Remote Sensing of Environment 217 (2018) 61–71

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Wave spectrum retrieval from airborne sunglitter images

Maria Yurovskaya[a,b,*], Nicolas Rascle[c,d], Vladimir Kudryavtsev[a,b], Bertrand Chapron[b,d], Louis Marié[d], Jeroen Molemaker[d]

[a] Marine Hydrophysical Institute of RAS, Sevastopol, Russia
[b] Satellite Oceanography Laboratory, Russian State Hydrometeorological University, Saint Petersburg, Russia
[c] Division de Oceanologia, Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California, Mexico
[d] Institut Français de Recherche pour l'Exploitation de la Mer, Plouzané, France

ARTICLE INFO

Keywords:
Sunglitter
Sea surface waves
Directional wave spectrum
Aerial photography
Field measurements
Remote sensing observations
High resolution
Drone

ABSTRACT

Reconstruction and evolution of two-dimensional spectra of surface waves in the Gulf of Mexico are derived from airborne sun-glitter imagery. As the proposed method is based on a linear transfer function deduced from the shape of the sunglitter brightness, the absolute wavenumber elevation spectrum does not require any additional assumption or information about sky brightness, wind or wave energy. The detailed description of the airborne image processing method is given. As demonstrated, retrieved spectra agree well with nearby NDBC buoy data, both for spectrum shape, level and energy angular distribution. The 180-degree wave direction ambiguity, inherent to image-derived spectra, is eliminated by using cross-correlation analysis between two consecutive images. A case study corresponding to the spectral evolution with increasing distance from shore in slanting-fetch conditions is then considered. Energy level and peak position transformation are consistent with established approximations and laws of wind-sea development. The technical requirements (flight altitude, image resolution, view angles, etc) and applicability of the suggested methodology are also discussed. These results demonstrate the potential efficiency of high resolution sea state monitoring from drones or light aircrafts using sunglitter imagery.

1. Introduction

For a wide range of applications, such as coastal management, the design and operational safety of harbours, ships, and offshore structures, a precise knowledge of the directional spectrum of ocean waves is needed. The directional wave spectrum describes the distributed energy contributions from waves propagating in different directions with different wavelengths. It is key to help determine the consequences of interactions between waves and other structures, i.e. breakwaters and offshore structures, but also to evaluate wave-induced upper ocean transport and erosion processes.

Significant advances have thus been made to estimate these directional wave statistical properties. Today, a large number of measuring devices, working on different principles, are available (e.g. Herbers et al., 2012). Yet, the directional and frequency response of these systems may often be limited and not sufficient to fully resolve directional surface wave spectra. Further, requirements for near-simultaneous, high spatial resolution observations, to provide more direct directional wavenumber measurements of the local surface field over entire regions, has attracted the attention on remote sensing technologies. To complement sparse in-situ buoy measurements, techniques can include sea level radars (coastal HF radars, Barrick and Lipa, 1985), microwave and marine X-band radars (Senet et al., 2008; Nieto et al., 2004), scanning altimeter and lidar high-resolution topography instruments from airplane platforms (Walsh et al., 1998; Melville et al., 2016), and also synthetic aperture or rotating real-aperture airborne radar instruments (Caudal et al., 2014). As well, photographs of the ocean surface have long been proved to contain quantitative information about ocean surface slope statistics (e.g. Barber, 1949; Cox and Munk, 1956), to help infer directional spectra of surface waves (Stilwell, 1969; Stilwell and Pilon, 1974). Today, with the significant cost reduction and improvement of both instruments and drones, the photograph techniques may become more widely used to observe and monitor surface waves at regional or coastal scales.

