RETRIEVAL OF HIGHER ORDER OCEAN WAVE SPECTRA FROM SUNGLINT

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1. INTRODUCTION

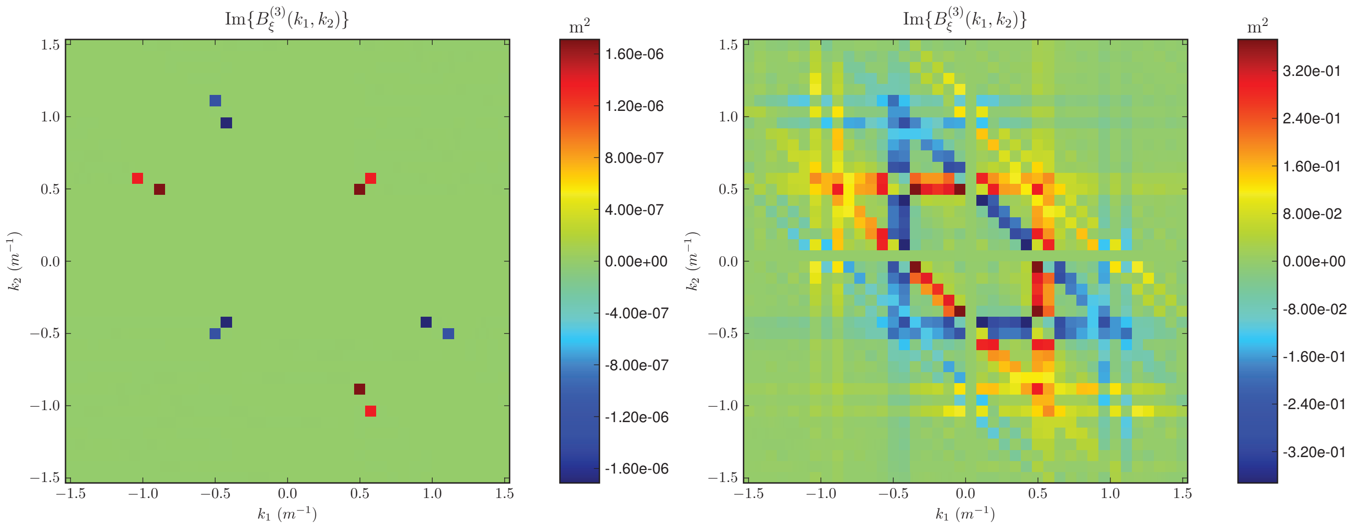
The description and measurement of wind-generated ocean waves is essential for a diverse range of human activities, including the design and operation of ships, the construction and servicing of marine structures such as offshore oil and gas drilling platforms, the management of coastal environments, and, increasingly, for the design and deployment of wave energy extraction systems. Perhaps even more importantly, the fluxes of mass, momentum, sensible heat, kinetic energy, and individual chemical species across the air-sea interface are fundamentally related to ocean wave structure and dynamics. An understanding of these processes provides the physical basis for models of the large-scale mechanisms that drive weather and climate, and, with rapidly-growing concern about the prospects for climate change, the importance of acquiring, analyzing and interpreting ocean wave data, which may serve as a key indicator of global changes, is apparent.

The geometry and temporal evolution of the ocean surface are strongly influenced by physical processes which are nonlinear, such as wave breaking, formation of spray and foam generation, molecular viscosity and eddy viscosity due to microscale turbulence, ponderomotive response to fluctuating air pressure and variable bathymetry, and so on. These phenomena are often ignored, in a simplified mathematical model, by assuming that the fluid is incompressible and inviscid, the flow irrotational, the surface single-valued and the space above the fluid occupied by a vacuum. With these simplifications it might be thought that the problem would reduce to one which is linear and hence analytically tractable, but that is not the case. There is an essential nonlinearity arising from the special boundary conditions that constrain the kinematics and dynamics of the free surface.

