Measurements of sea level, wave height and slopes by analysis of sea surface image sequence from polarization camera

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Abstract – A method of investigation sea surface roughness by analysis polarization images is suggested. Equipment and software were developed and tested at the Pacific Oceanological Institute (POI) in 2003 - 2004. Equipment includes a polarization camera and systems of floats. The float heights obtained from its image coordinates. The slopes of the sea surface were determined as orientation triangles, formed by centers of floats, and as slopes calculated from Stokes parameters image. Heights of sea surface obtained from polarization images and float heights was comparison. Field experiments were conducted at the POI marine station in the Japan Sea. The developed methods and equipment may be used as a source of unique in situ information on the sea surface roughness during satellite optical and radar sensing.

Keywords: Brightness, polarization camera, sea surface, sea slopes.

1. INTRODUCTION

Measurement of the sea surface slope distribution and the mean-square slope (MSS) in field experiments are significant for comparison of ocean remote sensing data and ocean surface data. Although a series of experiments have been undertaken over the last 20 years to collect suitable measurements by optical and microwave radar technologies, our knowledge in this area is far from satisfactory (Trokhimovsky, 2000). Purpose of this paper is development of optical techniques and instruments for measurement of sea wave's height and slopes. Techniques based on light reflection ('shape from reflection') are basically only useful to derive wave slope statistics. Techniques based on light refraction (`shape from refraction') turn out to be most suitable to take wave slope images. They have been successfully used in the laboratory, but will be applied to the ocean study in the near future. Secondly, calibration objects formed from thin transparent Perspex sheets with known slope and height profiles are retrieved. The results show that the measurements of the water surface shape are accurate enough to compute 2D wave number spectra (Jaehne at al., 1992). Here is attempt to consider additional support for accuracy: a) floating ball in instrument field of view, b) analysis of sequence of the polarization images of the sea surface.

Sky radiance and Fresnel's reflectance specify relationship between surface slope and observed pixel intensity. The measured light intensity B_{SEA} has the following relation with sky brightness B_{SKY} and the Fresnel reflection coefficients $R(\varphi, n)$ (for light polarized in reflecting plane P_I) and $R_S(\varphi, n)$ (for light polarized in plane P_G) see Fig.1:

$$B_{SEA} = B_{SKY} [R_P (\varphi, n) + R_S(\varphi, n)]: \quad (1)$$

where φ = angle of reflection
n = refraction index

For polarization image, formed by polarized light pixel intensity B_{FP} is:

$$B_{FP} = B_{SKY}\cdot[R_S (\varphi, n) - R_P (\varphi, n)]\cdot\cos^2(\beta-\nu) + R_P (\varphi, n) \quad (2)$$

where β = angle between P_I and P_G,
ν = angle between P_G plane and the polarization plane of polarizer

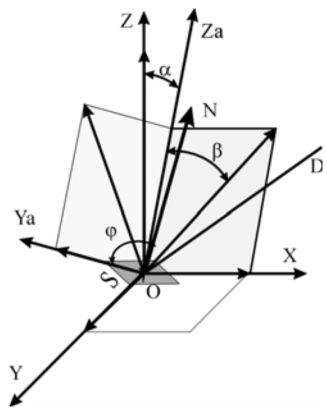

Figure 1. Light reflection Geometry.
S = a facet of the sea surface, N = normal to the facet, (DO) = incident beam direction, α = viewing angle, φ = angle of reflection, P_V (YOZ) = vertical plane, P_I = reflecting plane ($DZaOYa$), Plane P_G = ($XOYa$) at right angle to P_I, (YaO) = viewing direction, $XOYZ$ = left coordinates. XOY is horizontal plane.

The degree of polarization is determined by an incidence angle and refraction index. Angle β between P_I and P_V, taking into account viewing direction may be defined as an angle between polarization plane of reflected light and plane P_V.

Projections ξ_x and ξ_y of slope ξ for facet S are calculated from values of φ and β. In order to derive β and φ values, the measurements of B_{FP} at three or more different angles ν are required. They are selected in such a manner that $\nu_2 = \nu_1+\pi/4$ and $\nu_2 = \nu_1+\pi/2$. The φ and β values can be derived from the Fresnel equations for angles ν_1, ν_2, and ν_3 using the following formulas:

$$\beta = arcsin[(B - D)/P]/2$$

$$\varphi = arcsin\{sqrt\,[-Q\cdot(n^2 + 1) + V]/sqrt[2\cdot(1 - Q)]\} \quad (3)$$

where $A = B_{FP}(\nu_1)$

$B = B_{FP}(\nu_2)$

$C = B_{FP}(\nu_3)$

$D = A + B$

$P = sqrt[2\cdot(C^2 + A^2)+4\cdot B\cdot(B - A - C)]$

$G = sqrt[(D + P)/(D - P)]$

$Q = [(G + 1)/(G - 1)]^2$

$V = sqrt[(Q\cdot n^2 + Q)^2 + 4\cdot(1 - Q)\cdot Q\cdot n^2]$

Stokes parameters to the for reflected light can be obtained by using the following simple formulas:

$S_1 = A + B$

$S_2 = P$

$S_3 = (D + P)\cdot(D - P)$

$S_4 = 0$

Under condition of continuous cloudiness the second, third and forth Stokes parameters for incident light will be equal to zero.