Since almost two centuries (Spooner, 1822), it has been understood that the shape of the sunglint on the sea surface contains information on the statistical properties of wave slopes. Airborne and satellite sunglint images at medium (~1 km) resolution have then been used to precisely estimate sea surface slope statistical properties (Cox and Munk, 1956; Breon and Henriot, 2006), and modulations by various dynamical

* Corresponding author at: Federal State Budget Scientific Institution "Marine Hydrophysical Institute of RAS", Sevastopol, Russia.
E-mail address: mvkosnik@gmail.com (M. Yurovskaya).

https://doi.org/10.1016/j.rse.2018.07.026
Received 27 February 2018; Received in revised form 6 July 2018; Accepted 26 July 2018

ocean processes like currents and fronts, internal waves, or surface slicks (Barber, 1954; Apel et al., 1975; Hennings et al., 1994; Kudryavtsev et al., 2012; Kudryavtsev et al., 2012; Rascle et al., 2016, 2017). At higher (~1–10 m) resolution, glitter modulations are more directly connected to the wavy surface. Indeed, wave contrasts on the image result from the modulation of sun reflected radiation by individual tilting wave slopes, and those can be used to estimate the wave directional elevation spectrum (Stilwell and Pilon, 1974; Monaldo and Kasevich, 1981).

To derive wave elevations from these brightness variations, a transfer function must thus be determined. Using airborne photographs, this task is eased, as the overall sunglitter shape can be captured, to help directly infer a linear transfer function (Bolshakov et al., 1988). Recently, Yurovskaya et al. (2018) demonstrated the technical implementation to retrieve wind wave spectrum from sunglitter photographs taken from a drone. Adapted to a satellite configuration, such a method was also successfully applied (Kudryavtsev et al., 2017a,b) to reconstruct the spectrum of long (energy containing) waves from satellite sunglitter images, taking advantage of the high resolution and specific viewing geometry of the radiometers on-board the satellite Sentinel-2.

In this paper, we further dwell on this capability of airborne sunglitter imagery to capture the overall glitter pattern. As mentioned above, this property provides direct means to determine a linear transfer function. Our motivation is then to further assess how robust is our proposed methodology to efficiently provide quantitative estimates of the directional wave spectrum, including energy containing waves and also short waves. The development is specific to airborne measurements and applied to data collected over a coastal area in the northern Gulf of Mexico.

The paper structure is as follows. The experiment is described in Section 2; theory and spectrum reconstruction algorithm are presented in Section 3; method implementation and validation are given in Section 4; the results of the study of wave development and transformation with fetch are presented in Section 5, and finally, the discussion of method applicability and some recommendations on experimental setup are suggested in Section 6.

2. Experiment and data

The airborne sunglitter images were obtained on Jan. and Feb. 2016 during the Lagrangian Submesoscale Experiment (LASER), where a large number (~1000) of surface drifters were deployed to study surface dispersion within the Gulf of Mexico (D'Asaro et al., 2018; Rascle et al., 2017), close to the site of the Deep Horizon oil platform accident in 2010 (Fig. 1a). The images were acquired from airplane (a Partenavia P.68) flying at altitudes up to 3000 m.

The visible light intensity was measured by two panchromatic cameras (JAI BM-500GE) equipped with a 5 mm focal length low distortion lens to ensure a large field of view. The cameras setup is sketched in Fig. 1b. To capture the sunglint, the two cameras were arranged symmetrically about the airplane nadir with a pitch of ± 35° for the forward/aftward cameras. The camera aperture angles are 80°× 70° along-track and across-track, respectively, with 2456 × 2058 pixels in the respective directions. For a flight altitude of 1000 m, this leads to a ground resolution from 0.5 m to 6 m. The cameras acquired images at 2 Hz. The images were geolocated using an internal motion unit Applanix POS AV V610.

We selected cases corresponding to measurements made during flights with trajectories close to National Data Buoy Center (NDBC) buoy locations, to benefit from synchronous wind and wave ancillary data. A step by step algorithm is provided for images obtained close to NDBC 42012 in developed wind-sea conditions on 11-Feb-2016 (green star on Fig. 1a). Further we analyze the wave evolution on 23-Jan-2016, when sunglitter images were acquired (in cloudless regions) at different distances from the shore along the plane tracks shown in Fig. 1a.

