Sea Surface Manifestation of Along-Tidal-Channel Underwater Ridges Imaged by SAR

Xiaofeng Li, Chunyan Li, Qing Xu, and William G. Pichel

Abstract—A group of submerged ocean bottom sand ridges in the Bohai Sea, China, are shown in RADARSAT-1 and ENVISAT synthetic aperture radar (SAR) images. The sand ridges appear as fingerlike quasi-linear features in the SAR images. Examining the detailed local bathymetry chart, we find that these features coincide with the satellite images. The heights of the sand ridges are less than 10 m, and the water depth is between 10 and 30 m. The spacing of the sand ridges is about 10 km, and the length of the sand ridges is about 20 km. The same sand ridges are also visible on a Moderate Resolution Imaging Spectroradiometer (MODIS) true-color image. The semidiurnal and diurnal tidal currents in this area are almost parallel to the major axis of these sand ridges. These observations cannot be explained using the existing 1-D SAR imaging model, which is not applicable to sand ridges parallel to the tidal current. In this paper, we consider the shallow-water current bathymetry in a 2-D space. An analytical ocean model was applied to demonstrate the temporal variations of the current divergence and convergence that are induced by the along-sand-ridge-direction current and ridge interaction. A radar simulation model is used to simulate the variation of normalized radar cross section (NRCS) induced by the ocean surface current. The simulated NRCS variation is similar to that extracted from the calibrated SAR image. Simulation results also show that the NRCS variation becomes negligible when the ocean current is set to about half of the maximum tidal current.

Index Terms—Sea floor and tidal model, sea surface, synthetic aperture radar (SAR).

I. INTRODUCTION

SHALLOW-WATER bathymetry features were first discovered on radar images in 1969 [1], [2]. Since then, numerous studies have been conducted to understand the imaging mechanism of bathymetry in shallow water. It has been found that under low-wind and strong-tidal-current conditions, shallow-water bathymetry features, i.e., sand ridges or underwater mountains, can be imaged by real aperture radar and SAR.

Although a microwave radar signal does not penetrate through water, the bathymetry features can still be imaged indirectly through the sea surface imprints of the interaction between the current and bathymetry. The existing existing radar bathymetry imaging theories are based on the following three processes: 1) the current and bathymetry interaction generates sea surface current divergence and convergence zones; 2) the sea surface current divergence and convergence modulate the wind-generated sea surface wave spectrum, which can be described by the weak hydrodynamic interaction theory; and 3) the variation of the height of short sea surface waves induces the backscatter variations seen in the radar image. One-dimensional radar-imaging models involving the above three processes were first developed by Alpers and Hennings [3]–[5] and then further enhanced by Van der Kooij et al. [6], Vogelzang et al. [7], and Romeiser and Alpers [8]. Field experiments have been conducted in Europe [7]–[12] and in the U.S. [13]–[15]. A historical overview of radar imaging of ocean bathymetry can be found in [5].

The overall assumption of 1-D radar-imaging models is that the current velocity vector is primarily normal to the direction of the sand ridge orientation. In other words, the current convergence and divergence over the topography is governed by the 1-D continuity equation. The flow parallel to the sand ridge is assumed uniform.

The hydrodynamic modulation is given by the action balance equation. After a series of simplifications, Alpers and Hennings [3] derived the relationship between the radar cross-sectional modulation and the current crossing the sand ridge

$$\frac{\delta \sigma}{\sigma_o} = \frac{4 + r}{\mu} |U_o|d_o \cos \psi \cos^2 \phi \frac{d'}{d^2}$$

(1.1)

where $\sigma_o$ is the normalized radar cross section (NRCS), $\mu$ is the relaxation rate, $\phi$ is the angle between the satellite flight direction and the sand ridge orientation, $\psi$ is the angle between the tidal flow direction and the sand ridge orientation, $d_o$ is the mean water depth outside the sand ridge area, $d$ is the depth profile along a cross section that is perpendicular to the sand ridge, and $d'$ is the gradient of the depth profile in the flow direction, $U_o$ is the cross-ridge current velocity, and $r$ is
variable of the wavenumber, surface tension, and water density. When the tidal flow direction or the satellite flight direction is parallel to the sand ridge orientation, i.e., $\psi$ or $\phi$ is 90°, then $(\delta \sigma / \sigma_o) = 0$, which indicates that the sand ridge cannot be imaged by the radar under these conditions. The radar backscatter modulation is also independent of the wind direction. Alpers and Hennings [3] further assumed that the image relative intensity modulations due to hydrodynamic interaction and velocity bunching are small. Therefore, the modulation of the synthetic aperture radar (SAR) image intensity is proportional to the tidal current velocity, the water depth, and the depth profile gradient. When the water is shallow (small $|d_o|$) and the tidal current is strong (large $|U_o|$), the image intensity modulation is large. This type of theory has been used in various studies with X-band, parallel to the sand ridge orientation, i.e., $\Phi = 90°$.