2. INSTRUMENTS

All instruments were developed at the V.I. Il'ichev Pacific Oceanological Institute. A polarization camera (see Fig. 2) has three mirrors and polarizers to form the polarization images on its CCD matrix.

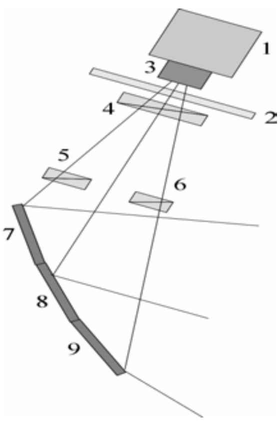

Figure 2. Optical scheme of polarization camera. 1 = CCD camera, 2 = light filter. 3 = focal lens, 4 ÷ 6 = polarizers, 7 ÷ 9 = flat glass mirrors.

A chosen polarizer had the poor performances at the wavelengths $\lambda > 800$ nm. Thus light filter passing waves in the range $\lambda = 600\text{-}800$ nm was installed in front of a camera. Additional argument to use such a filter is due to the fact that in this spectral band a contribution of diffused radiation of the sea to registered signal is negligible (Bukin at al., 1999). The distance between mirrors is chosen minimal in order to minimize a parallax influence on the measurements.

Floats were placed on the 7 fixed vertical lines: in the center and corners of two horizontal hexagons as shown in Fig. 3. The floats can move along the lines in vertical direction only. Such construction of system of floats has been developed for determination of the sea surface level variations from their images taken by a polarization camera.

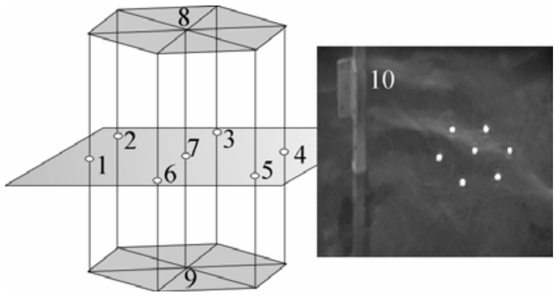

Figure 3. The scheme (a) and an image (b) of the sea surface with floats. 1 ÷ 7 = spherical balls of diameter 1 cm. 8 and 9 = upper and lower hexagons with a side of length 9 cm. 10 = metal rectangular assembly.

The light polyfoam floats always remain on the sea surface due to forces of buoyancy and surface tension.

3. IMAGES PROCESSING

During measurements three images with different polarizations are recorded on CCD matrix. The following procedures were used to retrieve information on wave height and on a shape of the sea surface. At first, the fields corresponding to each polarization are selected from a registered image and then three images are aligned using the floats as control points. After alignment they are packing in BMP color image, with polarization components *A*, *B* and *C* (see formulas (3)) substitute the RGB components. The following values are computed for all pixels of the obtained false-color RGB image:

- mean values of luminosity; viewing angle α, reflecting angle φ, angle β, slopes projections ξ_x, and ξ_y.

Float's coordinates (*X, Y* and *Z*) are determined from float's image coordinates.

Analyses of mean value of float's height enable to find mean level for series. These calculations base on known laws of spatial geometry.
At last the computed geometric characteristics of the recorded sea surface are transformed into plane image.

4. RESULTS

Field measurements were conducted at the POI marine experimental station in May 2003. The polarization camera was installed at a height of 3 m above the sea surface. The viewing angle of camera was 62 degrees. A polarizer was mounted as described above. The images of the sea surface were recorded with frequency 50 Hz. Time sets consisted usually of 10000-60000 images.
Below the results of processing of optical measurements carried out on 6 May 2003 are presented. During experiments weather conditions were characterized by continuous cloudiness and wind speed did not exceed 2 m/s. At continuous cloudiness skylight is not polarized that is key importance for accurate optical measurements in particular for validation of suggested technique of the sea wave slope measurements. Dimension sea surface region, viewing of polarization camera is 100 x 220cm. The region of sizes 400 by 600 mm was exposed to analyses.
Image coordinates of the float centers were derived by application of subpixel technology (Forsyth, 2004). The error of float height estimate was about 0.2 cm. The wave slopes were found through measurements as slopes of triangles formed by the float centers. Histograms of sea surface heights and slopes derived by this way shown in Fig.4.

