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Cross-Spectral Analysis of SAR Altimetry Waveform Tails

Marcel Kleinherenbrink^{1b}, Frithjof Ehlers^{1b}, Sergi Hernández^{1b}, Frédéric Nougier^{1b}, Ourania Altiparmaki^{1b}, Florian Schlembach, and Bertrand Chapron^{1b}

Abstract—Until recently, intensity modulations in synthetic aperture radar (SAR) altimetry waveform tails have been considered a nuisance for geophysical-parameter retrieval. These modulations are actually predictable and might be exploited using a spectral analysis of the waveform tails. After Altiparmaki et al. (2022), a more elaborated analysis is performed to improve the interpretation of these SAR altimeter spectra. A fast numerical model is developed to explain the modulation mechanisms in focused SAR altimetry waveform tails. Using numerical solutions, standard analytical closed-form solutions, are demonstrated to be invalid to retrieve ocean-wave-spectra retrievals from nadir altimeters. Although not valid, a closed-form derivation provides intuitive insights about the information contained in an SAR altimetry cross-spectrum. Under moderate environmental conditions (significant wave heights (SWHs) of ~ 2 m), a closed-form solution might still be useful to infer swell-wave spectra from swath-altimetry SAR spectra at incident angles of $\sim 4^\circ$. Comparable to side-looking SAR ocean processing, the cross-spectral analysis for nadir signals reduces noise and might remove the 180° ambiguity of the wave direction. Since the synthetic aperture length of nadir altimeters is larger than sidelooking imaging SARs (e.g., Sentinel-1, RadarSat, Gaofen-3), sublook processing can be performed to compute multiple cross-spectra for the same scene. With a slightly changing observation geometry, the cross-spectra reveal slightly different parts of the ocean-wave spectrum. The resulting stack of cross-spectra can thus be used to improve the retrieval of ocean-wave parameters. Retrieved ocean-wave parameters shall then enhance the sampling of the global wave field, but also serve to advance more consistent sea-state-bias corrections.

Index Terms—Cross-spectral analysis, ocean-wave spectra, sentinel-6, synthetic aperture radar (SAR) altimetry, SAR spectra.

I. INTRODUCTION

SATELLITE radar altimetry has already provided observations of sea-surface height (SSH), significant wave height

(SWH), and wind speed (WS) for a continuous period of more than three decades. Traditional low-resolution mode (LRM) is characterized by a large footprint with diameters of 8–30 km, depending on the antenna size, platform altitude, and carrier frequency. The large footprint makes LRM fit for open-ocean observations, but less to for other targets like inland waters, coastal zones, or sea ice. CryoSat-2 with its delay/Doppler altimeter allowed for the first unfocussed synthetic aperture radar (SAR) processing to improve the resolution to ~ 300 m in the along-track direction [1]. Delay/Doppler, or unfocused SAR, processing also enhanced the number of independent observations per kilometer, which improves the estimation of the geophysical parameters (SSH, SWH, and WS). The resolution was further improved to ~ 0.5 m for static, coherent targets by focused SAR processing [2]. Yet, focused SAR data from delay/Doppler altimeters, like CryoSat-2 and Sentinel-3A/B, suffer from strong azimuth ambiguities as a consequence of the closed-burst-mode operation of the onboard instruments [2]. With the launch of the first interleaved (continuously pulsing) SAR altimeter satellite, Sentinel-6 Michael Freilich, focused SAR processing can now be fully exploited [3].

The resulting enhanced resolution makes altimeter measurements sensitive to long-wave modulations of backscatter (Fig. 1) [4], [5], [6]. The long-wave modulations, induced by swell, alter the waveform shapes and reduce the accuracy of the estimated geophysical parameters. Often long-wave modulations are regarded as a nuisance, but recent studies have shown that the modulations may be exploited to retrieve swell-wave parameters [5]. Altiparmaki et al. [7] first attempted to interpret the backscatter modulations using a spectral analysis. The spectral analysis was performed on a part of the waveform, after the leading edge, corresponding to cross-track locations between ~ 4 and 7 km on both sides of the track because the projected cross-track resolution nearer to nadir was too low. Altiparmaki et al. [7] concluded that two mechanisms were mainly responsible for the modulations in the radargram: 1) velocity bunching (VB), which is the clustering of backscatter near the crest or troughs of the swell wave as a consequence of lines-of-sight motion on the long-wave slopes and 2) range bunching (RB), which is the clustering of backscatter on the satellite-facing swell-wave slope as a consequence of foreshortening. RB, however, is highly nonlinear for altimeters as wave slopes are often equal or larger than the close-nadir incident angle, resulting in overlay (i.e., the signal of the crest is received earlier than that of a trough at shorter cross-track distance). The latter was not captured in the model introduced by [7]. They also noted that the SAR altimetry spectrum exhibited four ambiguities:

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two resulting from a spectral analysis on a real signal as also present in side-looking SARs, and an additional two from the simultaneous illumination of the surface on both sides of the ground track. Between two of the four ambiguities, a discrepancy in spectral density was observed, which remains to be interpreted.

This motivates the present study, to extend the work of [7] to provide a more consistent and elaborate interpretation of SAR altimetry modulations. A numerical solution (Section II) is compared to a tailored closed-form model [8], [9] (Section III) and to discuss its properties and validity for nadir SAR altimetry (Section III-B2). We extend the analysis to swath altimetry (Section III-B3) as the European Space Agency (ESA) intends to launch two interferometric altimeters covering two swaths (~ 10 – 50 km) on both sides of the ground track that will allow for ocean-wave-spectra inversion. Then, the numerical model is expanded to include nonzero-Doppler (forward and backward looking) geometries, and the principles of sublook and cross-spectral analysis [10] for nadir altimetry (Section IV). The long aperture length (~ 2 s) of nadir altimeters indeed enables to compute a “stack” of cross-spectra, to provide means to improve ocean-wave-spectra retrievals. For validation, the forward model is compared to Sentinel-6 cross-spectral stacks for a few scenarios (Section IV-C). Note that the models used in this article support the description of the SAR altimetry modulation mechanisms, but would require further adjustments (e.g., curved Earth, instrument and platform properties, multilooking, and potentially nonlinear waves [11]) used for accurate ocean-wave-spectra inversions.

II. NUMERICAL MODEL

We first describe a numerical model to compute an SAR altimetry spectrum in a zero-Doppler configuration. A flat Earth and a straight, parallel orbit are assumed. The integration time is assumed to be sufficiently short to neglect backscatter changes during the integration time. A right-handed reference system will be used with the x -, y -, and z -axis pointing cross-track, along-track, and up, respectively, with the origin at the satellite nadir location.

A. Scene Generation

A typical wavy scene is generated from the spectral domain on an (N_x, N_y) regular grid. It consists of the superposition of a Gaussian swell-wave spectrum and a wind-wave spectrum based on [12], such that

$$S(k_x, k_y) = S_{\text{swell}}(k_x, k_y) + S_{\text{wind}}(k_x, k_y) \quad (1)$$

normalized as

$$\text{SWH} = 4 \sqrt{\int \int S(k_x, k_y) dk_y dk_x}. \quad (2)$$

The maximum wavenumbers (k_x, k_y) correspond to wavelengths of about 5 m to ensure most of the velocity variance is captured. Alternatively, buoy or wave-model spectra can also be considered for model verification with Sentinel-6 data. The unresolved wind waves are in that case also modeled with the

Elfouhaily spectrum. From the wave spectrum, the elevation h is computed as

$$h = \mathcal{F}^{-1} \left\{ \sqrt{0.5 S(k_x, k_y) \Delta k_x \Delta k_y N_x^2 N_y^2} \cdot \exp(i2\pi X) + c.c. \right\} \quad (3)$$

where $\mathcal{F}^{-1}$ denotes the inverse discrete Fourier transform (DFT), X is a uniformly distributed random variable to introduce random phase offsets, $\Delta k_x, \Delta k_y$ is the 2-D spectral resolution, and $c.c.$ denotes the complex conjugate. Using the deep-water dispersion relation for the pulsation $\omega = \sqrt{gk}$ of long waves and $k = (k_x^2 + k_y^2)^{1/2}$, we compute the vertical velocity field as

$$v = \mathcal{F}^{-1} \left\{ -i\omega \sqrt{0.5 S(k_x, k_y) dk_x dk_y N_x^2 N_y^2} \cdot \exp(i2\pi X) + c.c. \right\}. \quad (4)$$

Finally, the surface slope in the cross-track direction, is given by

$$s_x = \mathcal{F}^{-1} \left\{ -ik_x \sqrt{0.5 S(k_x, k_y) dk_x dk_y N_x^2 N_y^2} \cdot \exp(i2\pi X) + c.c. \right\}. \quad (5)$$

For the slopes, the integral is limited to $k_{\text{lim}} = 2\pi/5$ rad m $^{-1}$ as the rest of the surface slopes are inherently captured by the quasi-specular scattering model in Section II-B. Note, vertical-velocity contribution drops quickly at wavelengths shorter than 10 m, and error estimates for the correlation between vertical velocity and filtered slope are negligible. The integration time is assumed to be short $T \ll 1$ s so that the viewing geometry can be assumed constant. If multiple sublooks are considered, the surface evolves using phasors of the form $\exp(-i\omega t)$, where t is the time with respect to zero-Doppler. Surfaces are generated on both sides of the track corresponding to the part of the waveform tail to be considered. An example of such a realization for both sides of the track is shown in Fig. 2.

