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NEARSHORE BATHYMETRY AND SURFACE CURRENT RETRIEVAL FROM MOVING WAVE PATTERNS OBSERVED BY SPACEBORNE RADAR

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As reported previously [1], we have developed an innovative technique for ocean wave observations from space: A dedicated reprocessing of spotlight-mode synthetic aperture radar (SAR) data enables us to produce a video-like series of images covering a total time of a few seconds, in which moving wave patterns become visible. In most cases, the duration and quality of the image series is sufficient for computing a wavenumber-frequency spectrum and applying a dispersion relation filter to separate signatures of actual ocean waves from contributions of other physical phenomena and noise. Then the extracted wave signatures can be inverted into surface slope and displacement fields and / or spectra by applying a relatively simple linear modulation transfer function. Altogether this process is much more straightforward than traditional wave retrieval techniques for SAR, and we think it produces more accurate results for a broader range of conditions. This poster presentation focuses on the capability of the proposed wave retrieval algorithm to provide coastal water depth and surface current estimates as byproducts of the spectral filtering.

Water Depth and Surface Current Retrieval

Spectral filtering on the basis of the theoretical dispersion relation of ocean waves is a well-established technique in the marine radar community, where image sequences are obtained from a rotating antenna on a ship or stationary platform. Since the theoretical frequency-wavenumber relation depends on the water depth and on Doppler shifts due to surface currents, these parameters need to be estimated or fitted to the data to maximize the overlap between observed and theoretical spectral energy distributions in the frequency-wavenumber domain before applying the spectral filter. As a result of this process, depth and current estimates are obtained together with the retrieved wave spectra, as demonstrated, for example, in [7],[8]. The same is true for our SAR-based wave algorithm, but with some interesting differences.

The ocean wave signature extraction described in the orange box on the right can be extended to a complete image by performing the Fourier analysis and spectral filtering for overlapping $(1024\ m)^2$ subimage tiles on a 512 m × 512 m grid. To minimize artifacts and to obtain seamless transitions between tiles when returning to the space-time domain, a $\sin^2$-shaped tapering function is applied to the image intensity variations in each tile. After completing the spectral analysis, we can use the phases of each original subimage spectrum to transform the filtered amplitudes back to the space-time domain with correct phasing, such that a coherent picture of the extracted moving wave signatures in the entire image becomes visible.

Figure 3 below illustrates how we get from an original SAR image to extracted wave signatures and water depths (to see the series of extracted subaperture images and moving wave patterns in motion, please scan the QR codes). The example case is a TerraSAR-X Sliding Spotlight Mode image of the area around Rottnest Island, Australia, acquired in October 2009. The same image has been used before by Andrey Pleskachevsky and coworkers for wave and water depth retrievals with a more conventional technique [9], so we can compare our results with theirs.

Our subaperture reprocessing and spectral filtering techniques are described in the green and orange boxes on the right. The two diagrams below show the distribution of wave period - wave length combinations in the subimage spectra from all tiles before and after the application of the dispersion relation filter. One can see that most of the spectral energy in the filtered spectra is in bins consistent with ocean wave motions at depths of about 20-60 m. The right part of the figure shows the spatial distribution of the fitted depths with the extracted wave patterns in the background. The estimated depths are consistent with Pleskachevsky et al.'s results and with the reference bathymetry shown in their paper. An advantage of our method is that it does not require a reference depth or wave period from an external source. Furthermore, we can track multiple wave components independently, so we are not limited to cases with a single dominant spectral peak.

An important difference between the spectra from marine radar and spotlight-mode SAR data is that our series of subaperture images are not long enough to apply a fully-3d Fourier transform in space and time. With our method, we obtain just a mean frequency for each wavenumber component instead of a complete frequency spectrum. This can cause interpretation problems where significant non-ocean-wave contributions occur at the same wavenumbers as ocean wave signatures of interest, reducing the latter's apparent frequencies and increasing their apparent power. While this effect was significant in some of our early test images of relatively short waves, the longer ocean wave patterns in the image discussed here could be separated from noise very well.

This early version of our algorithm is capable of providing wave and depth retrievals for scenes with negligible currents. Where currents are present, Doppler shifts of wave frequencies will occur and will have to be taken into account in the data interpretation. We hope we can exploit this effect for combined wave, depth, and current retrievals and as an alternative or complementary method to SAR-based current retrievals by Doppler centroid analysis [10],[11], along-track interferometry [12],[13], or the estimation of surface current gradients from image intensity variations due to wave-current interaction (e.g. [14]). However, the feasibility of combined depth and current retrievals from the kind of spectra we get from spotlight-mode data is a matter of ongoing research.