3. Theoretical background

Based on the classical model of the sea surface brightness formation in the visible range (Cox and Munk, 1956), the intensity in each pixel of sunglitter image is proportional to the sun reflected radiance, or the energy brightness of the surface (the spectral energy flux per unit area per unit solid angle):

$$N = \frac{\rho E_s}{4\cos\theta\cos^4\beta} P(Z_1, Z_2), \tag{1}$$

where P is the probability density of two slope components, Z_1, Z_2, satisfying the conditions of specular reflection:

$$Z_1 = -\frac{\sin\theta_s\cos\phi_s + \sin\theta\cos\phi_\nu}{\cos\theta_s + \cos\theta}$$
$$Z_2 = -\frac{\sin\theta_s\sin\phi_s + \sin\theta\sin\phi_\nu}{\cos\theta_s + \cos\theta}, \tag{2}$$

θ and θ_s are zenith angles for the camera and the sun, respectively, ϕ_ν and ϕ_s are corresponding azimuth angles, ρ is the Fresnel reflection coefficient, E_s is the solar radiance, $\tan\beta = \sqrt{Z_1^2 + Z_2^2}$.

Local modulations of $B = N\cos\theta/\rho$, or equivalently, of P, can arise for two reasons: variations of the slope statistics mostly governed by changes of mean square slope (MSS) due to different upper ocean processes (fronts, internal waves, surface slicks, etc), or the tilting of the ocean surface while a long wave is propagating. The latter can also lead to a short wave (and thus, MSS) modulation along the wave profile. As demonstrated by Bolshakov et al. (1988) and Kudryavtsev et al. (2017a), one can ignore these MSS modulations in the vicinity of brightness contrast inversion zone, i.e. $0.5 < Z_n^2/s^2 < 2$, where $Z_n^2 = Z_1^2 + Z_2^2$, and s^2 is the surface MSS to the first order estimated from the assumption of Gaussian brightness and slope distribution as $s^2 = -2\overline{Z_n}\cdot\overline{B}/(\partial B/\partial Z_n)$. The brightness variation due to the long wave propagation then writes

$$\widetilde{B} = B(Z_1 + \zeta_1, Z_2 + \zeta_2) - B(Z_1, Z_2) = \frac{\partial B}{\partial Z_i}\zeta_i \equiv G_{zi}\zeta_i, \tag{3}$$

where $\zeta_{1,2}$ are the components of tilting wave slope. G_{zi} is the transfer function, relating brightness and slope variations. This transfer function is then determined as the brightness gradient in specular slope space and can be obtained through the observed brightness gradients:

$$G_{z1} = (G_2 Z_{2,1} - G_1 Z_{2,2})/\Delta$$
$$G_{z2} = (G_1 Z_{1,2} - G_2 Z_{1,1})/\Delta, \tag{4}$$

where $G_i = \partial B/\partial x_i$, $Z_{i,j} = \partial Z_i/\partial x_j$, $\Delta = Z_{1,2}Z_{2,1} - Z_{1,1}Z_{2,2}$.

Eq. (1) relates the mean brightness to surface slope statistics, as in the work of Cox and Munk (1954). On the contrary, Eqs. (3) and (4) relate local brightness variations to local slope variations. In the Fourier space the surface slope ζ_j and the surface elevation ξ are linked by$\hat{\zeta}_j = ik_j\hat{\xi}$, where i stands for imaginary unit. Thus, Eq. (3) in the Fourier space reads: $\hat{\widetilde{B}} = ik_jG_{zj}\hat{\xi}$, and the relationship between the surface elevations and brightness spectra writes

$$S_\xi(\mathbf{k}) = S_B(\mathbf{k})/(G_{zi}k_i)^2. \tag{5}$$

The linear combination of wave vector components in the denominator of Eq. (5) vanishes in a direction perpendicular to the gradient direction. Close to this direction, the spectrum cannot be simply retrieved. For Sentinel-2 multi-spectral satellite imagery, recently reported by Kudryavtsev et al. (2017a,b), this limitation was mitigated by interpolating the spectrum in a narrow wavenumber sector encompassing the singularity. A clear advantage of airborne photography (compared with satellite scanners) is that it captures the two-dimensional field of view of the sunglitter brightness. Therefore, relation like Eq. (5) can be obtained in different parts of the sunglitter, corresponding to directions for which the brightness gradients are different. As suggested by Bolshakov et al. (1988) and also Lupyan (1988), the