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The magnitude and direction of the major axes of the diurnal (red) and semidiurnal (yellow) tides from the literature [17] are overlaid on the MODIS image. One can see that both the semidiurnal and diurnal tidal currents are primarily parallel to the sand ridge orientation. According to the theory summarized in (1.1), there should not be any backscatter modulation in the SAR image. On the contrary, the backscatter modulation in the SAR images is apparent in this case. The sea surface divergence and convergence caused by the interaction of the tidal currents and sand ridges cannot be described by (1.1).

III. TIDAL CURRENTS OVER SAND RIDGES SOLVED BY AN ANALYTIC MODEL

A. Analytic Model Development

To examine the mechanisms of flow convergence and divergence, we have developed an analytic tidal model. The following is the model applicable to flows over a few sand ridges in a basin with an otherwise flat bottom. The basic assumptions are: 1) Earth rotation is negligible compared to the effect of significant depth variations (i.e., the relative vorticity induced by the velocity shear is much greater than the planetary vorticity due to Earth rotation) and 2) flow is a linear tidal wave. The nonlinear tidal effect may be important at the second order, i.e., to the residual flow field only. Our main interest here is the first-order intratidal oscillation that may possess convergence and divergence under the influence of underwater sand ridges.

We consider a rectangular basin with one open side, through which tide is propagating inside. The opening of the basin is at $x = 0$, and the length of the channel is $L$. The $y$-axis is in the cross-channel direction, and the channel width is $D$. The governing equations are

$$\frac{\partial h}{\partial t} = -g \frac{\partial \zeta}{\partial x} - \frac{\beta}{h} u$$

$$\frac{\partial u}{\partial t} = -g \frac{\partial \zeta}{\partial y} - \frac{\beta}{h} v$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0$$

where $h = h(y)$, and $u, v, \zeta, h, y, x, y, t$, and $\beta$ are the velocity components in $x$ and $y$ directions, surface elevation, water depth, the 2-D coordinates, time, and friction coefficient, respectively. The friction coefficient $\beta$ is expressed as $\beta = 8C_D U_0 / 3 \pi$, where $C_D$ and $U_0$ are the bottom drag coefficient.
Fig. 1. (a) RADARSAT-1 SAR image over the Bohai Sea. The RADARSAT-1 SAR image was taken at 22:00:03 UTC on March 22, 2003. The fingerlike quasi-linear features in the middle of the image represent the sea surface imprints of sand ridges. Based on the bathymetry charts, these sand ridges are ranked from S2 to S7. S1 is a very small ridge and not visible in the SAR image. (b) ENVISAT SAR image over the Bohai Sea. The image was taken at 13:44:34 UTC on January 3, 2007. The fingerlike quasi-linear features in the middle of the image represent the sea surface imprints of sand ridges. The locations of the sand ridges S2–S7 match those found in (a).
TABLE I
CHARACTERISTICS OF THE TWO SAR IMAGES USED IN THIS STUDY

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Mode</th>
<th>Acquisition Time/Date</th>
<th>Pixel Spacing</th>
<th>Spatial Resolution</th>
<th>Swath</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADARSAT-1</td>
<td>ScanSAR Wide B</td>
<td>22:00:03 UTC March 22, 2003</td>
<td>50 m</td>
<td>100 m</td>
<td>500 km</td>
<td>HH</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>Wide Swath</td>
<td>13:44:34 UTC January 3, 2007</td>
<td>75 m</td>
<td>150 m</td>
<td>400 km</td>
<td>HH</td>
</tr>
</tbody>
</table>

and the magnitude of the longitudinal velocity, respectively. The linear bottom frictional terms of (3.1.1)–(3.1.3) are derived from the quadratic law by decomposing the quadratic friction into a linear part and a higher order term correct to the second order, as shown in, e.g., [18] and [19] and used in [20]–[23].