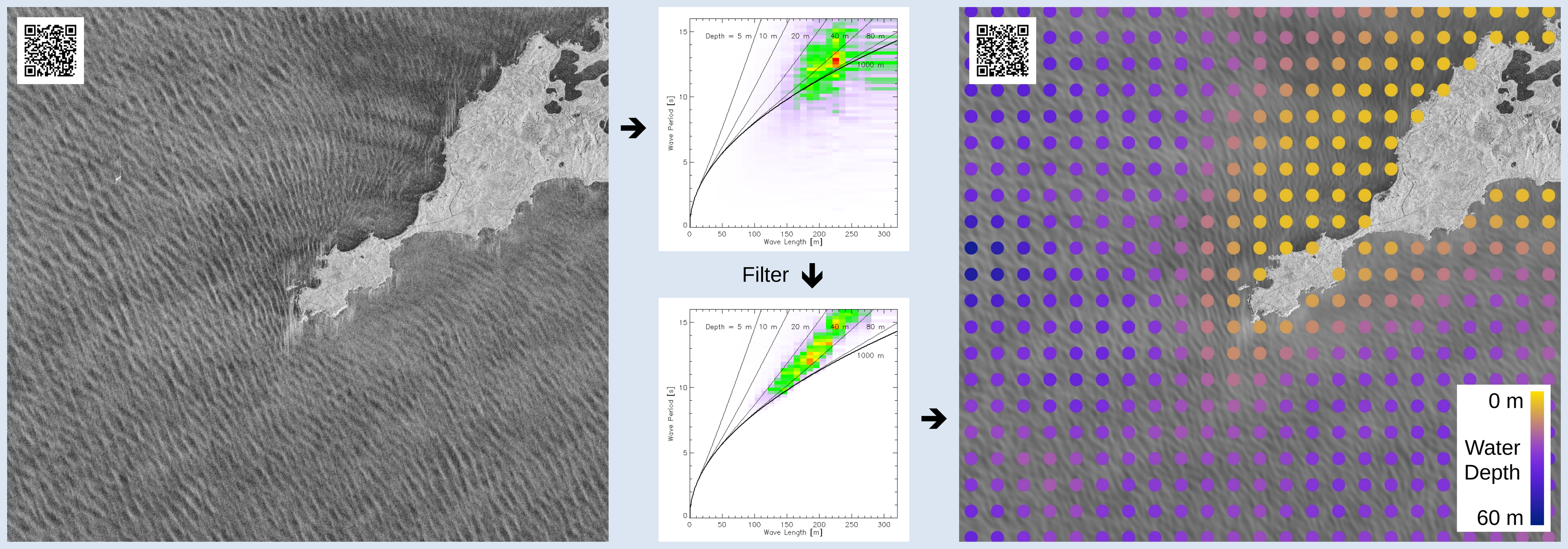


Fig. 3: Example of wave field and bathymetry retrieval from a TerraSAR-X Sliding Spotlight Mode image acquired at Rottnest Island, Australia, on October 20, 2009. Total area size = 11.7 km × 10.4 km, total SAR integration time = 1.22 s, subaperture image sequence duration = 0.79 s. Left: original image. Center: wave period vs. wave length distributions before and after dispersion relation filtering. Right: retrieved ocean wave signatures and retrieved water depths on a 512 m × 512 m grid.

Scan the QR codes to view animated GIFs of the original image sequence (left) and the extracted moving ocean wave signatures (right).

For better visibility of the wave motions, the time step and total duration of the extracted wave pattern animation have been increased by a factor of 10.

How We Take "Wave Videos" by SAR

The X-band SARs on the German TerraSAR-X and the Italian COSMO-SkyMed satellites can be operated in spotlight mode, where the beam is electronically steered to dwell on the same spot for up to several seconds. This is done over land to achieve very high spatial resolutions on the order of decimeters. Over the ocean, the advantages of spotlight-mode SAR are less obvious since wave motions tend to make the initial images look blurry, similar to photos taken with a long exposure time.

