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To cite this version:
Lary Bliven, Piotr Sobieski, A. Guissard, Hubert Branger. Friction velocity estimation using dual-frequency altimeter data. Donelan, Hui and Plant eds. Air-sea interface, University of Toronto Press, pp.686-691, 1996, 0930050002. hal-00229827

HAL Id: hal-00229827
https://hal.science/hal-00229827
Submitted on 2 Jun 2023

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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 \( \sigma_0 \) 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 (Guillouille 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 \( \sigma_0 \) 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 Ku-band altimeter show that \( \sigma_0 \) is predominantly a function of short-waves, which are coupled to the local wind friction velocity \( u_\ast \); however, long-wave steepness also affects \( \sigma_0 \) 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

$$\zeta_d$$

is the rms value of the vertical displacement. $\lambda_p$ is that particular wavelength that is related to the peak frequency $\omega_p$ 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 $\omega^{-m}$, 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 $\delta$ 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 $u_*$, $\delta$ and $k_p$, however the transition
typically occurs at wavelengths between one-fourth and one-twentieth of $\lambda_p$.

3 Model Results

3.1 $\delta$ 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: $k_p$, $\delta$ and $u_*$. In open ocean regions, $\delta$ is less than $\sim 0.1\%$ for
swell dominated seas and the upper limit for wind-generated seas is $\sim 2\%$. We
are interested in wind-dominated seas, so $\delta$ 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 $\sigma_o$ values for various
combinations of the independent parameters and conducted a sensitivity analy­
sis. It shows that $\sigma_o$ is very weakly dependent upon $k_p$ for typical oceanic values
(dominant wavelengths greater than 20 m). On the other hand, the $\sigma_o$ values
are predominantly a function of $u_*$, with a secondary dependence on $\delta$. These
results are due to the fact that altimeters measure scattering mainly from spec­
cular facets on the sea-surface and specular facet distributions are closely related
to sea-surface roughness. Sea-surface roughness is controlled by small-scale fea­
tures 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 conclu­
sions, we reduce the three parameter space to a two parameter space with $k_p$
corresponding to 25 m wavelength, a $\delta$ 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 $\delta$ 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 $\delta$ increases. This $\delta$ dependence is consistent
with expectations of reduced backscattered power as the sea-surface becomes
rougner. It is also conspicuous that the isopleths converge as $u_*$ increases be­
cause the fraction of surface-roughness attributable to long-waves decreases as $u_*$ increases. Lastly $\sigma_o$ is more sensitive to $u_*$ at lower winds ($\partial \sigma_o/\partial u_*$ in­
creases). These factors lead to the following assessment. For a given $\sigma_o$, $u_*$
depends upon $\delta$. As a matter of fact, a confidence interval of $u_*$ values can be
associated with each $\sigma_o$. At high wind speeds, the isopleths of $\delta$ are close to each
other. At low wind speed, the isopleths of $\delta$ are nearly horizontal, but they are
further apart. Consequently, the width of the $u_*$ confidence interval is nearly
constant over the entire range of $\sigma_o$. Thus the uncertainty of $u_*$ estimates from
$\sigma_o$ that can be attributed to long-wave slope effects, i.e. to rising or falling seas,
is $\pm 15$ cm s$^{-1}$. 

3
Simulations with SymALT-CK reveal a technique to infer significant slope using dual-frequency data. $\delta$ 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 $\delta$, then use Figure 1 with both $\sigma_o(K_u)$ and $\delta$ 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 $\sim 0.4$ dB and the ratios differed from those shown in Figure 2 by less than $\sim 0.01$. 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 Ku-bands (which were justified in order to obtain propagational time delays for 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 validation 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-frequency 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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