Slope Variance Obtaining from Buoy Data and Validation by TOPEX/Poseidon Measurements

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***Abstract*—The method to calculate large-scale, in comparison with the probing wavelength, sea waves slope variance from buoy measurements is proposed. The idea is to use integration of model sea wave spectrum which parameters can be fully determined by buoy measurements in case of pure wind sea and mixed sea containing fully developed wind waves and swell. The algorithm is validated and corrected by TOPEX altimeter data collocated with buoy measurements.**

I. Introduction

Slope variance (or mean square slope - mss) of large-scale, in comparison with the probing wavelength, waves is a crucial parameter affecting backscattering radar cross section (RCS) both at low and at moderate incidence angles. The purpose of the paper is to obtain the algorithm for slope variance estimation from sea buoys data. Sea buoys provide us information about significant wave height (SWH), wind speed and peak period in the spectrum. Wave spectrum measured by buoy is truncated at wavelengths approximately 7 meters due to construction of sea buoy. In result the mss calculated from this spectrum will be underestimated in comparison with mss which is required for calculation of the RCS for microwave band. In Fig. 1 mss from buoy spectrum is compared to mss retrieved from radar measurements by Precipitation Radar (PR) at wavelength 0.021 m and with Cox & Munk formula for mss from optical measurements [1]. The smaller the probing wavelength the shorter waves in the sea spectrum influence scattering and reflecting processes of incident radiation. For study of microwave scattering it is necessary to know the variance of large-scale, in comparison with radar wavelength, slopes (let us call it LSmss). The model of spectrum suggested in [2] describes the sea wave spectrum good enough. This model spectrum is defined completely by the following parameters: wind speed, dimensionless wind fetch, swell period and swell SWH which can be retrieved from buoy data. So LSmss for microwaves can be obtained by integrating of the model spectrum up to the boundary wave number which separates large-scale (in comparison with radar wavelength) part of the spectrum.

In general case buoy data are not enough to obtain fetch and swell parameters uniquely but it is possible under the two assumptions. The first case is pure wind waves, the second is mixed sea containing fully developed wind waves and swell.

Total LSmss can also be retrieved from RCS at nadir. The algorithm was developed by use of Precipitation Radar (PR). PR was developed in Japan and is a part of equipment stalled on board of Tropical Rainfall Measurement Mission (TRMM) satellite. PR operates in Ku-band and scanning ocean surface at low incidence angles in the direction perpendicular to the flight direction. PR data can be applied to extract total LSmss from altimeter measurements [3]. In the present study this method is the reference one to validate LSmss for Ku-band retrieved from buoy data.

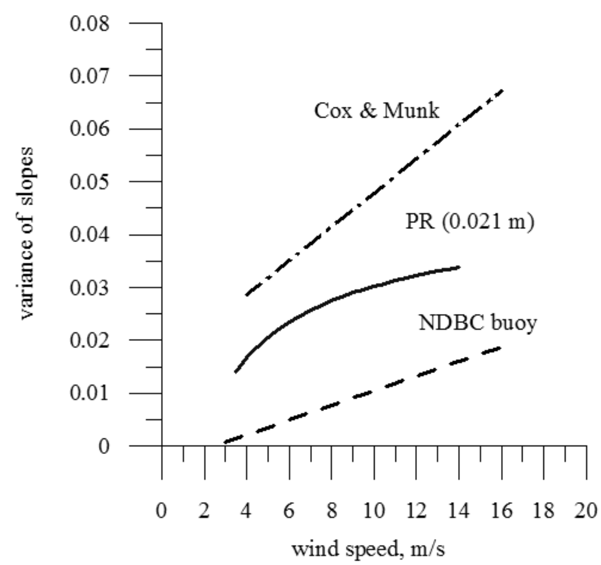

Fig. 1. Comparison of mss calculated by Cox & Munk's formula (dashed-dotted line) with slopes retrieved from PR data for fully developed wind waves (solid line) and NDBC buoy data (dashed line).

II. Collocated Measurements by NDBC Buoys and TOPEX Altimeter

A collocated set of buoy (of US National Data Buoy Center) and TOPEX/Poseidon altimeter measurements for the period September 1992 through December 1998 was compiled. The spatial and temporal collocation windows are 50 km and 30 minutes respectively.