The water depth is taken to be a general function of $x$ and $y$

$$h = h_0 (1 + \gamma h_1(x, y))$$  (3.2)

where $h_0$ and $\gamma$ are constants, and $h_0$ can be chosen to be the mean depth; $h_1$ is a specified dimensionless function of $x$ and $y$. To analytically solve the problem, we assume that $\gamma$ is a number smaller than $O(1)$. The depth range is thus $\delta h = \gamma h_0 \delta h_1$. We further require that the range of $h_1$ or $\delta h_1$ is $O(1)$. Therefore, $\gamma$ is a nondimensional measure of the variation of the depth function and is roughly proportional to the depth range over the mean depth, i.e., $(h_{\text{max}} - h_{\text{min}})/h_0$.

Equations (3.1.1)–(3.1.3) can be nondimensionalized using the following transformations:

$$\hat{\xi} = \sigma t \quad \hat{x} = x/L \quad \hat{y} = y/D \quad \hat{u} = u/U \quad \hat{v} = v/V$$
$$\hat{h} = h/h_0 \quad \hat{\zeta} = \zeta/a \quad U = a\sqrt{g/h_0} \quad V = \varepsilon\sigma D$$
$$\varepsilon = a/h_0 \quad L = \lambda/2\pi \quad T = \sqrt{g/h_0}/2\pi \quad T = 2\pi/\sigma$$  (3.3)
Substituting (3.6) and (3.7) into (3.4) and grouping all terms of order $\gamma^i$ yield the following governing equations:

$$\frac{\partial u_i}{\partial t} = -\frac{\partial \zeta_i}{\partial x} - \tilde{D} \frac{u_i}{h} + F_{xi}$$  \hspace{1cm} (3.8.1)

$$\frac{\partial v_i}{\partial t} = -H \frac{\partial \zeta_i}{\partial y} - \tilde{D} \frac{v_i}{h} + F_{yi}$$  \hspace{1cm} (3.8.2)

$$\frac{\partial \zeta_i}{\partial t} + \frac{\partial u_i}{\partial x} + \frac{\partial v_i}{\partial y} = F_{zi}$$  \hspace{1cm} (3.8.3)

where $i = 0, 1, \ldots, M$ [where $M$ is an integer that defines the number of terms to use for approximation, and the error resulting from the truncation of the perturbation expansion is $O(\gamma^{M+1})$], and

$$(F_{xi}, F_{yi}) = -\tilde{D} \left[- (u_{i-1}, v_{i-1}) h_1 + (u_{i-2}, v_{i-2}) h_2 + \cdots + (-1)^m (u_{i-m}, v_{i-m}) h_1^m + \cdots \right]$$

$$+ \left(-1\right)^i (u_0, v_0) h_1^i$$

$$F_{zi} = -\frac{\partial h_1 u_{i-1}}{\partial x} - \frac{\partial h_1 v_{i-1}}{\partial y}.$$  \hspace{1cm} (3.9)

We seek for a tidal solution in a standard format

$$(u_i, v_i) = \text{Re} \{ (U_i, V_i) e^{jt} \} \quad \zeta_i = \text{Re} \{ A_i e^{jt} \}$$  \hspace{1cm} (3.10)

where $\text{Re}\{\}$ indicates the real part of the complex function within the braces, and $j$ is the unit imaginary number $\sqrt{-1}$. Similarly, if we denote

$$(F_{xi}, F_{yi}) = \text{Re} \{ (G_{xi}, G_{yi}) e^{jt} \} \quad G_{zi} = \text{Re} \{ F_{zi} e^{jt} \}$$  \hspace{1cm} (3.11)

then

$$(G_{xi}, G_{yi}) = -\tilde{D} \left[- (U_{i-1}, V_{i-1}) h_1 + (U_{i-2}, V_{i-2}) h_2 + \cdots + (-1)^m (U_{i-m}, V_{i-m}) h_1^m + \cdots \right]$$

$$+ \left(-1\right)^i (U_0, V_0) h_1^i$$

$$G_{zi} = -\frac{\partial h_1 U_{i-1}}{\partial x} - \frac{\partial h_1 V_{i-1}}{\partial y}.$$  \hspace{1cm} (3.12.1)