Satellite-based remote sensing techniques have vastly extended our ability to accumulate datasets of some relevant wave parameters over vast swathes of ocean, employing various active or passive sensor systems. One such technique involves the air- or space-borne remote sensing of sunglint, which is the observed image of the solar disc perceived via specular reflection from the sea surface. It is a familiar phenomenon, best known for its nuisance value, especially to the users of satellite imagery of ocean colour and sea surface radiometric properties. The solar disc provides an informative probing signal, which elicits a highly structured response when reflected from the ocean surface. It is available much of the day, even in the presence of light cloud, and it can be interrogated over a wide range of spatial and temporal scales.

It is significant that the most celebrated experimental characterization of ocean slope distributions was carried out using sunglint [1], where the solar specular point on the ocean surface was photographed from an airborne platform under a variety of conditions. Due to the geometry of the problem, wave facets in different parts of the image need to have different slopes $\xi(x)$ in order to satisfy the specular condition and return a glint to the camera. If one interprets the density of glints as being proportional to the probability of a certain slope, then a glint image is a graphical indication of the relative probabilities of the different slopes.

More recently, a model has been developed to retrieve wavenumber spectra from images of sunglint, by determining an invertible relationship between the slope and glint autocorrelations [2] . This technique is highly appealing for its simplicity



(a) simulated (b) retrieved

Fig. 1. The (a) simulated and (b) retrieved imaginary components of the slope bispectrum $B_\xi^{(3)}(k_1, k_2)$, where there is quadratic phase coupling between wave components.

and ease of implementation. However, this method as implemented relies on the relationship between second order statistical functions of the wave slope and sunglint data, and assumes normally distributed slopes. As a result the model is insensitive to characteristics of the wave surface that would arise from a consideration of higher order terms in the hydrodynamic equations of the wave surface, such as phase coupling between wave components, wave tilting and energy transfer between wave modes.

The work reported in this paper extends the linear technique to account for nonlinear hydrodynamic effects, and shows how additional information about the sea surface geometry and dynamics can be extracted. This is achieved by formulating, and then inverting, a relationship between the wave slope and sunglint triple correlation functions. This relationship was developed primarily though the derivation of a suitable model of the nonlinear slope probability density [3], allowing a convenient parameterization of the surface slopes for use in the slope-to-sunglint forward model.

The Fourier transform of the retrieved slope triple correlation is the slope bispectrum $B_\xi^{(3)}(k_1, k_2)$, which is also known as the triple product of the slope Fourier spectrum $F(k)$ at wavenumbers defined by the wavenumber triad $[k_1, k_2, k_1 + k_2]$, i.e.:

$$B_\xi^{(3)}(k_1, k_2) = E[F(k_1)F(k_2)F^*(k_1 + k_2)]\,,$$

where the asterisk denotes complex conjugation. The bispectrum is nonzero only when the phases of the wave components in the triad satisfy the relation $\phi(k_1 + k_2) = \phi(k_1) + \phi(k_2)$.

Many realisations of the wave elevation were generated, and phase correlations were introduced by adding harmonics for which the peaks of the fundamental and harmonic waves were in phase for the elevation, and in quadrature for the wave slope. This results in nonzero values of the real elevation and imaginary wave slope bispectra respectively. It was found that the nonlinear process of clipping the wave slope to model the sunglint introduces broadband phase correlations which manifest themselves in the real part of the sunglint bispectrum, and the imaginary sunglint bispectrum has a series of small peaks corresponding to the phase correlations in the slope bispectrum. The large real component in the glint bispectrum, introduced by the clipping process, results in a low signal-to-noise ratio for the glint bispectrum component due the the slope phase correlations. As we can see in Figure 1, the retrieval of the the slope bispectrum was correspondingly noisy, but we can clearly identify the contribution to the retrieved slope bispectrum from the slope phase correlations.

2. REFERENCES

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