The final dataset contained 4443 data points. The dataset contained altimeter measurements of RCS (Ku-band) σ_0^{TOP} and buoy measurements of wind speed at 10 meters U_{10}, SWH H_s and period of the spectral peak in the buoy spectrum T_p. Data points where wind speed is less than 3 m/s were omitted because winds lower than 3 m/s do not generate waves as it was shown in [4]. To estimate the stage of sea development the two wave ages were introduced in [5]. First one is $age_H = H_s / H_{fd}$, where H_{fd} is SWH of fully developed waves depending on wind speed as

$$H_{fd} = -0.0125 + 0.000926U_{10} + 0.02337U_{10}^2 + \\ + 0.0000006U_{10}^3 + 0.028\exp(-U_{10}). \tag{1}$$

The second age is $age_U = C_p / U_{10}$ where $C_p = gT_p / 2\pi$ is the phase velocity of the spectral peak.

The two arrays corresponding to wind and mixed seas were selected. The first one (let us call it W-array) is developing pure wind sea case satisfying the condition $age_H < 1$ and $age_U < 1.2$. It contained 626 samples. The second one (let us call it S-array) for fully developed waves with swell was selected by the condition $age_H > 1$ and $age_U > 1.2$ and contained 2153 points.

III. Slope Variance Retrieval from Altimeter Data

To estimate LSmss from altimeter data we used the algorithm obtained by the data of PR. In frames of Kirghoff approximation the algorithm for mss and RCS at zero incidence angle retrieval was suggested. RCS and mss are in a good correlation as shown in Fig. 2.

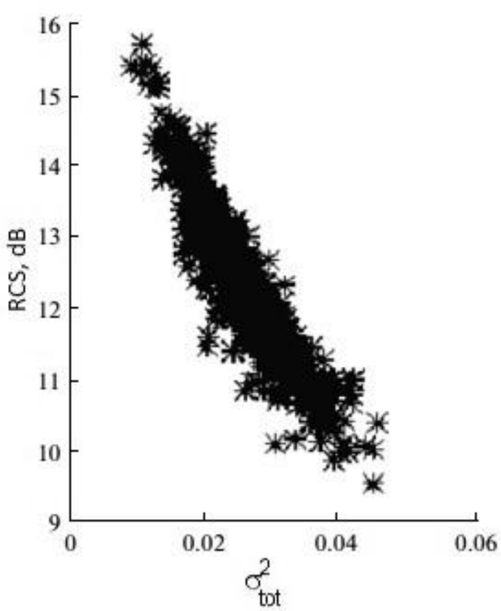

Fig. 2. RCS dependence on LSmss by PR data from [2]

The simple algorithm for LSmss retrieval from RCS at nadir incidence was suggested in [3]

$$\sigma_{tot}^2 = -0.00591 + 0.74352 / \sigma_0^{PR} - 4.07817 / (\sigma_0^{PR})^2 + \\ + 13.7317 / (\sigma_0^{PR})^2. \tag{2}$$

Comparison of RCS at nadir dependence on the wind speed for PR and TOPEX showed that PR measurements are shifted on average by 1 dB in comparison with TOPEX RCS. Calibration differences for TOPEX and PR are taken into account by

$$\sigma_0^{PR} = \sigma_0^{TOP} + 1\text{dB}. \tag{3}$$

It should be noticed that formula (2) is valid for σ_0^{PR} between 9.5 and 16 dB.

IV. Slope Variance Retrieval from Buoy Data

LSmss can be obtained by integrating over the elevation sea spectrum multiplied by the wave number squared up to the boundary wave number. The problem of the boundary determination is discussed below. Thus the total LSmss is defined by the following equation

$$\sigma_{tot}^2 = \int_0^{k_b} S(U_{10}, \tilde{X}, \vec{k}, H_{swell}, T_{swell}) k^2 dk\ , \tag{4}$$

where $\tilde{X}$ is a dimensionless fetch, H_{swell} and T_{swell} are swell SWH and period, k is a wave number of sea wave, k_b is a boundary wave number separating large-scale waves for Ku-band. Parameters $\tilde{X}$, H_{swell} and T_{swell} are defined differently for W-array and S-array. Since we suggested that W-array is for pure wind developing waves without swell and S-array is an array for fully developed sea in presence of strong swell all the parameters can be defined uniquely from the buoy data.

For S-array we assume that spectral peak measured by buoy corresponds to swell so that $T_{swell} = T_p$. This assumption is not correct in general but we use it in the present research because buoy data are not enough for accurate determination of swell and wind wave contribution. The second assumption, we consider wind waves to be fully developed. This means that $\tilde{X} = \tilde{X}_{\max} = 20170$ from spectrum [2] and $H_{swell} = H_s - H_{fd}(U_{10})$.