B. SAR Altimetry Model

A top-view geometry for a nadir-looking SAR altimeter is given in Fig. 3. At near-nadir angles ($< 1^\circ$) considered in the model, the dominant mechanism is quasi-specular scattering. For a rough Gaussian random surface without any long waves, specular backscatter is approximated by [13]

$$\sigma_{0,\text{ref}} = \frac{1}{2 \cos^4(\theta) s_{\text{aw}} s_{\text{cw}}} \exp\left(-\frac{\tan^2(\theta)}{2s_c^2}\right) \quad (6)$$

where s_{aw}^2 and s_{cw}^2 are the maximum (along wind) and minimum (cross wind) mean-square slopes in perpendicular directions, respectively, while s_c^2 is the cross-track mean-square slope, computed as

$$s_c^2 = \int \int k_x^2 S(k_x, k_y) dk_x dk_y. \quad (7)$$

The mean-square slopes are computed using an Elfouhaily spectrum between the wavelengths of ~ 10 and 1 cm [14]. For a nadir altimeter, the incident angle θ varies rather rapidly as a function of cross-track distance, and backscatter intensities

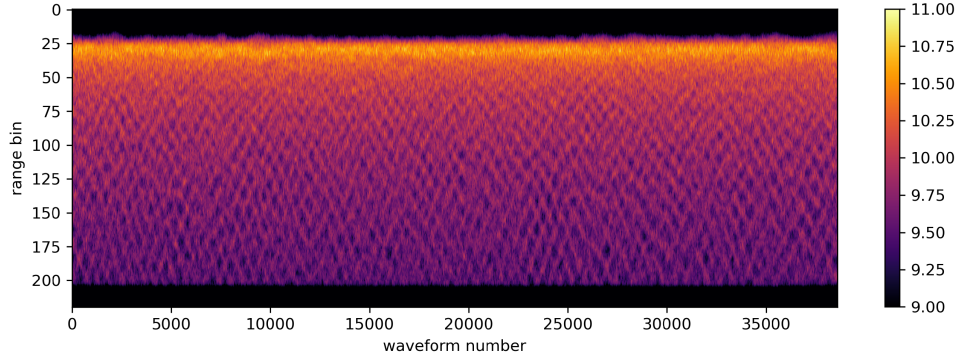


Fig. 1. Focused SAR radargram from Sentinel-6 acquisition over the Pacific Ocean on January 5, 2021. The along-track posting distance is just over 1 m and the range sampling is 0.19 m. The tails of the waveforms exhibit backscatter modulations induced by long ocean waves.

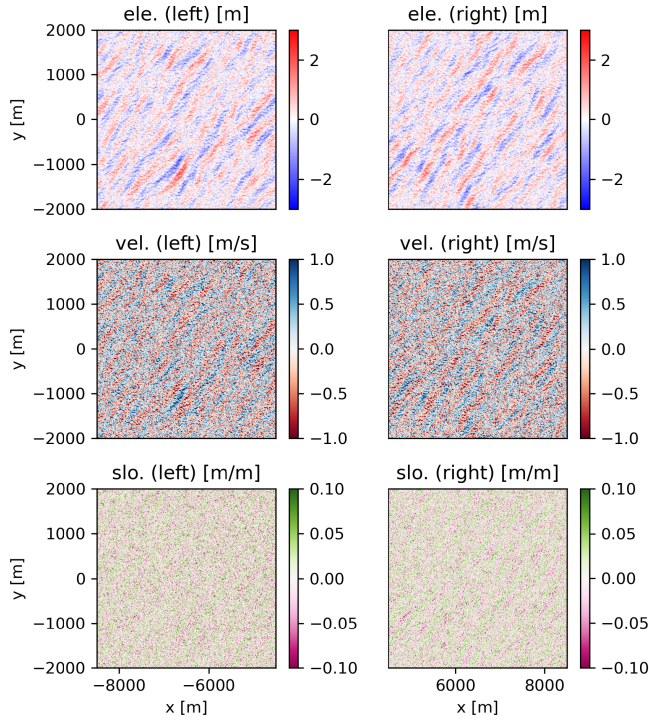


Fig. 2. Example of input elevation, velocity, and slope grids for both sides of the track.

are not constant over the waveform tail. Local long-wave tilt further alters the local incident angle

$$\theta_l = \arctan(\tan(\theta) + s) \quad (8)$$

so that the normalized radar cross section (NRCS) becomes

$$\sigma_0 = \frac{1}{2 \cos^4(\theta_l) s_{aw} s_{cw}} \exp\left(-\frac{\tan^2(\theta_l)}{2s_c^2}\right). \quad (9)$$

For each of the scatters in a narrow Doppler strip, the range is a function of cross-track distance x and elevation

$$R = \sqrt{(H - h)^2 + x^2} \quad (10)$$

where H the satellite altitude. The scatter velocity causes a different Doppler compared to a static target, to induce an along-track shift. Under the assumption that the along-track distance over which the scatter travels is small, the along-track

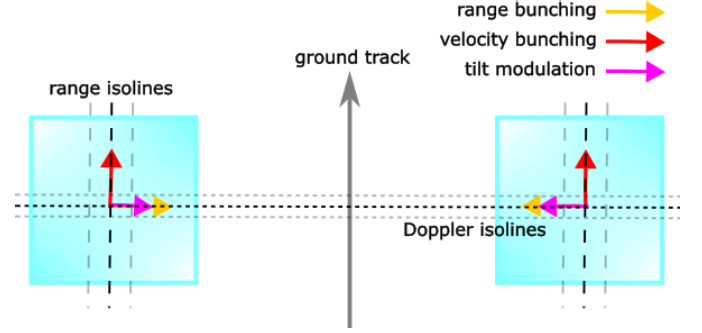


Fig. 3. Topview of the zero-Doppler geometry where the arrows indicate the direction of sensitivity. VB occurs due to shifts in the along-track direction and is maximal near peaks or troughs. RB occurs due to shifts in the cross-track direction and has its maximum on the slope facing the instrument. Tilt modulation is not a shift, but has its maximum on the slope facing the satellite.

shift is computed as

$$\Delta y = \frac{R}{V} v \quad (11)$$

where V is the platform velocity. Using a 2-D sinc-function, the unnormalized intensity in a waveform bin n for Doppler strip m is then computed as

$$I(n, m) = \sum \text{sinc}^2\left(\pi \frac{R - R_n}{R_{\text{res}}}\right) \text{sinc}^2\left(\pi \frac{y + \Delta y - y_m}{y_{\text{res}}}\right) \sigma_0. \quad (12)$$

The along-track mean waveform tail is then used for normalization [7]. A realization of the normalized waveform tail and its associated SAR spectrum are shown in Fig. 4.

III. CLOSED-FORM SOLUTION

A closed-form mapping between the ocean and SAR-altimetry spectra could provide interpretation leading to fast inversion algorithms. A closed-form solution will unfortunately quickly lose its validity for wave slopes close to, or larger than the incident angle. However, a closed-form derivation provides insights into the behavior of the measurable nadir spectra. This will also benefit a more elaborated explanation of the detected modulations obtained from nonzero-Doppler sublooks, discussed in Section IV-A. While for nadir SAR altimeters (CryoSat-2, Sentinel-3, and Sentinel-6), a closed-form is not formally valid, a reasonably

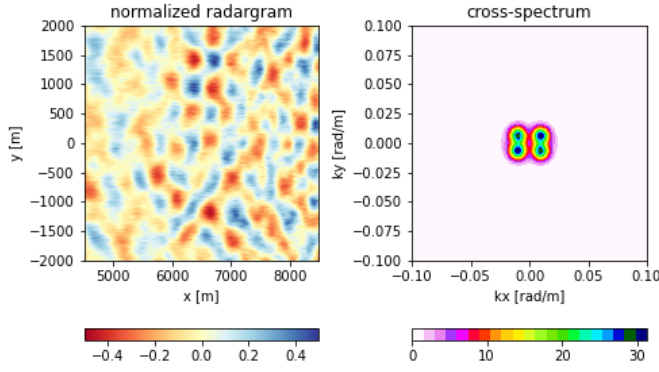


Fig. 4. Realization of the normalized waveform tail and its associated spectrum based on the input of Fig. 2. In this example, the normalized radargram is projected as a function of cross- and along-track distance on the right side of the ground track.

accurate closed-form solution exists for swath altimeter observations at incident angles of $\sim 4^\circ$, under moderate environmental conditions. The latter would lead to similar type of inversion as for Sentinel-1 Wave Mode spectra [15].

A. SAR Spectral Transform

Consider a surface that is analytically described by

$$h(x, y) = \sum_k h_k e^{i(k_x x + k_y y)} \quad (13)$$

where h_k is the amplitude at wavenumber (k_x, k_y) . Then, we can map any ‘linear’ image distortion using a simple transfer function $T(k_x, k_y)$, which results in

$$\tilde{I}(x, y) = \sum_k T(k_x, k_y) h_k e^{i(k_x x + k_y y)}. \quad (14)$$

With that, it is possible to derive a transfer function for the tilt modulation based on the scattering theory discussed in Section II-B, given as [16]

$$T_I = -ik_x \frac{1}{\sigma_0} \frac{\delta \sigma_0}{\delta \theta} \quad (15)$$

in line with transfer functions used for wave-spectrometers, like the SWIM instrument on-board CFOSAT satellite. The latter equation inherently assumes a linear change in slope, causes a linear change in backscatter, whereas the numerical model explicitly takes into account the change in local incident angle (9).

RB and VB do not alter the scattering properties of the surface, but cause misregistrations, which can be interpreted as random shifts of scatters. In a similar way as the tilt modulations, the shifts are modeled using transfer functions, such that

$$\begin{aligned} \Delta x &= \sum_k T_x(k_x, k_y) h_k e^{i(k_x x + k_y y)} \\ \Delta y &= \sum_k T_y(k_x, k_y) h_k e^{i(k_x x + k_y y)} \end{aligned} \quad (16)$$

with the transfer functions for cross-track migrations [17]

$$T_x = -\frac{1}{\tan(\theta)} \quad (17)$$

which are implicitly taken into account in 10 for the numerical model, and the along-track migrations [18]

$$T_y = -\frac{R}{V}(i\omega) \approx -\frac{H}{V}(i\omega) \quad (18)$$

which is the spectral equivalent to (11) for the numerical model.