Substituting (3.10) into (3.8) and using (3.11) and (3.12), we obtain the equations for $U_i$, $V_i$, and $A_i$

$$U_i = -\frac{1}{j + \tilde{D}} \frac{\partial A_i}{\partial x} + \frac{G_{xi}}{j + \tilde{D}}$$  \hspace{1cm} (3.13.1)

$$V_i = \frac{-\tilde{H}}{j + \tilde{D}} \frac{\partial A_i}{\partial y} + \frac{G_{yi}}{j + \tilde{D}}$$  \hspace{1cm} (3.13.2)

$$\frac{\partial^2 A_i}{\partial x^2} + \frac{\partial^2 A_i}{\partial y^2} + \alpha^2 A_i = G_i$$  \hspace{1cm} (3.13.3)

where $\alpha^2 = 1 - j \tilde{D}$, and

$$G_i = \frac{\partial G_{xi}}{\partial x} + \frac{\partial G_{yi}}{\partial y} - (j + \tilde{D}) G_{zi}.$$  \hspace{1cm} (3.14)
y-direction. To better visualize the divergence and convergence, the y-component of the velocity is exaggerated by 10 times in Fig. 5. It can be seen that during flood tide (tidal currents flow from \( x = 0 \) toward \( x = l \), i.e., from left to right), the flow around the central sand ridge is divergent in front of the sand ridge (the up-current side) and convergent in part of the leeward side (down-current side), which changes to divergent again as it is further away from the sand ridge. During ebb tide (tidal currents flow from \( x = l \) toward \( x = 0 \), i.e., from right to left), the flow around the central sand ridge is convergent on the left side of the sand ridge (the down-current side) and divergent on the right side of the sand ridge (up-current side), which changes to convergent again as it is further away from the sand ridge toward the right. This behavior of alternating convergence and divergence between flood and ebb tides is similar around the two sand ridges near the side walls, except that the flow around these two sand ridges are not symmetric—a result of the lateral boundary effects. Nevertheless, the divergence and convergence are all present. Fig. 6 is a zoomed-in view of Fig. 5, focusing only on the central sand ridge and the up-current portion, which clearly shows the alternating convergence and divergence.

D. Mechanism Analysis

The model results demonstrate that the sand ridges cause tidal divergence and convergence during different tidal phases around the bathymetry features. To analyze the mechanism that causes the alternating convergence and divergence, we further simplify the problem and look mainly at the 1-D momentum equation

\[
\frac{\partial u}{\partial t} = -g \frac{\partial \zeta}{\partial x} - \frac{\beta}{h} u. \tag{3.15}
\]

Using (3.10) and dropping the subscript \( i \), we obtain

\[
U = -\frac{g}{j\sigma + \beta/h} \frac{\partial A}{\partial x}. \tag{3.16}
\]

The magnitude of \( U \) is therefore

\[
|U| = \frac{\alpha h}{\sqrt{(\sigma \alpha)^2 + \beta^2}} \tag{3.17}
\]

in which \( \alpha \) is a constant with a unit of meters per square second. The magnitude of the along-channel flow \(|U|\) increases with increasing depth \( h \). However, this increase is nonlinear, and it slows down after \( h > 20 \) m [24]. Equation (3.16) also gives a phase relationship

\[
\varphi_U = \varphi_{AX} - \tan^{-1}(\sigma h / \beta) \tag{3.18}
\]

where \( \varphi_U \) and \( \varphi_{AX} \) are the phases of the complex functions \( U \) and \( \partial A / \partial x \), respectively.

The phase \( \varphi_{AX} \) is generally a constant for a given \( x \) if we extend the theory to 2-D with the condition that the tide propagates mainly in the \( x \)-direction [25]. Thus, this relation demonstrates that the phase of the along-channel tidal current is dependent on \( h \) such that tidal flow in shallow water leads that in deeper water. In summary, 1) the depth variation causes

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**Fig. 4.** Analytic model simulation domain. Three parallel sand ridges are located within a rectangular basin.

**B. Application of Analytic Model**

The solution for (3.13) is similar to that presented in [20, Appendix]. The only difference is that here, we apply this model to sand ridge problems with the depth function and domain configuration as shown in Fig. 4. The length and width of the basin are all 30 km. The maximum depth is 15 m, and the minimum depth is 7 m (at the center of the sand ridges). Three sand ridges are defined equally spaced across the basin. In the flow field, but we can reasonably assume that the flow near the central sand ridge is least affected by the boundaries. In addition, the sand ridges do not have to be parallel to the lateral boundaries. For brevity, we will not discuss situations in which the sand ridges are not parallel to the lateral boundaries. With these conditions, the analytic model can reasonably illustrate the process of tidal divergence and convergence detailed below.

