A NEW TECHNIQUE FOR PHASE-RESOLVING OCEAN WAVE OBSERVATIONS BY SPACEBORNE SPOTLIGHT-MODE SYNTHETIC APERTURE RADAR

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ABSTRACT

The retrieval of quantitative information on ocean waves from SAR images is a challenging problem because of the nonlinearities of the imaging mechanism, the presence of speckle noise, and the directional ambiguities associated with the interpretation of a SAR image as a single snapshot in time. We present a new methodology that overcomes some of these problems by utilizing spotlight-mode data from TerraSAR-X and COSMO-SkyMed in combination with advanced subaperture processing. We are able to derive short time series of subaperture images, which show propagation directions and speeds of moving patterns. Then we can use Fourier analysis and a dispersion relation filter to separate actual ocean wave signatures from other contributions. This process is phase-preserving and lets us reconstruct short "videos" of the spatio-temporal evolution of the extracted wave signatures, which are easier to invert into surface slope and elevation fields than conventional SAR images.

Index Terms—SAR, ocean waves, subaperture processing

1. INTRODUCTION

Traditional wave retrieval techniques for SAR images are based on iterative procedures to invert an image spectrum into the most likely corresponding ocean wave spectrum. This usually requires some kind of first-guess wave spectrum, which is fed into a forward simulator of the SAR imaging mechanism and modified step by step until satisfactory agreement between simulated and observed image spectrum is obtained [1–2]. This inefficient and somewhat ambiguous methodology was developed in response to three major shortcomings of SAR images of wave fields, which are the nonlinearities of the imaging mechanism, the presence of speckle noise, and the fact that a conventional SAR image is just a snapshot that shows neither the propagation direction nor the speed of moving patterns.

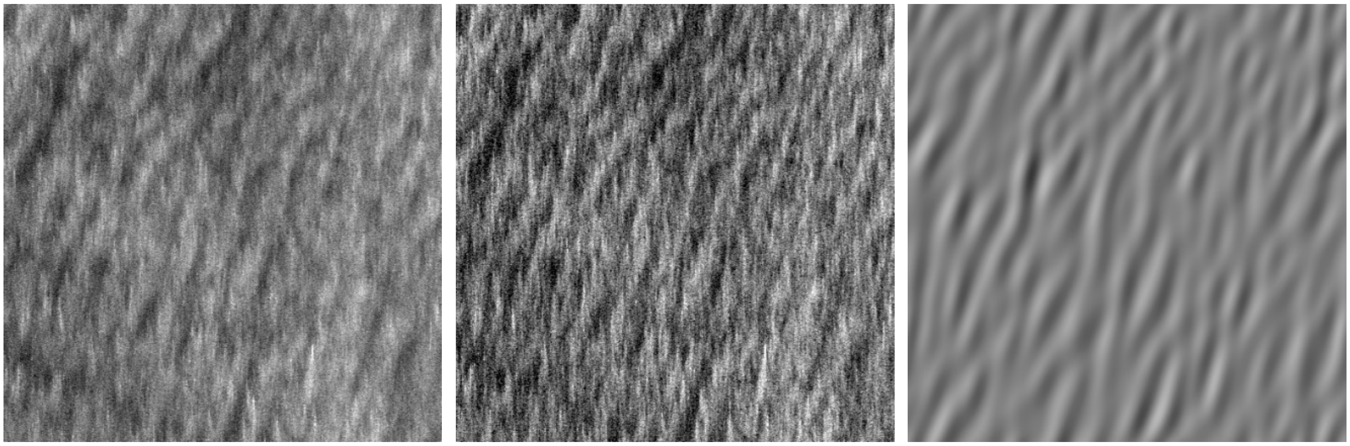
The advanced imaging modes of the latest spaceborne SARs enable us to try new approaches. We will show in the following how an innovative use of spotlight-mode SAR images from TerraSAR-X and COSMO-SkyMed allows us to separate signatures of ocean waves from other contributions before starting their quantitative interpretation. This makes the process easier and less ambiguous than with traditional methods. While parts of the new algorithm are still under development and will be discussed in full detail in a longer journal article, we are ready to present the key ideas and first examples of intermediate results in this conference paper. First complete results (retrieved surface elevation and slope fields and wave spectra) will be shown and discussed in our talk at IGARSS 2018.

We would like to acknowledge in this context that the use of subaperture images for resolving 180° directional ambiguities and reducing noise has been discussed by other authors since the 1990s [3–6]. The main innovations of this work lie in the use of spotlight-mode data and up to 15 subaperture images instead of 2 for a better noise reduction, a dispersion relation filter for identifying ocean wave signatures, nonlinear modulation transfer functions for the inversion, and a phase-resolving processing approach that enables us to reconstruct 2-d surface slope and elevation fields in the spatial domain.