This problem can be overcome by reprocessing the data with a shorter effective dwell time (in fact a reduced processing bandwidth in azimuth, a technique also known as subaperture processing). The reprocessed image has a lower pixel resolution but appears better focused, with higher contrast. Since subaperture processing can be done for different parts of the total dwell time interval, it is possible to generate a short video-like image sequence in which motions of wave patterns become visible.

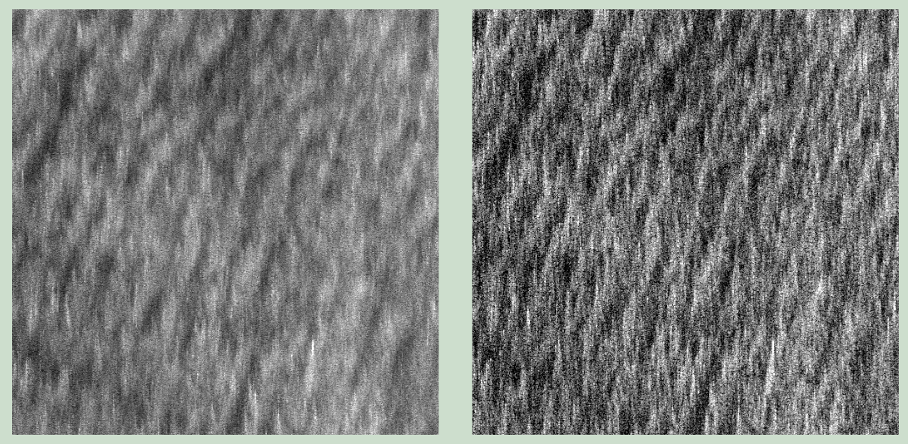
Fig. 1: $(1024\ m)^2$ part of a TerraSAR-X Staring Spotlight Mode image acquired at the coast of California on June 26, 2015, before (left) and after (right) reprocessing.

Scan QR codes to view animated GIFs:

Processing bandwidth reduction in 15 steps

Sequence of 15 subaperture images

Total SAR integration time = 6.72 s, subaperture image sequence = 4.36 s.



Our Ocean Wave Retrieval Technique

It has been known for decades that ocean waves are visible in SAR images. Their surface slopes and orbital motions modulate the incidence angle and surface roughness, thus the radar reflectivity. The sensitivity of SAR to scatterer motions causes an additional modulation effect known as velocity bunching [2]. Different dependencies of these modulation mechanisms on wavelength and direction and the nonlinearity of velocity bunching make the quantitative interpretation of wave patterns in SAR images a challenging problem for which no perfect solution has been found so far. In most cases, a single image does not even reveal the propagation direction of waves without additional information.

Traditional wave retrieval techniques (e.g. [3],[4]) use an iterative approach where a first-guess ocean wave spectrum (e.g. from a numerical wave model) is fed into a SAR simulator to compute a theoretical image spectrum. By comparing the simulated image spectrum to the observed one and tuning the input wave spectrum until best possible agreement is obtained, a most likely solution for the wave spectrum at the time of the SAR overpass is found. This is a complicated, time-consuming, and somewhat ambiguous process, where different solutions may be obtained depending on the first-guess spectrum and the individual iterative optimization algorithm.

Several authors have demonstrated since the early 1990s how cross spectra of subaperture image pairs can be used to resolve the propagation direction ambiguity (e.g. [5],[6]). The long duration of subaperture image sequences from today's spotlight-mode data enables us to take this idea to a new level and derive speeds of moving wave patterns, which can be used to separate signatures of actual ocean waves from other contributions.

Our algorithm decomposes a spotlight-mode image into up to 15 subaperture images with almost uncorrelated speckle noise. By resampling the data onto a 2 m × 2 m grid, computing Fourier transforms for 512 × 512 pixel windows, and averaging spectral power densities and phase differences of the subaperture image spectra in each window, we obtain relatively clean image spectra whose phases are proportional to mean wave frequencies. Then we remove spectral components with negative frequencies as wll as components whose frequency-wavenumber relation is inconsistent with the dispersion relation of ocean waves. With some further noise removal and adjustments of the remaining spectral components to restore the original image contrast, we obtain a clean spectrum of just the ocean wave signatures, which can be transformed back into the space-time domain with correct phasing if desired.