**C. Results From the Analytic Model**

Tidal velocity in the model domain is calculated at 15-min intervals. Fig. 5 shows the flow vectors throughout the domain at two time intervals that are 5.25 h apart. Because the major axis of the current is in the \( x \)-direction, the velocity magnitude is about 1.5 m/s in the \( x \)-direction and about 0.15 m/s in the
Fig. 5. Velocity vectors in the entire domain. Shown here are two velocity vectors at time of 5.25 h apart at each point. The black-colored vectors are at the 18th time step, and the red-colored vectors are at the 39th time step, with a uniform time step of 15 min. We did not choose 6-h time difference just for visual effect: the vectors with 6-h time difference give vectors of opposite direction, which make it harder to view the two vectors at each position.

the tidal current to have different magnitudes and 2) the current in shallow water leads that in deeper water along a cross-channel line with a given $x$. The phase difference makes the tidal ellipses of adjacent positions of different depth values to rotate with a phase lag, and thus, their velocity vectors are not parallel to each other when there is a nonzero cross-channel velocity in the $y$-direction if the problem is further extended to 2-D. Furthermore, the velocity magnitude change in the $x$ direction will produce a velocity gradient in $x$. For a 2-D problem, such as in the present sand ridge case, the continuity will require that the flow have divergence or convergence, i.e., nonzero values for $\partial v/\partial y$ resulting from nonzero $\partial u/\partial x$. Both of these arguments lead to the conclusion that the tidal flow across bathymetry change (i.e., in the $y$-direction) will have convergence or divergence, depending on the tidal phase and position within the sand ridge.

IV. SIMULATION OF SAR OBSERVATIONS

A. NRCS Variations Over the Sand Ridge Area

The RADARSAT-1 SAR and ENVISAT ASAR images are first calibrated to get the NRCS values at each pixel. The NRCS signal level is primarily dominated by the wind speed. In the small sand ridge area, the wind can be considered uniform. Thus, the observed NRCS variation is primarily due to the convergence and divergence of the ocean surface current fields. The mean NRCS values within the sand ridge area are extracted from the SAR images and then subtracted from the signal. Fig. 7 shows a histogram plot of residual NRCS values extracted from two small areas (100 $\times$ 100 pixels for the RADARSAT-1 SAR image and 80 $\times$ 80 pixels for the ENVISAT ASAR image) over the sand ridge and the background in the calibrated SAR image, respectively. For the RADARSAT-1 SAR [Fig. 7(a)], the
The peak of NRCS values in the SAR background (darker area) is about \(-0.63\) dB from the mean, while the peak of NRCS values over the brighter sand ridge area is about \(+0.60\) dB from the mean. The same NRCS peak values for the ENVISAT ASAR [Fig. 7(b)] are \(-0.59\) and \(+0.68\) dB, respectively. Overall, the NRCS values in the sand ridge area are about 1.2–1.3 dB higher than those in the background.

### B. SAR Simulation

To quantitatively analyze the contribution of sand-ridge-induced surface current fields to the observed NRCS variations (1.2–1.3 dB) in the SAR image, we adopt the M4S SAR simulation model developed by Romeiser to simulate SAR images based on the RADARSAT-1 and ENVISAT orbital parameters and the actual environmental conditions. For a given satellite orbit, radar characteristics, and its incidence and looking angles, the M4S model can simulate the SAR image of a given surface current and wind field using either the Bragg scattering model or the full composite surface model. The detailed description of the M4S model can be found in the M4S 3.2.0 User’s Manual, which can be downloaded at ftp://ftp.ifm.zmaw.de/outgoing/romeiser/M4S320/M4S320installationpackage.exe. In this paper, we use the complete composite model for the simulation.

The wind speed and direction are obtained from Navy NOGAPS operational meteorological model outputs that are matched closest in time with the SAR observations. In both cases, the ambient wind speed is fairly low (3.8 ± 0.2 m/s southerly wind when the RADARSAT-1 image was taken and 6.0 ± 0.3 m/s northerly wind when the ENVISAT image was taken), a necessary condition for imaging the sand ridges by SAR.