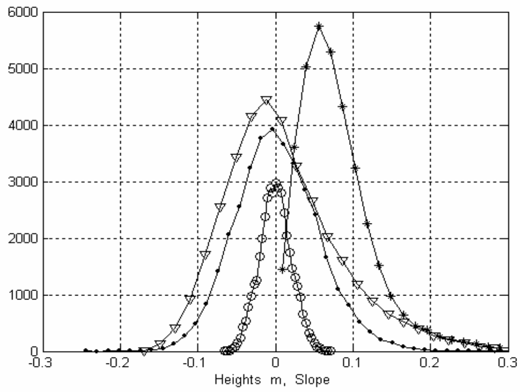

Figure. 4. Histograms of sea surface heights (circles) taken for 7 floats and wave slopes along x (ξ_x, triangle) and y (ξ_y, crosses) axes and the overall (ξ, dots). Height is given in meter and slopes are given in radian. Sample size is 6000.

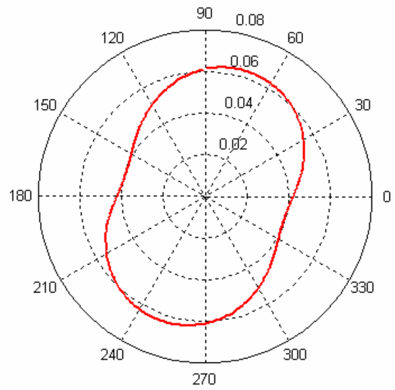

Figure. 5. Angle distribution of sea wave slopes ξ.

Polar diagram of slopes is shown in Fig.5. Relationship between maximum intensity of slopes ξ projections and its minimum is 1/0.67 are corresponding to field of gravity-capillary wave. (Liu, 2000). Mean slope for this conditions is 0.06.

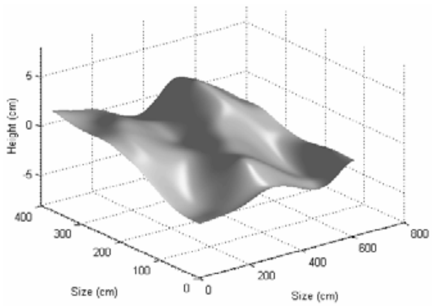

Figure. 5. Shape of the sea surface found from Stokes parameters of three polarization images

Shape of the sea surface (Fig.6) obtained by integration slope projections from Stokes parameters. Heights of sea surface by slope integration to get impossible because constant of integration unknown. However differences of its heights should be defined correctly. Validation of polarization camera carried out by method of comparison floats heights. Difference of their heights was been considered (Fig.6).

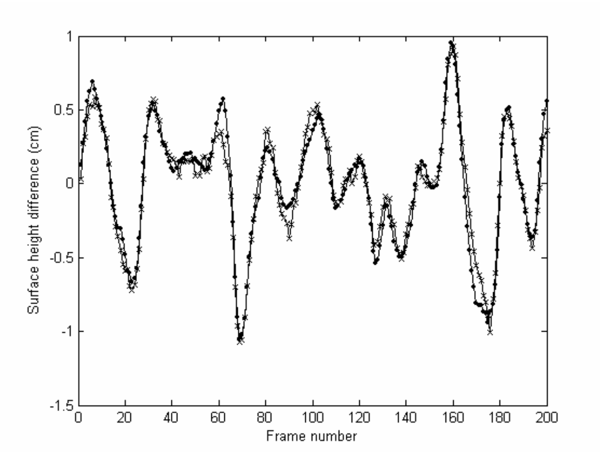

Figure. 6. Surface heights retrieved from two neighboring floats as a function of frame number. Dots = difference – heights floats 2 and 3, star = difference heights of reconstructed surface (Fig.5) in the same points

Reliability of the developed techniques was estimated by a comparison of the differences of floats height found (a) by analysis of displacements of floats (floating heights) and (b) from shape of the sea surface retrieved from polarization images (polarization heights) (Fig. 6). For all horizontally (on image) neighboring floats the coefficient of correlation between floating heights and polarization heights amount not less 0.97. For all vertically neighboring floats the coefficient of correlation between floating heights and polarization heights amount not less 0.84. That distinction related to the accuracy of definition angles β and φ. Angle β can be calculated with more accuracy because of low dependence its from optical characteristics of sea water and light condition.

The preliminary analysis of measurement result has shown that:

In continuous cloudiness condition when relatively skylight is high and it is depolarized the measuring of sea slopes by polarization camera may be enough correctly.

The angle β are measured to a closer approximation, than,
an angle of reflection φ.

Floats are very useful at carrying out of field measuring and can be control for development of optical methods of slopes measuring.

Floats represent and the self-dependent tool, for measuring of sea wave's characteristics with high accuracy. It is possible to work and at dark time if to light up its.

Gained from a surface recovered on polarization measuring and it is immediate from a spatial standing of floats. The difference between (polarization heights) and floating heights) is very insignificant. That demonstrates correctness of the chosen approach. Application of methods of machine sight (Zhang, 1997) in our opinion will allow to raise precision surfaces reconstruction. Analyses of image sequence enable to find many temporal and spatial characteristics of sea surface, which no discussed in this paper.

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