepness variability in u_* inversion algorithms by using data from dual-frequency altimeters.

2 Numerical Methods

The results reported herein are derived from the composite scattering model of the Université Catholique de Louvain (UCL), which computes backscattered power values for altimeters and scatterometers by using various sea-surface spectral models. This simulator is amply documented by Guissard *et al.* (1994) and Sobieski *et al.* (1994). Since composite models start with the intuitive observation that the sea-surface appears as a superposition of large waves and small waves, microwave scattering from the sea-surface is commonly represented by a two-scale random processes: a large scale random process satisfying the conditions for the Kirchhoff method and a small scale random process satisfying the conditions for the small perturbation method.

For this analysis, the sea-surface is represented by the Wallops-Toba-Cox wavenumber spectrum $S^{WTC}(k)$ because this model represents a broad range of sea-states with just a few independent variables. $S^{WTC}(k)$ contains two independent regions : a long-wave region in which waves are characterized by their steepness and wavelength, and a short-wave region in which the waves are dependent upon the local wind. A concise description of the $S^{WTC}(k)$ follows. Long-waves can be represented by the Wallops model developed by Huang (1981), for which the spectral shape is a function of a wave-form parameter called the significant slope k, that is defined as

(1)

ζ_d is the rms value of the vertical displacement. λ_p is that particular wavelength that is related to the peak frequency ω_p of the sea-surface frequency spectrum by the wave dispersion relationship for deep-water gravity waves $\omega^2 = gk$. In this last expression, k is the wavenumber and g is the acceleration of gravity. The long-wave spectral decay is described as a function of ω^{-m}, where the value of m is related to the significant slope. For the microwave scattering simulations, wavenumber spectra are needed rather than frequency spectra, so the original Wallops frequency spectrum has been converted to a wavenumber spectrum. Thus the Wallops wavenumber spectral model has only two parameters : the significant slope δ and the peak wavenumber k_p, hence it is a long-wave model with two degrees of freedom that does not explicitly depend on the local wind conditions. Short-waves will be represented by two spectral regions that are dependent upon u_*. In this spectral region, wind action generates gravity-capillary waves. Spectra of small waves are usually related to the wind-friction velocity u_*, which is a measure of the downward transfer of horizontal momentum from the wind. We use the traditional gravity-capillary wave models by Toba (1973) and Cox (1958) to span the short-wave spectral region. The spectral sections are combined to obtain a spectrum that extends from long to short waves. The wavenumbers for the transitions between the spectral sections are chosen by matching spectral densities. The wavenumber for the transition from the Wallops to Toba sections is a function of u_*, δ and k_p, however the transition typically occurs at wavelengths between one-fourth and one-twentieth of λ_p.

3 Model Results

3.1 δ Effects on friction velocity determination

A broad range of sea-surface conditions can be characterized by using the Wallops-Toba-Cox model in the UCL simulator. The parameter ranges for the S^{WTC} model need to be specified. Recall that S^{WTC} is a function of three parameters : k_p, δ and u_*. In open ocean regions, δ is less than ~ 0.1 % for swell dominated seas and the upper limit for wind-generated seas is ~ 2 %. We are interested in wind-dominated seas, so δ will vary from 0.4 to 2 % and the u_* range will be from 5 cm s^{-1} to 140 cm s^{-1}, *i.e.* from the initiation of wave generation to full gale conditions.

For a 13.6 GHz altimeter (SymALT-K), we computed σ_o values for various combinations of the independent parameters and conducted a sensitivity analysis. It shows that σ_o is very weakly dependent upon k_p for typical oceanic values (dominant wavelengths greater than 20 m). On the other hand, the σ_o values are predominantly a function of u_*, with a secondary dependence on δ. These results are due to the fact that altimeters measure scattering mainly from specular facets on the sea-surface and specular facet distributions are closely related to sea-surface roughness. Sea-surface roughness is controlled by small-scale features and although large-scale features are of secondary importance, it is their slopes, rather than their wavelengths, that are notable for backscattered power. Therefore to simplify the presentation without affecting the results or conclusions, we reduce the three parameter space to a two parameter space with k_p corresponding to 25 m wavelength, a δ range from 0.4 to 2 %, and a u_* range from 5 to 140 cm s^{-1}.