The derivation of the closed-form transform follows previous developments [8], [9], [10], [18]. Consider a Fourier transform taken of an SAR image I_v

$$\chi(\vec{k}) = \frac{1}{2\pi} \int I_v e^{-i\vec{k}\vec{x}} d\vec{x}. \quad (19)$$

The signal at SAR image location $\vec{x}$ actually originates from a set of scatters, shifted there from other locations $\vec{x}'$. It can be written as [18]

$$\chi(\vec{k}) = \frac{1}{2\pi} \int I_r e^{-i\vec{k}(\vec{x}' - i\Delta\vec{x}')} d\vec{x}' \quad (20)$$

where $\Delta\vec{x}'$ represent the cross-track and along-track shifts and I_r is the intensity image after tilt bunching only. The (cross-)spectrum is computed as $\langle \chi_1(\vec{k}) \chi_2^*(\vec{k}) \rangle$. The SAR image spectrum can be written

$$P(k_x, k_y) = \frac{1}{(2\pi)^2} \iint G(x, y, k_x, k_y) e^{-i(k_x x + k_y y)} dx dy \quad (21)$$

which is a slightly modified version in [10, eq. (6)], where the integral should be computed for each (k_x, k_y) separately. Following Gaussian statistics, the G-function is described with a set of cross-correlations as

$$\begin{aligned} G(k_x, k_y, x, y) &= e^{k_x^2 \mu_{xx} + k_y^2 \mu_{yy} + k_x k_y (\mu_{xy} + \mu_{yx})} \\ &\cdot (1 + \rho_{II} + ik_x(\rho_{Ix} - \rho_{xI}) + ik_y(\rho_{Iy} - \rho_{yI}) \\ &\quad + ik_x^2 \mu_{Ix} \mu_{xI} + ik_y^2 \mu_{Iy} \mu_{yI} \\ &\quad + ik_x k_y (\mu_{Ix} \mu_{yI} + \mu_{Iy} \mu_{xI})) \end{aligned} \quad (22)$$

with

$$\mu_{ab}(x, y) = \rho_{ab}(x, y) - \rho_{ab}(0, 0). \quad (23)$$

For clarity, the (x, y) dependence of the cross-correlations is left out. The complete derivation of the G-function can be found in [10]. The cross-correlations are computed in the spectral domain as

$$\begin{aligned} \rho_{ab} &= \frac{1}{(2\pi)^2} \iint \\ &\times \left[\frac{1}{2} T_a(k_x, k_y) T_b^*(k_x, k_y) S(k_x, k_y) \right. \\ &\quad \left. + \frac{1}{2} (T_a(-k_x, -k_y) T_b^*(-k_x, -k_y))^* S(-k_x, -k_y) \right] \\ &\times e^{i(k_x x + k_y y)} dk_x dk_y \end{aligned} \quad (24)$$

with S the wave spectrum and $T_{a,b}$ are transfer functions. Higher order terms are ignored leading to

$$G(k_x, k_y, x, y) = e^{k_x^2 \mu_{xx} + k_y^2 \mu_{yy} + k_x k_y (\mu_{xy} + \mu_{yx})} (1 + \rho_{II}) \quad (25)$$

and the SAR altimetry spectrum

$$\begin{aligned}
 P(k_x, k_y) &= \frac{1}{(2\pi)^2} \int \int e^{k_x^2(\rho_{xx} - \rho_{xx}(0,0)) + k_y^2(\rho_{yy} - \rho_{yy}(0,0))} \\
 &\quad \cdot e^{k_x k_y (\rho_{xy} - \rho_{xy}(0,0) + \rho_{yx} - \rho_{yx}(0,0))} \\
 &\quad \cdot L e^{-i(k_x x + k_y y)} dx dy \\
 &= \frac{1}{(2\pi)^2} e^{-k_x^2 \rho_{xx}(0,0) - k_y^2 \rho_{yy}(0,0) - k_x k_y (\rho_{xy}(0,0) + \rho_{yx}(0,0))} \\
 &\quad \int \int e^{k_x^2 \rho_{xx} + k_y^2 \rho_{yy} + k_x k_y (\rho_{xy} + \rho_{yx})} \\
 &\quad \cdot L e^{-i(k_x x + k_y y)} dx dy
 \end{aligned} \quad (26)$$

with $L = (1 + \rho_{II} + \text{h.o.t.})$, where h.o.t. indicates the higher order cross-terms outside the exponential of the G-function. Compared to previous efforts [7], this expression explicitly includes nonnegligible nonlinear RB as cross-track shifts (exponential terms involving ρ_{xx}).

B. Discussion of the Closed-Form Solution

At near-nadir angles, the closed-form solution has certainly more limitations than at higher incident angles, but can still be useful to derive information regarding along- and across-track resolution.

1) *Cut-Off Wavelengths*: The terms outside the integral of (26), $e^{-k_x^2 \rho_{xx}(0,0)}$ and $e^{-k_y^2 \rho_{yy}(0,0)}$ encode the cross- and along-track resolution of the resulting SAR spectra, respectively. The term with zero-lag azimuth autocorrelation $\rho_{yy}(0,0)$ corresponds to the azimuth fall-off function [19]. Using the transfer function for the along-track migrations, it is related to the along-track cut-off wavelength

$$\lambda_c \propto \pi \sqrt{\rho_{yy}(0,0)} = \pi \frac{R}{V} \sqrt{\sigma_v^2} \quad (27)$$

and depends on the vertical velocity variance σ_v^2 of detected wave systems [20]. Note, the equation omits correlations between velocities and slopes, acting to reduce the velocity variance detected by the altimeter [21]. σ_v^2 shall thus be interpreted as a weighted velocity variance. Besides that, short-time life of scatters, for example, wave breakers, is ignored [16], possibly leading to an underestimation of the cutoff at high sea states. The relatively high altitude of Sentinel-6 (1300 km) causes an increased resolution loss with respect to that of other nadir SAR altimeters (CryoSat-2, Sentinel-3). At a typical velocity variance of $0.4 \text{ m}^2\text{s}^{-1}$, the along-track cut-off wavelength for Sentinel-6 is $>200 \text{ m}$, nearly twice larger than for CryoSat-2 and Sentinel-3.

The term with zero-lag autocorrelation $\rho_{xx}(0,0)$ describes the cross-track fall-off function. With

$$\rho_{xx}(0,0) = \frac{\sigma_e^2}{\tan^2(\theta)} \quad (28)$$

a function of the elevation variance σ_e^2 . The cross-track resolution is therefore proportional to the SWH, such that

$$\lambda_{ct} \propto \pi \sqrt{\rho_{xx}(0,0)} = \pi \sqrt{\frac{\sigma_e^2}{\tan^2(\theta)}} = \pi \frac{\text{SWH}}{4 \tan(\theta)}. \quad (29)$$

Note that near nadir, incident angle θ quickly changes in the waveform tail (between $\sim 0^\circ$ and 0.7°), so it cannot be

considered constant. At an incident angle of 0.4° and a SWH of 2 m , the cross-track cut-off is already $>200 \text{ m}$. Swell-wave spectral retrieval will benefit from a large measurement window that covers the full beam-limited footprint of Sentinel-6.

2) *Nadir Altimeter*: We consider an altimeter altitude of 800 km , a chirp bandwidth of 320 MHz and a synthetic aperture length of 500 m . For both the numerical model and the closed-form solution, we estimate the expected value for a spectrum without noise generated from two square scenes between 4000 and 7000 m on both sides of the ground track. For the closed-form solution, we use an incident angle corresponding to 5500 m across track in a flat-Earth geometry. It is assumed that the satellite does not roll and is located at zero-Doppler. For the numerical model, an average of ten realizations is taken.

Fig. 5 shows a comparison of the closed-form and numerical model for swell waves propagating in three different directions. We only model the right side of the altimeter ground track, which yields only two ambiguities. Analysis of a single side or track enhances the interpretation and simplifies the discussion on the discrepancies between the numerical and closed-form models. In the comparison, we assume the presence of a moderate wind-sea system, which reduces the resolution in the cross-track and along-track directions. The reduced resolution eliminates any signals from the wind waves and therefore only swell waves modulate the intensity, with signals visible in the spectra. The power spectral density of the swell signal changes with direction because RB is dominant across track while VB is dominant along track [7]. The discrepancies between the closed-form and numerical models also depend on the wave direction. In the cross-track direction, the power spectral density for this particular scenario differs by almost an order of magnitude, while in the along-track direction, both models agree quite well.

Among the processes responsible for these discrepancies, two are related to the nonlinear range migration. To discuss this in detail, we first expand the range-migration term into a Taylor series

$$\exp(k_x^2 \rho_{xx}) = 1 + \frac{k_x^2 \rho_{xx}}{1!} + \frac{k_x^4 \rho_{xx}^2}{2!} + \dots \quad (30)$$

Consider a monochromatic swell system $\eta = A \sin(k'_x y)$, it results in a range-migration cross-covariance function

$$\rho'_{xx} = \frac{A^2 \cos(k'_x x)}{2 \tan^2(\theta)}. \quad (31)$$

Inserting it into the Taylor expansion

$$\begin{aligned}
 \exp\left(k_x^2 \frac{A^2 \cos(k'_x x)}{2 \tan^2(\theta)}\right) &\approx 1 + \frac{k_x^2}{\tan^2(\theta)} \frac{A^2 \cos(k'_x x)}{2} \\
 &\quad + \frac{k_x^4}{\tan^4(\theta)} \frac{A^4 \cos^2(k'_x x)}{8} + \dots
 \end{aligned} \quad (32)$$

the monochromatic swell system appears to cause responses at $k_x = N k'_x$, where N is a (positive) integer. This results in peaky modulations, the orange lines in Fig. 6. For a constant incident angle and low waves, a numerical 1-D model well