2. SUBAPERTURE REPROCESSING

Spotlight-mode SAR images are generated with a longer integration time than conventional stripmap-mode images. While this improves the spatial resolution over land, the initial effect over the moving ocean surface is a blurring of wave signatures like in a photo taken with a long exposure time. This can make waves less visible in a spotlight- than in a stripmap-mode image. However, if the spotlight-mode image is provided as a complex single-look image, one can apply a Fourier transform to retrieve the azimuth Doppler spectrum of the SAR raw data, which can then be divided into several pieces to generate a series of subaperture images with a short integration time, representing time steps during the SAR overpass. This reduces the blurring and reveals the spatio-temporal evolution of the imaged scene during the original SAR integration time of up to a few seconds. We are able to produce as many as 15 subaperture images with little spectral overlap, i.e. pretty independent speckle noise.

By computing the spatial Fourier transform of a given square subimage of each individual subaperture intensity image and looking at changes of its spectral components from time step to time step, one obtains positive phase changes for half of the Fourier components and negative ones of the same magnitudes for the other half at the corresponding opposite wavenumber vectors. By eliminating the components with negative phase changes and averaging the remaining components over all subaperture image spectra, a one-sided mean spectrum can be obtained, in which the spectral energy is located at the components whose wavenumber vectors point into the correct direction of propagation. Furthermore, the averaging process reduces spectral noise quite effectively, eliminating the need for further spatial averaging over adjacent subimages. This is important for a successful reconstruction of the wave field in the spatial domain, which will be discussed in Section 4.



a b c

Fig. 1: Example of ocean wave signatures in a 1024 m × 1024 m part of a TerraSAR-X Staring Spotlight Mode image: (a) original full-bandwidth image, (b) reduced-bandwidth image from the center subaperture, (c) extracted wave signatures for the center subaperture time step. Gray level range = 20 dB from black to white in each image.

3. DISPERSION SHELL FILTERING

In the next step, we use a dispersion shell filter to reduce the image spectrum to components that are consistent with the motion characteristics of ocean waves, i.e. the theoretical dispersion relation between wavenumber and frequency. This technique is well known from the marine radar community, where time series of images from a rotating antenna are easily converted into three-dimensional frequency-wavenumber spectra [7–8]. Our time series of SAR subaperture images are too short to do this directly, but we can convert the phase changes between the two-dimensional Fourier transforms of consecutive subaperture images, as computed in the previous step, into wave frequencies. These can then be compared to the known dispersion relation of ocean surface waves, and spectral components outside a reasonable uncertainty interval around this theoretical dispersion shell can be eliminated. We obtain a filtered version of the image spectrum that highlights contributions of actual ocean wave signatures and suppresses contributions that are too slow or too fast to be related to ocean waves.

One problem in the application of a dispersion shell filter is the potential elimination of higher harmonics of ocean wave signatures, which may show up at multiples of their fundamental wavenumbers and frequencies, outside the regular dispersion shell. The higher harmonics of ocean wave signatures in a SAR image can be quite significant because of the nonlinearities of the imaging mechanism. Since the nonlinearities are taken into account in the inversion of the SAR signatures into surface slope and surface elevation fields and wave spectra, an exclusion of the higher harmonics from the analysis can lead to incorrect results. This leads us to another break with tradition: We apply the Fourier analysis to logarithmically scaled intensity images (dB images) instead of linear ones. Ocean wave signatures look clearly more sinusoidal in dB images than in linear intensity images, significantly reducing the energy of higher harmonics in the image spectrum.

4. WAVE FIELD RECONSTRUCTION

Since our processing of image spectra does not involve any spatial averaging, we can use the original phases of the Fourier transform of the center subaperture image and a slightly smoothed version of the dispersion shell filtered mean amplitudes to reconstruct the ocean wave signatures in the center subaperture image in the spatial domain. As an example, Fig. 1 shows a 1024 m × 1024 m subimage of a TerraSAR-X Staring Spotlight Mode image at three processing stages, i.e. the original full-bandwidth image, the reduced-bandwidth center subaperture image with clearly enhanced wave signatures due to reduced blurring, and the extracted wave signatures. The known wave frequencies according to the dispersion relation enable us to reconstruct the complete time series of wave signatures in all subaperture images with correct phasing, as well as an extrapolation into the past and future to watch the theoretical evolution of these wave signatures over a longer period of time.

The next step after this is the inversion of the filtered SAR signatures into actual surface slope and surface elevation fields and the corresponding wave spectra. It will be more straightforward than the traditional inversion of SAR image spectra because our filtered wave signatures are very clean and their propagation directions and speeds are known from the beginning. Due to the fact that the proposed technique enables us to see the spatio-temporal evolution of the wave field over some period of time with correct phasing, we will also be able to analyze refraction patterns and to find optimized dispersion shells for individual subimages that account for local water depths and surface currents and let us extract 2d bathymetry maps and surface current fields as higher-level products.

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