Results from the simulations are presented in Figure 1, which shows u_* as a function of $\sigma_o(K_u)$, for δ from 0.4 to 2 %. The classic trend of decreasing cross-section with increasing wind speed is preserved. Additionally for each u_*, $\sigma_o(K_u)$ systematically decreases as δ increases. This δ dependence is consistent with expectations of reduced backscattered power as the sea-surface becomes rougher. It is also conspicuous that the isopleths converge as u_* increases because the fraction of surface-roughness attributable to long-waves decreases as u_* increases. Lastly σ_o is more sensitive to u_* at lower winds ($\partial\sigma_o/\partial u_*$ increases). These factors lead to the following assessment. For a given σ_o, u_* depends upon δ. As a matter of fact, a confidence interval of u_* values can be associated with each σ_o. At high wind speeds, the isopleths of δ are close to each other. At low wind speed, the isopleths of δ are nearly horizontal, but they are further apart. Consequently, the width of the u_* confidence interval is nearly constant over the entire range of σ_o. Thus the uncertainty of u_* estimates from σ_o that can be attributed to long-wave slope effects, *i.e.* to rising or falling seas, is $\pm$ 15 cm s^{-1}.

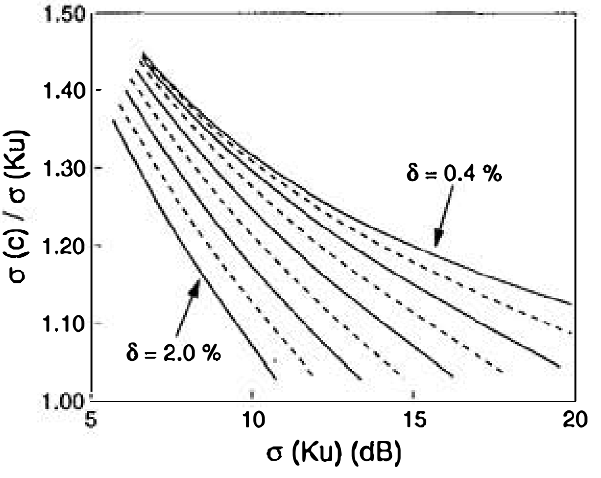

Fig. 2. Simulations with SymALT-CK reveal a technique to infer significant slope using dual-frequency data. δ increments = 0.2 %. Thus a two-parameter friction velocity algorithm may be viable for dual-frequency altimeters such as TOPEX-POSEIDON

parameter model. For example, one can simply use the results presented in Figure 2 to infer δ, then use Figure 1 with both $\sigma_o(K_u)$ and δ as input to obtain u_*. Hence for a particular $\sigma_o(K_u)$ value, u_* is unambiguously determined with respect to long-wave conditions.

The sensitivity of the results shown in Figures 1 and 2 was examined by changing the dominant wavelength by almost an order of magnitude, *i.e.* from 25 to 200 m. The cross sections differed from those shown in Figure 1 by less than ~0.4 dB and the ratios differed from those shown in Figure 2 by less than ~0.01. In both cases, this is typically smaller than the spacing between isopleths. Because the isopleths shown in these figures are only weakly dependent upon the dominant wavelength, this two-parameter model is practically insensitive to the dominant wavenumber k_p and hence this approach may lead to a useful operational algorithm.

4 Summary and Recommendations

This simulation shows that both long-wave significant slope and friction velocity are important parameters affecting $\sigma_o(K_u)$ values. Consequently we introduced a technique to use dual-frequency altimeter data to refine estimates of friction velocity by compensating for naturally occurring long-wave slope variability. The results of this analysis, however, are not intended to be applied immediately as an operational algorithm, but rather are intended to demonstrate a technique that should be further examined to assess its real potential to enhance the utilization of dual-frequency altimeter data for geophysical applications.

Accurate friction velocity values are needed for many oceanic processes to be effectively modelled and monitored. The TOPEX/POSEIDON satellite is the first spaceborne system that has an altimeter with both C- and K_u-bands (which were justified in order to obtain propagational time delays fior ionospheric corrections that improve range measurements). Because this altimeter operates at a high sampling rate with interleaved pulses on collocated ground tracks, input for two-scale algorithms should be available soon after the systems have been calibrated. Consequently an extraordinary opportunity will exist for vali-dation of two-scale techniques to derive u_* values. Feasibility studies should be conducted to ascertain if uncertainties in u_* estimates due to δ variability can indeed be reduced using dual-firequency altimeter data.

5 Acknowledgments

NASA (RTOP 972-461-31-08), the Office of Naval Research (ONR 972-146-70-11), the European Space Agency (ESA) and the Centre National de la Recherche Scientifique (CNRS) contributed funding for this research. E. Adant is acknowledged for reprocessing the text.

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