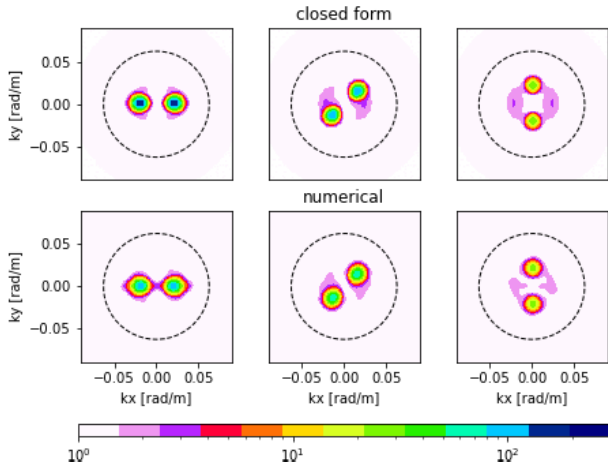


Fig. 5. (Top) Numerical and (Bottom) closed-form nadir-altimeter SAR spectra simulations for three swell-wave spectra with mean propagation directions of 0°, 45°, and 90° from left to right, respectively. The unresolved wind waves are based on a 10 m/s stress-equivalent WS with a fetch of 200 km.

reproduces the closed-form solution. Yet, the incident angle rapidly changes with increasing cross-track distance and the closed-form solution is not accurate. To illustrate this effect, the autocorrelation function for a monochromatic wave is approximated

$$\rho'_{xx} = \frac{H^2 A^2 \cos(k'_x x)}{2x^2} \quad (33)$$

where H is the satellite altitude and x the cross-track distance. This autocorrelation function corresponds to the normalized RB intensity modulation for a monochromatic wave [18]

$$I_{rb} = \exp\left(k'_x \frac{H A \cos(k'_x x)}{x}\right) \quad (34)$$

as shown by the pink line in panel-a of Fig. 6. The closed-form model (orange line) does not explicitly include the incident-angle dependence, e.g., the ratio (H/x) is set constant. Therefore, the closed-form understanding deviates from the numerical model, while the model from (34) more closely matches. A computationally efficient implementation of the incident-angle dependency in a closed-form solution is not trivial. The varying incident angle does not only cause a trend in modulation directly, but also indirectly a varying cut-off with the incident angle.

While this incident angle variation introduces a rather small discrepancy, the second issue is much more problematic. When $k_x A > \tan(\theta)$, the waves become supercritical: the slope becomes larger than the incident angle. It results in two maxima (panel b). The crest and trough switch range location at one-fourth of the wavelength. These maxima are normally not separable as the limited cross-track resolution smears the response. For (near-)supercritical waves, the spectral response changes from the analytical model and the closed-form solution are no longer valid. In the case of a 400 m cross-track swell, supercriticality is already reached at a fraction of a meter. Supercritical velocities can also occur for sea ice [22], which results in comparable patterns in the along-track direction. For the Doppler migration term, a similar

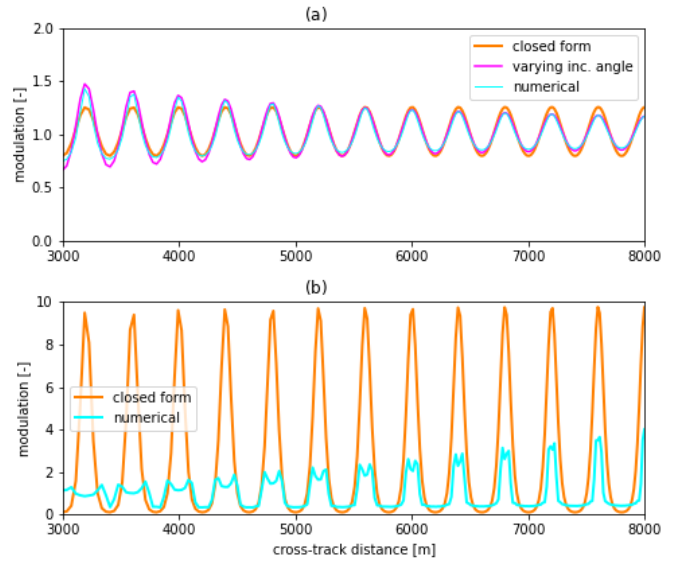


Fig. 6. (Top) Comparison of two 1-D analytical models with a numerical model at steep incident angles for very low swell-wave heights. (Bottom) Comparison between an analytical model with a numerical model for moderate wave height. Oversampling is applied for interpretation.

Taylor expansion can be used to illustrate that supercritical velocities correspond to $k_y A > (V/\omega R)$ and that upwind and downwind slope switch position if the Doppler shift becomes one-fourth of the swell wavelength [23]. Note that the swell radial velocities in the examples of Fig. 5 are not large enough to be supercritical.

More subtle, other differences are present between the numerical model and the closed-form solution. Given the instrument sampling rate, the normalization and the resampling of the waveforms can induce artifacts that should be carefully considered. However, the nonlinear range (and velocity) bunching terms already demonstrate that, unless the swell-wave height is very low, the closed-form solution does not provide an accurate representation of the nadir SAR altimetry spectrum.

3) *Swath Altimeter*: A swath altimeter illuminates one side at a time and uses cross-track interferometry with two antennas to estimate the SSH. The geometry of a swath altimeter can therefore be interpreted as a single side of Fig. 3, but note that a swath altimeter illuminates areas at a higher cross-track distance than a nadir altimeter with higher incident angles. Based on the preliminary design of Sentinel-3 Next Generation Topography (S3-NGT), a swath altimeter flying at an altitude of ~ 800 km with a chirp bandwidth of 200 MHz and a synthetic aperture length of 500 m is considered. We estimate the expected values of the signal spectrum for a small scene between 52 000 and 56 000 m across track with incident angles close to approximately 4°, which would be at the far end of S3-NGT's swath. The incident angle for the closed-form model is kept constant and corresponds to 54 000 m across track in a flat-Earth geometry.

The closed-form and numerical models for swell and wind waves traveling in three different directions are shown in Fig. 7. Compared to the SAR spectra of the nadir altimeter, wind-wave system starts to be visible with the high resolution

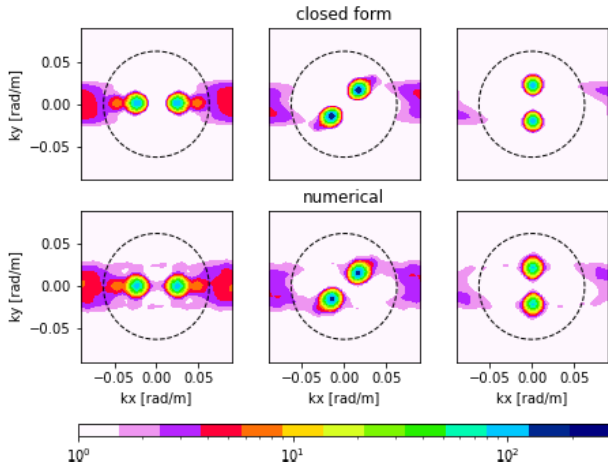


Fig. 7. (Top) Numerical and (Bottom) closed-form swath-altimeter SAR spectra simulations for three swell-wave spectra with mean propagation directions of 0°, 45°, and 90° from left to right, respectively. The unresolved wind waves are based on a 10 m/s stress-equivalent WS with a fetch of 200 km.

in the cross-track direction. Although the cross-track resolution of the swath altimeter is not as high as a side-looking SAR system, like Sentinel-1, the modulation due to RB is much stronger which allows to have a better constraint on the wind-wave system. A full inversion of the 2-D wind-wave system, without external information, is still impossible with the clearly visible cut-off in the along-track direction. The discrepancies of the swell signals between the closed-form and numerical spectra are now smaller than for the nadir altimeter, even though the slopes considered here are higher. Under moderate swell heights, typically lower than 4 m, the supercriticality threshold $k_x A > \tan(\theta)$ is not exceeded. Neither does the change of incident angle over the considered 3 km wide scene play a significant role (Fig. 8).

For low (swell-)wave heights, simplifications might be made using the first-order Taylor expansion (see Fig. 8) of the cross-track migration term

$$e^{k_x^2 \rho_{xx}} \approx 1 + \frac{k_x^2 \rho_{xx}}{1!} \quad (35)$$

with which we simplify (26) to

$$P(k_x, k_y) = \frac{1}{(2\pi)^2} e^{-k_y^2 \rho_{yy}(0,0)} \times \int \int e^{k_y^2 \rho_{yy}} L' e^{-i(k_x x + k_y y)} dx dy \quad (36)$$

where $L' = 1 + \rho_{II} + \rho'_{xx} + \dots \approx 1 + \rho_{II} + \rho'_{xx} = 1 + \rho'_{II}$ and $\rho'_{xx} = k_x^2 \rho_{xx}$. This form of the closed-form equation matches the approximation used in side-looking SAR [9], [24], and the one given by [7]. It inherently assumes that the cross-track resolution loss is negligible and/or that secondary peaks are not present. Considering a linear cross-track migration term substantially reduces the computation time and simplifies the inversion (see for the derivation in [10]) at the cost of limited applicability and reduced performance. Alternatively, a second- or third-order approach might be performed. In principle, this would allow the retrieval to follow a comparable path as the Sentinel-1 ocean-wave retrieval algorithm [15].

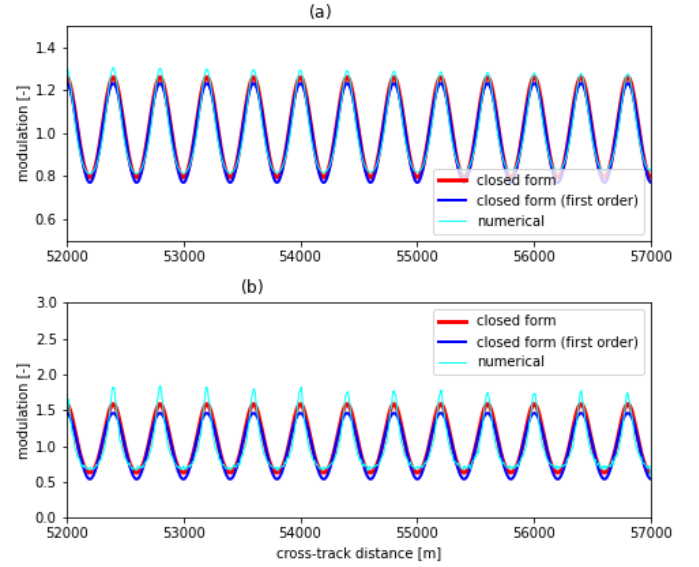


Fig. 8. Comparison of two 1-D analytical models with a numerical model at steep incident angles for a swell system only and a swell system in the presence of a wind-wave system.