Due to the filtering based on the theoretical dispersion relation of ocean waves, the extracted wave signatures are purely sinusoidal, representing just the linear modulation of the image intensity by the corresponding waves without higher harmonics or other nonlinear contributions. This permits a much more direct inversion into surface slope and wave-height spectra than with the traditional approaches, usually by simply applying a linear modulation transfer function. A detailed journal article on the new wave retrieval algorithm with example results and a quantitative validation is in preparation.

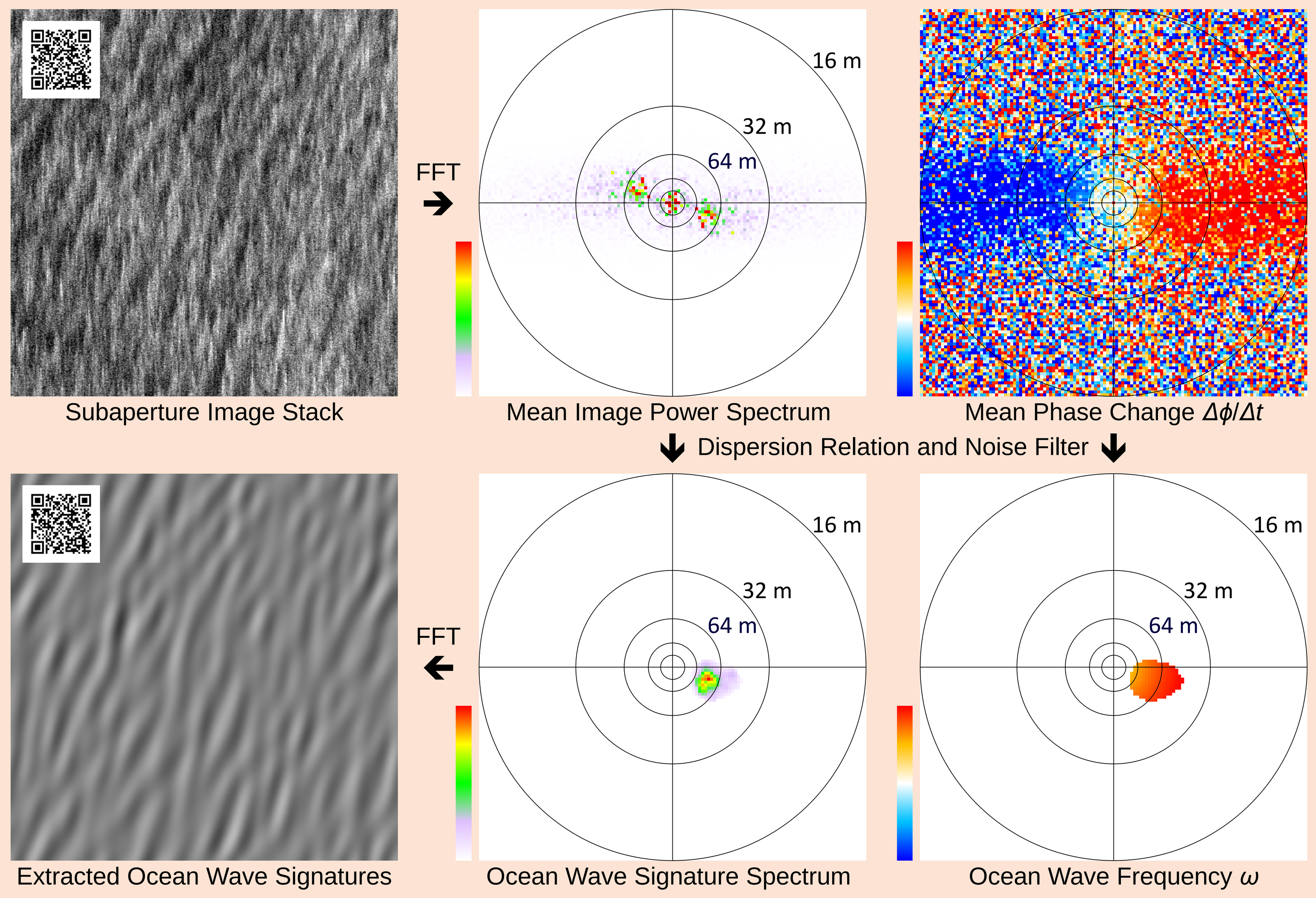


Fig. 2: Example of ocean wave signature extraction from the $(1024\ m)^2$ subaperture image sequence of Fig. 1.

Scan QR codes to view animated GIFs of original image sequence and extracted moving wave patterns.

References and Copyright Notice

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