Both the RADARSAT-1 and ENVISAT satellite platforms have similar orbital height and velocity. The two SAR images acquired are both at C-band with HH polarization. The
NRCS variations from the mean [Fig. 7(a) and (b)] are also similar. Therefore, we only present the ENVISAT M4S simulation results for brevity. The actual ENVISAT satellite parameters used in the simulation are: frequency = 5.3 GHz, incidence angle = 25.5°, radar look direction with respect to the x-axis = 283°, platform heading = 13° with respect to the x-axis, platform altitude = 800 km, and platform velocity = 7.45 km/s.

The surface current fields calculated from the analytical tidal model described in Section III are used as input to the M4S radar simulation model. The mean NRCS values are removed. The simulated residual NRCS image is given in Fig. 8(a). Since the mean wind is considered uniform and the mean NRCS values are removed, the residual NRCS variations are dominated by the ocean surface current signal. One can see that the simulated SAR images clearly show the dark and bright pattern over the sand ridge area. The top-to-bottom cross-sectional plot along the dash line in Fig. 8(a) is shown in Fig. 8(b). The ENVISAT simulation results show that the NRCS variation between the peak and trough is between 0.6 and −0.6 dB. The NRCS variation range (1.2 dB) is about the same as that extracted from the calibrated ENVISAT SAR image.

To understand the NRCS variations caused by the ocean surface current field, we purposely reduce the magnitude of current by half so that both components of the velocity in the along- and across-channel directions are reduced by half. The simulated ENVISAT SAR image is given in Fig. 9(a). One can see that the theoretical calculation still show the dark and bright pattern in the simulated image [Fig. 9(a)], but the NRCS variations [Fig. 9(b)] along the dash line in Fig. 9(a) is only at about 0.3 dB. This signal level is on the level of instrument noise floor. The smaller cross-channel velocity (or convergence and divergence) is the reason of a much-reduced simulated signal for the SAR image.
current induce the convergence/divergence that can be imaged by SAR. The NRCS variations between the bright and dark areas are about 1.2–1.3 dB for both SAR images. We have used the ocean surface current fields derived from the analytic model and performed a radar simulation using Romeiser’s M4S model. The simulated results show that the NRCS variations in the simulated image has the same range of variation as that extracted from SAR when the tidal current is strongest in magnitude (about 1.5 m/s). However, the NRCS variation becomes much smaller when the ocean current is set to about half of the maximum tidal current. This explains why the sand ridge can only be imaged when strong ocean currents exist.

Operationally, deriving ocean bottom features from a SAR image is still in the test phase. To achieve this goal, the first step is to understand the local tide information and bathymetry well enough to model the tidal current. The second step would be using the modeled tidal current as input to an advanced radar-imaging model to simulate the SAR image at a given satellite look angle and for various types of bathymetry. Our studies show that the current bathymetry interaction must be considered to understand the sea surface modulations observed by SAR.

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V. CONCLUSION

It is well known that strong surface current divergence and convergence can be imaged by SAR [26]. In this paper, we have demonstrated an interaction between tidal current and bathymetry that leads to current divergence and convergence. This mechanism explains the features in the SAR images containing sand ridges oriented parallel to the major tidal currents.

The backscatter modulation due to the current bathymetry interaction in the SAR image can be modeled if the local bathymetry and tidal currents are known. Existing theories are primarily based on 1-D models and require that the current is more or less perpendicular to the sand ridge, and thus, the sand ridge modulation of the surface currents is based on the 1-D continuity equation only, i.e., no dynamics are involved. The radar modulation is also a function of the radar look angle, the current velocity, the undisturbed water depth, and the gradient of the bathymetry feature. Although the 1-D models reveal the basic features of the sand ridge, they are too simple to explain the observations seen in the SAR images in tidal channels. The interaction between 2-D shallow-water sand ridges and the tidal current induce the convergence/divergence that can be imaged by SAR. The NRCS variations between the bright and dark areas are about 1.2–1.3 dB for both SAR images. We have used the ocean surface current fields derived from the analytic model and performed a radar simulation using Romeiser’s M4S model. The simulated results show that the NRCS variations in the simulated image has the same range of variation as that extracted from SAR when the tidal current is strongest in magnitude (about 1.5 m/s). However, the NRCS variation becomes much smaller when the ocean current is set to about half of the maximum tidal current. This explains why the sand ridge can only be imaged when strong ocean currents exist.

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