The processing of a swath-altimeter SAR spectrum involves either a Welch or Bartlett periodogram averaging. Averaging of periodograms for S3-NGT is done in the outer swath. If we assume this swath covers 48 to 60 km across track, it corresponds to incident angles between 3.4° and 4.3° in a flat-Earth geometry. A forward modeled spectrum using the mean incident angle will therefore differ from the observed average as $\tan(\theta)$ changes nonlinearly. Improved performance is expected when the same averaging is taken into account in the model, which comes at the cost of a higher computation time.

IV. SUBLOOK PROCESSING

We now focus on the use of numerical simulations for the nadir altimeter for which closed-form solutions are not valid. Nadir radar altimeter overpasses allow for a large integration time compared to side-looking SAR systems and swath altimeters. Instead of integrating over the full aperture, it is possible to split the aperture into sublooks and compute multiple independent single-look waveforms corresponding to the same location. By combining the DFTs of the normalized waveform tails of different sublooks, cross-spectra are computed. In side-looking SAR, sublook and its associated cross-spectral analysis are exploited to both remove the speckle noise pedestal [10], [25] and a 180° wave propagation ambiguity. It can be anticipated that the phase is not only a function of wave propagation, but also related to changes of the observation geometry. For the nadir altimeter, it will be shown that not only the cross-spectral phase is a function of the observation geometry, but also the cross-spectral density. Furthermore, because of the larger geometrical diversity (due to the long aperture length) of nadir altimeters, a stack of cross-spectra can be computed, which can be exploited to further constrain the ocean-wave spectral inversion procedure.

A. Nonzero-Doppler Geometry Model

Suppose we focus raw data in a narrow Doppler strip at an along-track distance $y_{\text{ref}} = Vt$ with respect to the platform nadir position. The local incident angle with a flat surface becomes a function of cross-track distance and the distance to the along-track strip

$$\theta = \arctan\left(\frac{\sqrt{y_{\text{ref}}^2 + x^2}}{H}\right). \quad (37)$$

The ground-range direction is not perpendicular to the along-track direction anymore. We therefore write the equation for the surface slope along the direction of the satellite as

$$s = s_x \cos(\phi_r) + s_y \sin(\phi_r) \quad (38)$$

where ϕ_r is the angle between the ground-range direction and the cross-track direction, given as

$$\phi_r = \arctan\left(-\frac{y_{\text{ref}}}{x}\right). \quad (39)$$

The cross-track and along-track slopes are computed with

$$\begin{aligned} s_x &= \mathcal{F}^{-1}\left\{-ik_x \sqrt{0.5 S(k_x, k_y) dk_x dk_y N_x^2 N_y^2} \right. \\ &\quad \left. \cdot \exp(i2\pi X) \exp(-i\omega t) + c.c.\right\} \\ s_y &= \mathcal{F}^{-1}\left\{-ik_y \sqrt{0.5 S(k_x, k_y) dk_x dk_y N_x^2 N_y^2} \right. \\ &\quad \left. \cdot \exp(i2\pi X) \exp(-i\omega t) + c.c.\right\}. \end{aligned} \quad (40)$$

From these equations, it can easily be shown that s is highest when the waves are traveling in the ground-range direction (perpendicular to the range-isolines in Fig. 9). Consider a Doppler strip ahead of the nadir location and assume that the altimeter would only illuminate the surface on the right side of the ground track. A wave traveling at 0° – 90° or 180° – 270° with respect to cross-track, will therefore experience a larger tilt modulation than waves traveling in the other two quadrants. If the altimeter would only illuminate the left side of the ground track, this would be reversed. As nadir altimeters illuminate both sides of the ground track, the tilt modulation is expected to be stronger in two quadrants in case a nonzero-Doppler geometry is considered, unless we have along-track traveling waves. For the numerical model, we also adjust the NRCS equation

$$\sigma_0 = \frac{1}{2 \cos^4(\theta_l) s_{aw} s_{cw}} \exp\left(-\frac{\tan^2(\theta_l)}{2s_r^2}\right) \quad (41)$$

where s_r^2 is the mean-square slope in the radar look direction given as [26]

$$s_r^2 = \frac{s_{aw}^2 s_{cw}^2}{s_{cw}^2 \sin^2(\phi_r') + s_{aw}^2 \cos^2(\phi_r')} \quad (42)$$

and therefore ϕ_r' is the ground-projected angle between the radar look direction and the semimajor axis of the surface roughness ellipse. Note that σ_0 and its derivative depend on both the magnitudes and directions of the long-wave slope (i.e., θ_l) and the mean-square slope.

RB will also enter in a nonzero-Doppler geometry. The along-track distance y_{ref} between the satellite and the target

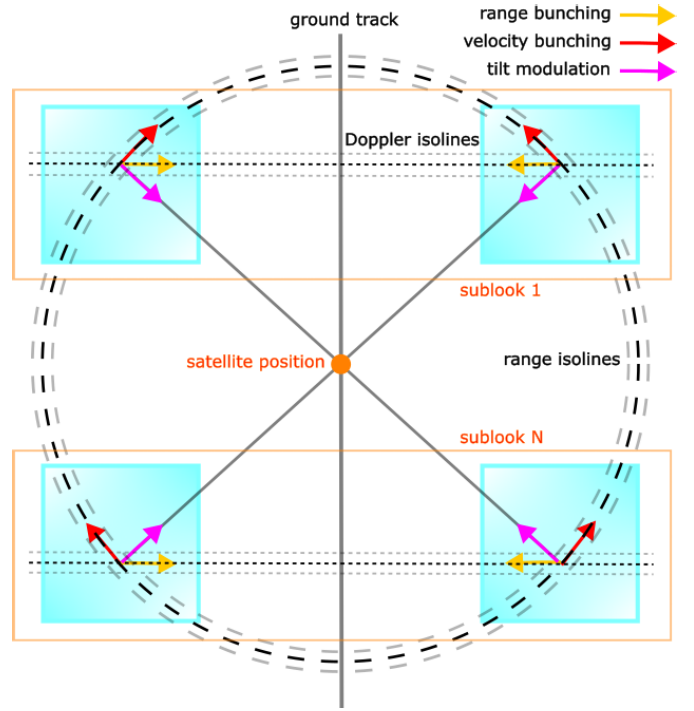


Fig. 9. Topview of a forward-looking geometry (sublook 1) and a backward looking geometry (sublook N). Elevation and Doppler shifts occur in the direction of the arrows. The peak of the RB modulation is therefore located on the wave slope facing the ground track. Doppler shifts are not perpendicular to the elevation shifts anymore. VB still occurs near the crests and troughs of the wave, but is maximal when waves are propagating perpendicular to the ground-range direction. Tilt modulation is maximal on the slopes facing the satellite. The blue squares indicate the illuminated area corresponding to the waveform tail.

should be considered when projecting the waveforms onto the surface. For a narrow Doppler strip, a rather simple adjustment to the range gives

$$R = \sqrt{(H - h)^2 + y_{\text{ref}}^2 + x^2}. \quad (43)$$

For a wider Doppler strip, the range varies in the along-track direction which cannot be ignored. This results in

$$R = \sqrt{(H - h)^2 + (-y_{\text{ref}} + dy)^2 + x^2} \quad (44)$$

where dy is the difference in along-track direction between the scatter and the reference range. Note that dy is considered to be positive in the flight direction and y_{ref} is considered negative for a forward-looking geometry. First, not considering any VB, it is possible to infer the RB effects. Let us consider a rather wide Doppler strip and a monochromatic wave with low amplitude. A crest at the furthest along-track location in the Doppler strip can compensate for the increased range of a positive dy . Therefore, scatters from troughs and crests might be mapped near each other, which would reduce the RB modulation. As with the tilt, this causes a left-right difference. Ignoring secondary effects, the maximum RB occurs when $\phi_k - \phi_r \approx 0$. A wide Doppler strip therefore acts as a filter that depends on the wavelength and direction of the waves, the width of the strip, and the distance between zero-Doppler and the strip. Note also that a scatter at the edge of two Doppler strips gets projected at a different range in both waveforms,

TABLE I

RELATIVE SIZE OF THE MODULATIONS FOR A MONOCHROMATIC WAVE TRAVELING BETWEEN 0° AND 90° WITH RESPECT TO CROSS TRACK. RANGE AND VB ARE ABBREVIATED AS RB AND VB, RESPECTIVELY

Look	Side	Tilt	RB	VB	Cut-off rot.
Forward	Right	+	+	-	+
Forward	Left	-	-	+	-
Backward	Right	-	-	+	-
Backward	Left	+	+	-	+

as in one Doppler strip and has along-track location $y_{\text{ref}} + dy$ and in the other $y_{\text{ref}} - dy$. For the numerical simulation, the ranges therefore also have to be recomputed for each Doppler strip.

The most prominent change of modulation occurs due to Doppler shifts and the associated VB. Doppler shifts do not cause scatters to move in the along-track direction alone in a nonzero-Doppler geometry. As shown in Kleinherenbrink et al. [27] (under review), line-of-sight-moving scatters experience a shift approximately along range isolines. For nadir altimeters, the range isolines are arcs on the surface (Fig. 9). At a sufficient distance from nadir, these arcs can locally be approximated by a straight line with the direction

$$\phi_{\text{sh}} = \phi_r + \frac{\pi}{2} \quad (45)$$

for the right side of the ground track. The scatter still requires the same along-track Doppler shift Δy_D as a consequence of its own geophysical Doppler and therefore the total shift will be larger than for a zero-Doppler geometry. The cross-track shift is related to the along-track shift as

$$\Delta x_D \approx \frac{\Delta y_D}{\tan(\phi_{\text{sh}})} = \frac{R}{V \tan(\phi_{\text{sh}})} v. \quad (46)$$

In fact, the negative cross-track shift ensures the increased range due to the positive along-track shift to be compensated. The inclined shift also introduces a left-right difference. Consider again a monochromatic wave propagating in the ground-range direction ϕ_r on the right side of the ground track. Scatters with vertical velocities are moved in the direction ϕ_{sh} , which is aligned with the wave slopes, so no VB will occur. On the left side of the track, scatters are moved in the direction $\pi - \phi_{\text{sh}} = \frac{\pi}{2} - \phi_r$. This is perpendicular to the wave slopes and therefore maximum VB will occur. The strengths of the modulations for the left and right sides of the track are summarized in Table I, where the plus and minus signs indicate relatively strong and weak modulations.