For W-array we assume that swell height is set to zero and T_p corresponds to wind waves. Wind fetch is a parameter in the spectrum [2] which determines the dimensionless spectral peak frequency $\tilde{\omega}_p = \omega_p U_{10} / g = age_U{}^{-1}$. To obtain the fetch we use the following formula [6]

$$\tilde{X} = (\tilde{\omega}_p / 3.5)^{-3.03}. \tag{5}$$

Boundary wave number k_b is introduced in frames of the two-scale model of the sea surface for radar observations and separates large-scale and small-scales waves in comparison with the probing radar wavelengths. Theoretical assessment for the boundary wave number depends on the probing radar wavelength only and does not take into account the sea state and wind conditions.

Our aim was to estimate the boundary wave number at different wind speeds for Ku-band observations. For that purpose the Precipitaion Radar data array [3] combined with buoy data containing wind speed was used. The idea is as follows.

First we selected the data where the sea state was close to fully developed. The criteria was

$$0.85 < age_H < 1.15. \quad (6)$$

The assumption was that in fully developed case LSmss takes the average value (between increased at swell cases and decreased at developing waves cases).

First the LSmss was obtained from the Precipitation Radar data as it was mentioned in previous paragraph. We considered this value as a reference one. Also the LSmss was calculated by the equation (4) using spectrum model [2]. The integration was done for fully developed pure-wind sea to match the condition (6). Boundary wave number was the parameter to adapt the result from the equation (4) to the LSmss from PR data. This procedure was done for wind speeds from 3 to 16 m/s. As a result the following approximation was obtained

$$k_b = 1.98 - 50.67/U_{10} + 981.38/U_{10}^2 + \\ + 3392.29/U_{10}^3 + 28556.68/U_{10}^4 - 30940.95/U_{10}^5 \quad . (7)$$

LSmss dependences on wind speed for S-array and W-array are presented in Fig. 3 and Fig. 4 respectively.

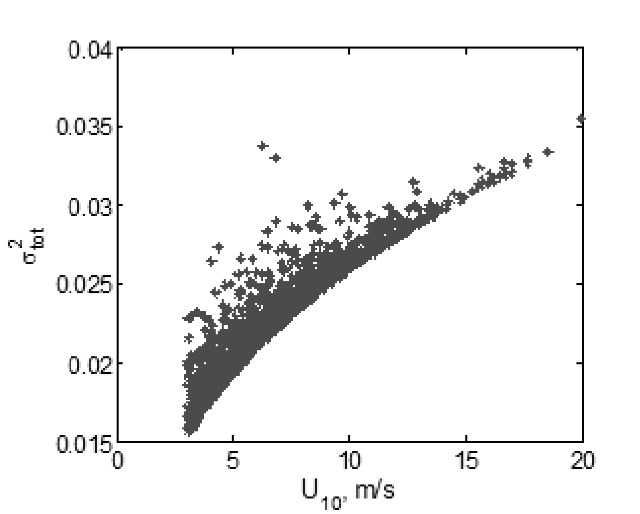

Fig. 3. LSmss dependence on wind speed for S-area

For W-area LSmss values lie lower than fully developed waves LSmss. The scatter is caused by differences in fetch.

LSmss for Ku-band for both cases is lower than slope variance from optical observations [1] because microwaves are less sensitive to smaller scale surface waves than optical waves. For better radar and buoy intercomparison analogical boundary wave numbers for others radar wavelengths should be obtained. It should be noticed that choice of boundary wave numbers also depends on the sea spectrum model.

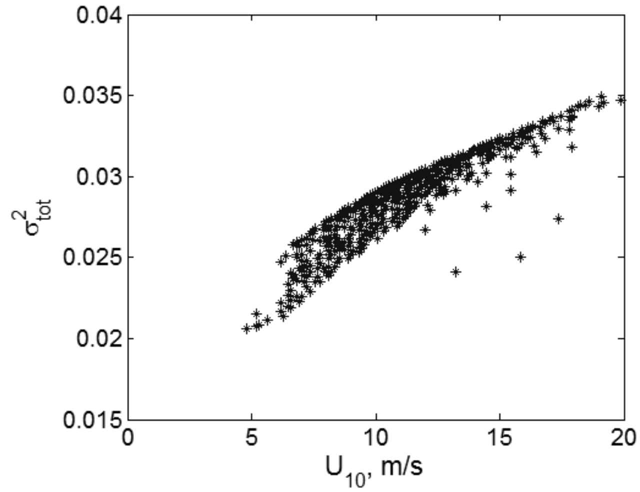

Fig. 4. LSmss dependence on wind speed for W-area

V. Comparison and Correction

For W-array and S-array σ^2_{totBsp} was calculated from buoy data by spectrum integration (2) and σ^2_{totA} from altimeter data by (3) and (2). Comparison revealed good correlation between σ^2_{totB} and σ^2_{totA} (0.87 for S-array and 0.83 for W-array) but bias and standard deviation were subject to improvement. For W-array bias=-0.002, std=0.004 before correction and bias=0, std=0.003 after correction