As the Doppler shift becomes 2-D in a nonzero-Doppler geometry, it will also contribute to the cross-track cut-off wavelength. This will introduce a rotation of the fall-off ellipsoid. Using the function for the cross-track shift, we can adapt the cross-track transfer functions to include a VB term

$$T_x = -\frac{1}{\tan(\theta)} - \frac{H}{V \tan(\phi_{\text{sh}})}(i\omega). \quad (47)$$

Inserting this into the cross-correlation functions leads to a nonzero contribution of the cross-term $e^{-k_x k_y (\rho_{xy}(0,0) + \rho_{yx}(0,0))}$ as $\rho_{xy}(0,0) + \rho_{yx}(0,0)$ does not cancel (see appendix). In the presence of wind waves, the variation of the PSD in the

spectral stack is dominated by the cut-off rotation as we will show in Section IV-B.

B. Cross-Spectral Stack Model Results

Sublooks are generated by assuming a quasi-static geometry, i.e., within the sublook linear Doppler shifts are considered and the geometry is kept constant during the 500 m integration length. The realizations of the intensities from both sides of the nadir track are linearly added together and consecutively normalized and resampled. A DFT is applied to the resampled normalized waveform tails of the sublooks after which a cross-spectrum is computed from two sublooks separated by 1000 m between their respective centers. Eventually, nine cross-spectra are computed and stored in a cross-spectral stack. For the discussion in this section, we assume a swell spectra with a mean propagation directly of 45° as a reference.

1) *Swell-Wave Modulations*: To isolate the various effects discussed in the previous section, we first consider a surface with only a swell-wave system and homogeneous roughness. In this section, we limit the discussion to swell traveling in the quadrants and omit the discussion of along-track and cross-track traveling waves. Fig. 10 shows the absolute value of spectral stacks computed from a time-varying ocean surface and observation geometry for the modulations due to tilt, range shifts, and velocity shifts separately. Any wind or wave direction mentioned in the coming section will follow the Cartesian convention: positive counterclockwise from the x -axis, which is across-track. To ease the discussion, we will designate quadrants 1–4 to be the upper-left, upper-right, lower-left, and lower-right quadrants, respectively.

a) *Tilt modulation*: Modulations due to tilt are typically orders of magnitude weaker than those from the elevation and Doppler shifts. For the results in panel a, we assumed a very low surface roughness, which causes the Jacobian of the specular scattering to be relatively large. Under mean sea states (SWH = 2 m, $U_{10} = 8$ m/s), the tilt modulation is even weaker than shown in the top panels of Fig. 10. Note that the relative change in modulation is rather strong. As expected, in the zero-Doppler geometry (center column), four ambiguities are present with equal power-spectral density (PSD), a consequence of the homogeneous roughness. The signal in Q1 stems from the left side of the mirroring of the signals on the left side of the track, while the signals in Q2 are the signal arriving from the right side of the track. The signals in Q3 and Q4 are their respective 180° ambiguities. In the forward-looking geometry (negative satellite y -locations), the slopes of swell propagating at a direction of 45° are facing the satellite if they are on the right side of the track. On the left side of the ground track, the swell crests are nearly aligned with the ground range. Tilt modulations from the right side of the track are therefore stronger and only a signal in Q2 is visible. At a backward-looking geometry (positive satellite y -locations), the modulations originating from the left side of the ground track are stronger. Fig. 11 shows how the peak PSD evolves in slow time (during the overpass). As visible, the histories are mirrored around zero-Doppler. The signals from the right side of the track (Q2 and its 180° ambiguity Q4) decrease in slow time, while the other two increase. Due to the relatively weak

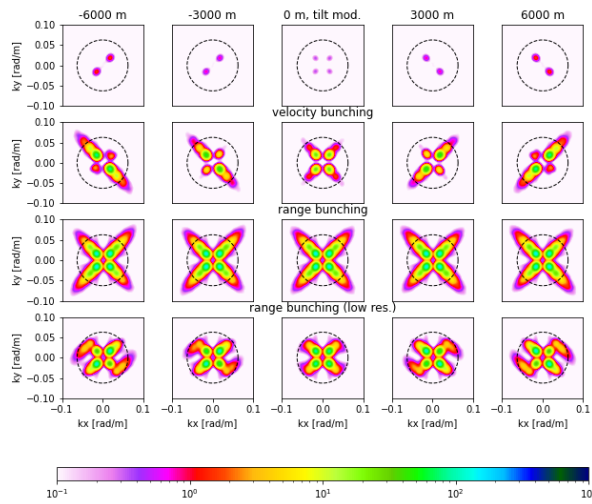


Fig. 10. Absolute values of numerically modeled cross-spectra for five geometries considering modulation mechanisms separately. The input is a Gaussian swell-wave system with a mean propagation direction of 45° . First row: spectral response of tilt modulation at 17 m along-track resolution. Second row: spectral response of VB at 17 m “along-track resolution.” Third row: spectral response of RB at 17 m along-track resolution. Last row: spectral response of RB at 88 m along-track resolution.

tilt modulation, its effect on the overall modulation history can be ignored under mean sea states.

b) *VB*: Far stronger modulations are observed as a consequence of VB (Fig. 10). Its history is opposite of that of tilt modulation, i.e., for the considered swell-wave direction, the VB is strongest in Q1 and Q4 for the forward looks. At -6000 m, the mean ground-range direction in the considered ocean surface is nearly 45° , which corresponds to the swell propagation direction. Remember that the maximum VB occurs when swell is propagating perpendicular to the ground-range direction, which is the case for the left side of the track. As such, in the forward-looking geometry, the maximum PSDs are found in Q1 and Q4.

c) *RB*: RB is the strongest modulation (Fig. 10), but has a relatively weak variation in slow time when processed at high resolution (Fig. 11). As discussed in the Section IV-A, the slow-time variation of RB is enhanced when the data are processed at a lower resolution. In the presence of wind waves, Doppler shifts also reduce the (along-track) resolution, which can result in similar behavior. However, as will be discussed later, wind waves introduce additional complexity so that the interpretation is not that trivial. RB is largest when the alignment of the wave direction and the line-of-sight is closest and therefore signals from the right side of the track (Q2 and its 180° ambiguity Q3) are stronger in the forward-looking geometry. The dominance of RB is contested by VB [7] for particular wave directions and observation geometries.

d) *Full response*: The spectral response of the combined modulations is shown in Fig. 12 for two swell-wave directions. As the modulations are not in-phase with each other and their (relative) amplitudes and phases (near the crest, trough, or maximum slope) depend on the observation geometry, the interpretation of a combined signal is not always straightforward. However, because the tilt modulation is an order

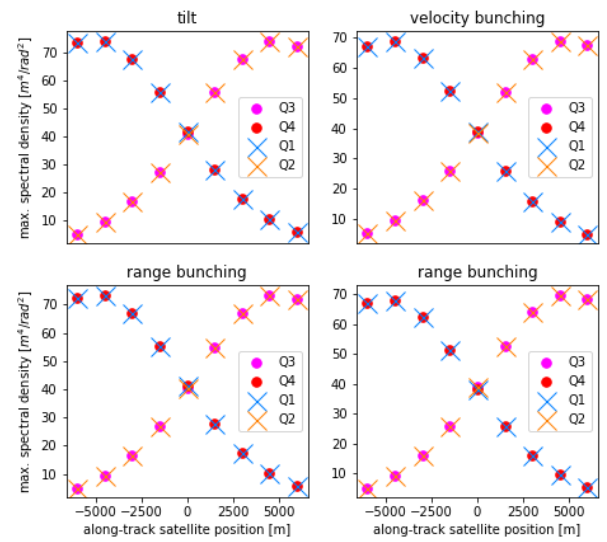


Fig. 11. Peak PSD variation in each of the quadrants as a function of the along-track position for each of the modulation mechanisms separately. The input is a Gaussian swell-wave system with a mean propagation direction of 45° . A 17 m resolution is considered for the first three panels. The last panels show RB at an along-track resolution of 88 m.

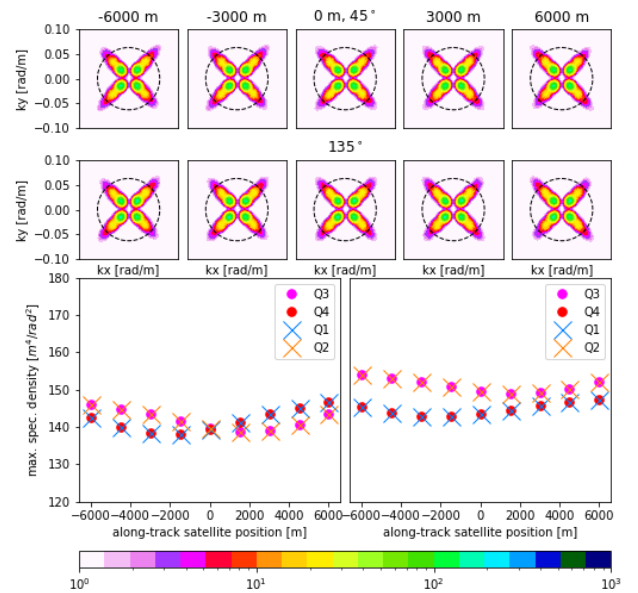


Fig. 12. (Top) Absolute values of numerically modeled cross-spectra for five geometries considering all modulation mechanisms for swell-wave systems traveling at 45° and 135° . (Bottom) Two panels, their associated peak PSD variations on the left and right, respectively.

of magnitude smaller, it can safely be ignored. The integral effect of all processes leads to a modulation that resembles the pattern of RB, independent of the observations geometry (first row). Its associated peak PSD variation (bottom left panel) is even weaker than that of RB at higher resolution. This suggests the opposing behavior of velocity and RB counter each other. The combined effects lead to an along-track variation of the peak modulation of only 5% for this particular set of conditions. Depending on the direction of the swell, it might be larger as the modulation variations of either velocity or RB will start to dominate.

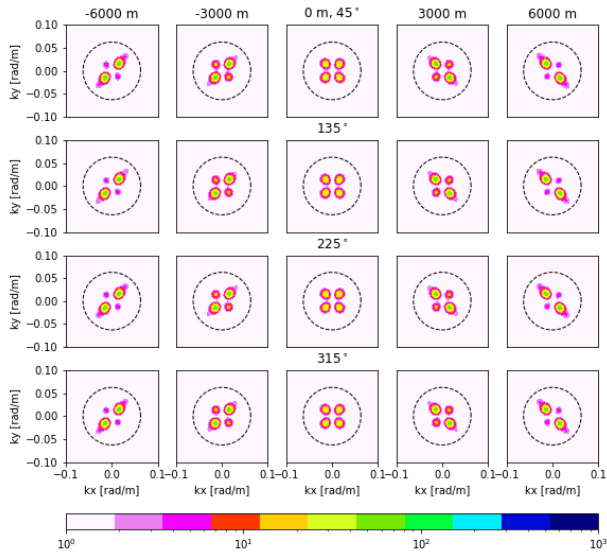


Fig. 13. Numerical model of cross-spectra (absolute values) for five different geometries and four different swell-wave directions in the presence of a fully developed wind-wave system at a stress-equivalent wind of 8 m s^{-1} .

The second row shows the spectral response of a similar swell system propagating at 135° . Its associated peak PSD variations are shown in the bottom-right panel. There is nearly no difference between the spectral response of a swell-wave system propagating at 45° or 135° as the signals get mirrored over the ground-track. Any minor deviations arise from differences in the realizations of the surface. However, the signals in Q2/Q3 originate from the left side of the track instead of the right. In terms of the absolute spectral response, there is also no difference between a swell system propagating at 45° and 225° or 315° . The peak VB will occur shift 180° in phase for linear waves, but the magnitude and phase difference with respect to RB will remain the same. So, even if modulations from the left and the right side of the track have different peak PSD variations, the absolute values of a cross-spectral stack will not solve ambiguities.

2) *Effect of Wind Waves*: In theory, the line-of-sight mean-square slope depends on the wind direction. The mean-square slope determines the backscatter and can therefore increase or reduce the relative ‘weight’ between the left and right side of the track. It can easily be shown that this effect is rather small for the considered incident angles. The Jacobian of the backscatter is also altered by wind direction, which would introduce a tilt modulation that is dependent on the alignment of swell and the short wind waves. If the wind direction is known, it would allow to removal of the left-right ambiguity in the cross spectra. However, as the tilt modulation is orders smaller than the VB and RB this effect will not be detectable.

In Fig. 13, cross-spectra are shown for the same swell-wave system as discussed before, but superpositioned with a fully developed wind-wave system. Wind waves are responsible for a large fraction of the wave height and the velocity variance, which reduces the cross-track and along-track resolution (see Section III-B1). As discussed in Section IV-A, the 2-D falloff

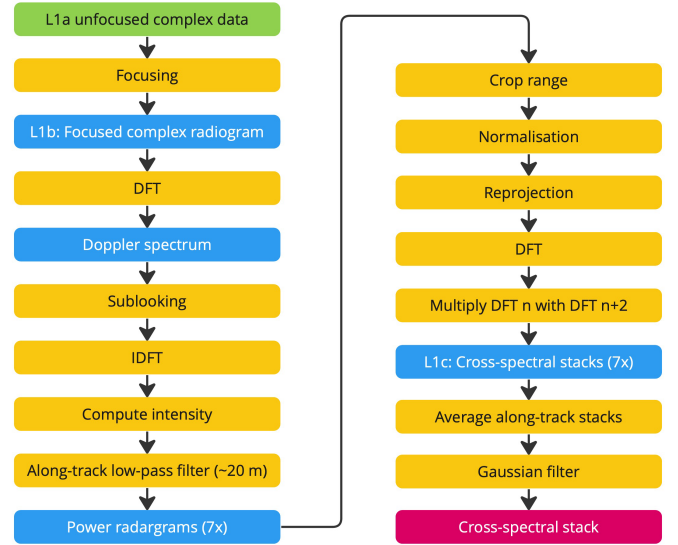


Fig. 14. Flowchart showing the steps to get from unfocussed Sentinel-6 level-1a radar altimetry echoes to a cross-spectral stack. Note that from seven sublooks, seven radargrams are computed. The seven DFT's of these radargrams are combined into a cross-spectral stack containing five cross-spectra. Cross-spectral stack are compute for seven along-track locations and averaged to reduce the noise.

ellipse changes orientation as a result of the cross-track shifts introduced by the radial velocity variance. The first row of cross-spectra shows that the cutoff indeed appears to rotate. The swell-system propagating at 45° has strong signals in Q2 and Q3 (originating from the right side of the ground track) for the forward-looking geometry, while the signals are strongest in quadrant Q1 and Q4 (originating from the left side of the ground track) is the backward-looking geometry. The imbalance in spectral energy between the four quadrant, described in [7], are therefore likely the result of a nonzero-Doppler processing geometry. Note that the spectral density can be even enhanced with respect to the zero-Doppler geometry. In part, the induced range-bunching variation can be interpreted as coming from the loss of the (along-track) resolution due to VB (discussed in Section IV-B1). Whether the swell is propagating at 45° , 135° , 225° , or 315° , the modulation behavior is nearly identical. Also, with wind waves present, the four ambiguities cannot be resolved using the absolute or real part of the cross-spectra. A discussion on the imaginary part of the cross-spectra is provided in the supplementary material S1 (Fig. 1). The noisy imaginary parts of the cross-spectra remain difficult to interpret.

C. Comparison With Sentinel-6

Our model is compared with SAR cross-spectra computed from the tails of focused Sentinel-6 waveforms. The full implementation of the Sentinel-6 is shown in the flowchart of Fig. 14. Input for our Sentinel-6 data processing are level-1a I/Q samples. Using the Delft AltimeterR Toolbox (DART), the waveforms are focused [28], [29], [30]. We ensure that the waveforms align (Fig. 1) to a fraction of the (oversampled) range bin size of 19 cm using a range-migration correction

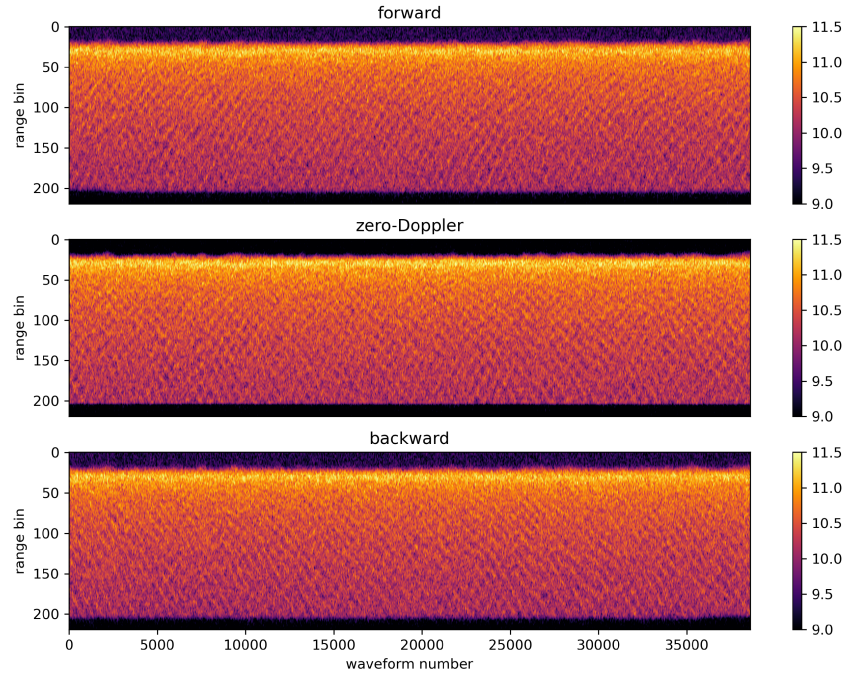


Fig. 15. Three radargrams obtained from splitting the Doppler spectrum of a Sentinel-6 aperture into seven sublooks. The top radargram is rendered from the first 1/7th part of 1.7 s total integration time and corresponds to a forward look, where the satellite is located 3.4 km before zero-Doppler. The bottom radargram corresponds to a backward look at 3.4 km from zero-Doppler. The along-track posting rate is kept at ~ 1 m.

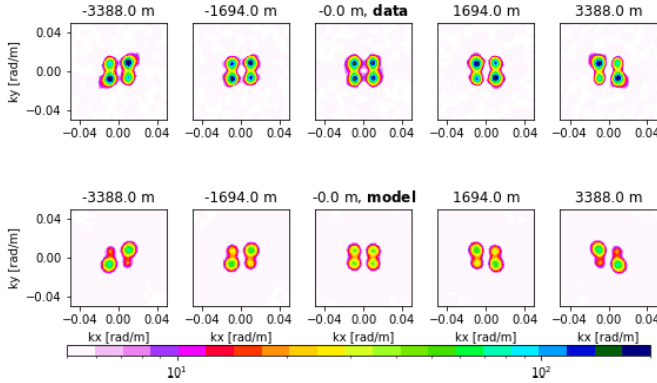


Fig. 16. Real part of five cross-spectra estimated from Sentinel-6 data compared to a model. The five cross-spectra are computed from seven sublooks of a 1.7 s aperture, so that the separation between the centers is two sublooks, or about 0.4 s. The imaginary part of the cross-spectra is shown in Fig. 2 of the supplementary material S1.