$$\sigma^2_{totB} = 1.795\sigma^2_{totBsp} - 0.0207 . \quad (8)$$

For S-array bias=-0.003, std=0.0028 before correction and bias=0, std=0.0025 after correction

$$\sigma^2_{totB} = 1.397\sigma^2_{totBsp} - 0.0075 . \quad (9)$$

Plot comparing LSmss from buoy and altimeter data is presented in Fig. 5 and 6 for both pure wind sea (W-array) and mixed sea with strong swell (S-array).

VI. Conclusion

The method for LSmss estimation from sea buoy data was developed for the two cases of sea wave development: pure wind sea and mixed sea (fully developed waves with swell). Assumptions concerning fetch and swell SWH for these cases are strong but the retrieved total LSmss is in a good agreement with one obtained from altimeter data (which we consider as reference one). It should be noticed that the algorithm can be applied for estimation of large-scale waves for Ku-band and bands of the same order.

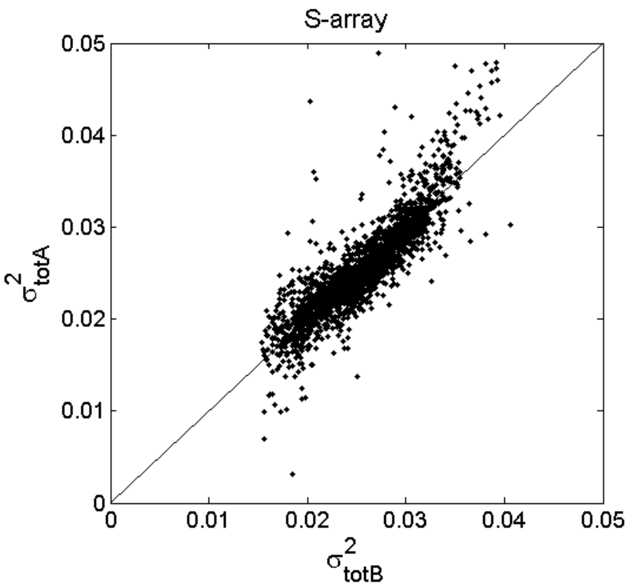

Fig. 5. Total LSmss obtained from buoy data and from TOPEX altimeter data for mixed sea with strong swell

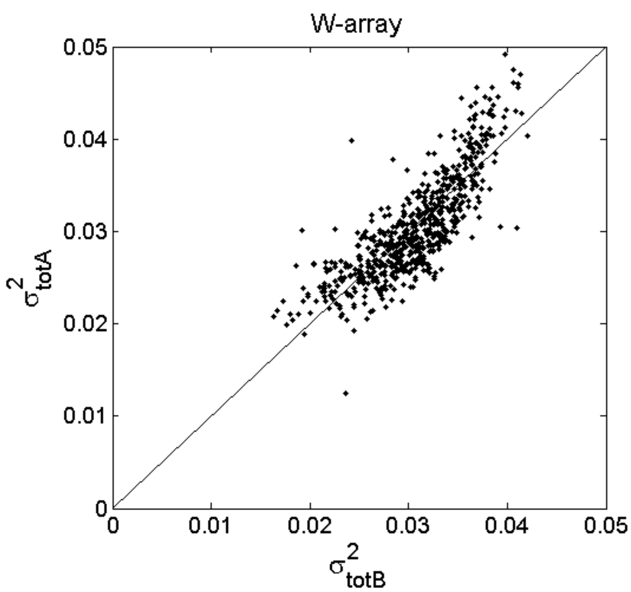

Fig. 6. Total LSmss obtained from buoy data and from TOPEX altimeter data for developing wind waves

Results of the present research can be applied for collocated buoy and radar data (from altimeters, scatterometers and SAR) analysis for estimation of LSmss influence on backscattering radar cross section. Also LSmss can be introduced as an additional parameter into the wind speed retrieval algorithms.

Acknowledgement

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