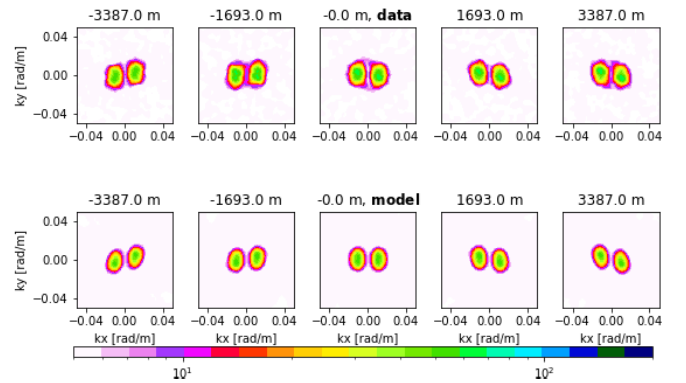


Fig. 17. Real part of five cross-spectra estimated from Sentinel-6 data compared to a model. The mean swell propagation direction is cross-track. The five cross-spectra are computed from seven sublooks of a 1.7 s synthetic aperture, so that the separation between the centers is two sublooks, or about 0.4 s. The imaginary part of the cross-spectra is shown in Fig. 3 of the supplementary material S1.

based on a smooth surface, which is in this case the geoid. An iterative approach might be applied, where the focused waveforms are retracked and the resulting SSHs along-track low-pass-filtered (LPF) to serve as a reference surface, although only marginal differences are observed in open-ocean observations at moderate conditions.

To avoid storing multiple waveforms for each ground-track location, we apply a procedure like in SAR wave mode data, where the Doppler spectrum is computed from a single-look complex image in order to generate the sublooks [31]. The (phase) alignment of the leading edge is critical for this procedure and therefore we avoid large tracker jumps. It is also not possible to keep the range cell migration correction (RCMC) constant over more than ~ 10 waveforms as it will

introduce discontinuities in the sublooked radargrams. The Doppler spectrum is computed with

$$D(x, ky) = \mathcal{F}_y\{I(x, y)\} \quad (48)$$

where $\mathcal{F}_y$ is the Fourier transform in the along-track direction and $I(x, y)$ is the single-look complex radargram. The Doppler spectrum is then split using a windowing function $W_i(k_y)$. The window has width N_w/N_s , where N_w is the number of waveforms to be considered and N_s is the number of sublooks we intend to create. Eventually, the radargram for sublook i is computed as

$$I_i(x, y) = \mathcal{F}_y^{-1}\{D(x, ky)W_i(k_y)\}. \quad (49)$$

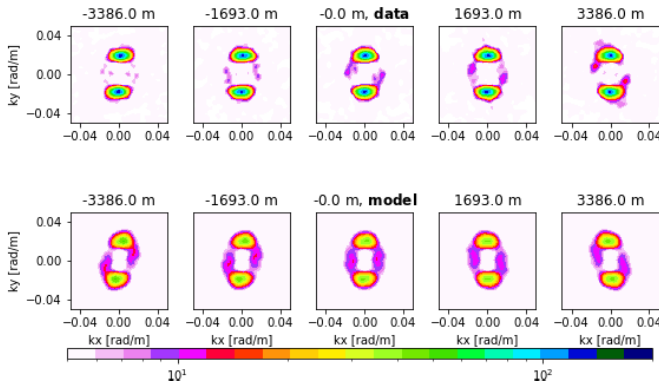


Fig. 18. Imaginary part of five cross-spectra estimated from Sentinel-6 data compared to a model. The mean swell propagation direction is cross track. The five cross-spectra are computed from seven sublooks of a 1.7 s synthetic aperture, so that the separation between the centers is two sublooks, or about 0.4 s. The imaginary part of the cross-spectra is shown in Fig. 4 of the supplementary material S1.

Three sublooked waveforms are shown in Fig. 15. If the range history is nearly constant over the considered region, this is comparable to splitting the aperture before focusing. As visible in the figure, the sensitivity to backscatter modulations is look-dependent. In the forward look, the curves bend with increasing along-track distance toward the leading edge and for the backward look vice versa. After that, the normalization is performed consistent with the numerical model. Note that we take the curvature of the Earth into account for the projection of the waveform samples onto the surface.

The forward model is computed using colocated ERA5 WA model (WAM) spectra supplemented by a parametrized short-wave spectrum [12] based on ERA5 winds. Note that ERA5 winds and WAM spectra are based on two-hour average outputs from the model. The WAM-based spectra will deviate from the true ocean-wave spectra, and are known to poorly perform in terms of directional spreading [32] and have difficulty separating swell and wind-wave energy [33]. Note that our forward model assumes a flat-Earth geometry, which changes the local incident angle with respect to a curved Earth and therefore slightly alters the modulations. Both will prohibit verification in terms of absolute PSD, but it will still be sufficient to describe the behavior of the cross spectra. The cross-spectral stacks for three different scenarios are compared with the forward modeled spectra based on WAM. A few additional cross-spectral stacks are provided in the supplementary material S2.

Fig. 16 shows a scenario where the swell system is propagating in one of the quadrants, which closely compares to the previously discussed scenarios (Section IV-B2). There is an offset in terms of peak PSD, but the behavior in slow time is well captured. The peak intensities in all four quadrants are close to equal in the zero-Doppler geometry. In the forward-looking geometry, the PSD in Q1 and Q4 is decreased while the PSD in Q2 and Q3 is increased, while for the backward-looking geometry, this behavior reverses. In the case of near-cross-track (Fig. 17) and near-along-track (Fig. 18), the spectral signals from left and right start to overlap, yielding only two spectral peaks. The overlap of signals from both sides

of the tracks leads to constructive or destructive interference. Using the forward and backward looks, swell signals from either side of the ground track (or quadrants) might be separated partly, but not the waves propagate exactly in the cross- or along-track direction. Retrieval of swell-spectral parameters near the along- and cross-track propagation direction is therefore prone to noise induced by interference between swell-induced signals of both sides of the ground track. The along-track autocorrelation of SAR processed waveform might provide additional information on along-track swell [34]. To limit interference, the along-track autocorrelation would need to be computed near the leading edge.

V. CONCLUSION

This article provides an in-depth analysis of SAR altimeter waveform tail modulation and its associated cross-spectral analysis. It describes the implementation of a fast numerical model. Using this numerical model, the closed-form solution, generally used for side-looking SAR spectra into ocean-wave spectra, is demonstrated to be inaccurate at steep incident angles. In contrast, SAR spectra from swath altimeters might be well interpreted by closed-form solutions for low to moderate sea states. Even though not fully accurate, closed-form solutions can still be used to derive first-order properties. In particular, it is confirmed that along-track and cross-track resolutions are proportional to the velocity variance and the SWH, respectively.

This article also introduces the concept of the cross-spectral stack, in which cross-spectra are formed from multiple sublooks of the seconds-long aperture of the altimeters. The cross-spectral stack enables improved analysis of the swell spectrum, thanks to a varying observation geometry. These changes indeed help infer the directional cut-off wavelength and the modulation, and to also increase the signal-to-noise of the long-wave signals. The nonzero Doppler left-right differences also provide an explanation for the uneven energy distribution in the four quadrants observed in [7]. The imaginary part, or phase, of the cross-spectra may then provide additional information on the wave propagation. The imaginary parts of the SAR altimetry cross-spectral stack, however, do not fully represent the ones computed from Sentinel-6 data. Still, the present model is useful to guide the interpretation and analysis of SAR altimetry waveforms under moderate conditions. It also provides a framework for modeling spectra from SAR altimetry waveform tails. It can be modified and extended to involve additional processes, like nonlinear waves [11] or a more realistic geometry.

Quite importantly, the present development opens to more systematically consider cross-spectral stacks to help more accurately retrieve ocean-wave spectral information for certain combinations of wavelength and propagation direction. Retrieved ocean-wave parameters shall then contribute to better monitor global wave field. It shall also serve to advance more consistent sea-state-bias corrections.

APPENDIX

The cross-correlation terms in (26) for a zero-Doppler observation are written as a function of transfer functions

[see (24)], such that

$$\begin{aligned}\rho_{xy} &= f(T_x(k_x, k_y)T_y^*(k_x, k_y)) = f\left(-\frac{H}{V} \frac{i\omega}{\tan(\theta)}\right) \\ \rho_{yx} &= f(T_y(k_x, k_y)T_x^*(k_x, k_y)) = f\left(\frac{H}{V} \frac{i\omega}{\tan(\theta)}\right)\end{aligned}\quad (50)$$

where we have inserted the transfer functions from Section III-A. This shows that the sum of the two cross-correlation terms becomes

$$\rho_{xy}(0, 0) + \rho_{yx}(0, 0) = 0 \quad (51)$$

and therefore cancel each other.

For the nonzero-Doppler geometry, the transfer functions from Section IV-A, which result in the cross-correlations

$$\begin{aligned}\rho_{xy} &= f(T_x(k_x, k_y)T_y^*(k_x, k_y)) \\ &= f\left(\frac{H^2}{V^2} \frac{\omega^2}{\tan(\phi_{sh})} - \frac{H}{V} \frac{i\omega}{\tan(\theta)}\right) \\ \rho_{yx} &= f(T_y(k_x, k_y)T_x^*(k_x, k_y)) \\ &= f\left(\frac{H^2}{V^2} \frac{\omega^2}{\tan(\phi_{sh})} + \frac{H}{V} \frac{i\omega}{\tan(\theta)}\right).\end{aligned}\quad (52)$$

By separating the Fourier Transform integrals for the imaginary and the real part, it can be shown that the resulting sum of the cross-correlations results in

$$\rho_{xy}(0, 0) + \rho_{yx}(0, 0) = 2 \frac{H^2}{V^2} \frac{\sigma_v^2}{\tan(\phi_{sh})} \quad (53)$$

where σ_v^2 is the velocity variance and ϕ_{sh} is the angular dependence as defined in Section IV-A.

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