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Short Communication

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How to Obtain a Detailed SAR Pattern of Currents on the Ocean Surface

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At present, the generally accepted method for remote measurement of current velocity on the ocean surface is to determine the Doppler centroid, i.e., the position of the maximum of backscattered radar signal Doppler spectrum (see, for example, [1] and the list of references given there). However, this measurement, generally speaking, is not enough to reconstruct a detailed pattern of the currents.

The point is that the measured velocity is implicitly attributed to the point on the traverse to which the SAR beam is directed. However, it is known that the SAR image of a moving scatterer is shifted in azimuth in accordance with its radial velocity. Since all scattering sources on the surface are in motion due to waves and currents, their images are randomly shifted and, in the general case, may even overlap [2]. Thus, due to random and ordered (caused by currents) movements of the surface, a traverse point is assigned an alien velocity; as a result, the pattern of currents is distorted. These distortions have scales of the order of one or several hundred meters, so when it comes to global currents, they can be neglected, but in the case of coastal regions, when a detailed picture is needed, this can be considered significant.

We consider this issue in relation to microwave synthetic aperture radar (SAR), the main tool for studying the ocean from space. The operation of aperture synthesis is determined by the matching filtering formula

$$a_{SAR}(t) = \frac{1}{\Delta t}\int_{t-\Delta t/2}^{t+\Delta t/2} dt' a(t') \exp\left[-i\frac{k}{R}V^2(t'-t)^2\right] \qquad (1)$$

where $a(t')$ and $a_{SAR}(t)$ are the complex amplitudes (i.e., the Doppler parts) of backscattered field and of SAR signal, respectively, and Δt is the integration time determining the nominal SAR resolution (the factor before the integral is introduced to preserve the dimension). Here, $k = 2\pi/\lambda$, where λ is the radar wavelength, V and R are the SAR carrier speed and the slant range, respectively; the nominal azimuthal SAR resolution

$$\Delta_{SAR} = \frac{\lambda R}{2V\Delta t} \qquad (2)$$

Let us turn to the formula for the intensity of the SAR signal (1) at traverse point $x = Vt$ of the image line along the x –axis [2]:

$$I_{SAR}(x = Vt, y) = \frac{\pi}{2}\Delta y \int dx' \sigma_0(x', y) \exp\left\{-\frac{\pi^2}{2\Delta_{SAR}^2}\left[Vt - x' - \frac{R}{V}v_{rad}(x', y)\right]^2\right\} \qquad (3)$$

It is assumed that the SAR moves in parallel the x -axis, and the size of resolution cell Δy (along the ground range y -axis) is small compared to the characteristic wavelength of the large ocean wave (further, we will omit the argument y, insignificant in this case).

Backscattering of electromagnetic microwaves occurs on small-scale gravity-capillary ripples that move orbitally in the field of large waves; $\sigma_0(x')$ is the corresponding normalized radar cross-section.

Obviously, the integrand in (3) is significantly different from zero only in vicinity of intersection points of the straight line $f_1(x') = Vt - x'$ and the random curve $f_2(x') = (R/V)v_{rad}(x')$, where v_{rad} is the radial component of surface velocity:

$$v_{rad} = v_{cur.rad} + v_{St.rad} + v_{w.rad} + v_{orb.rad} = \bar{v}_{rad} + v_{orb.rad}$$

Here, v_{rad} is the sum of radial velocity components of the constant current, Stokes current, and wind drift; $v_{orb.rad}$ means the radial velocity of the orbital movement of small ripples.

In Fig.1 the horizontal lines show the approximate limits of values of the random function $f2(x')$, and the vertical lines show the location and the average azimuthal size L_x along the x -axis of the surface segment, which gives the defining contribution in the SAR signal. More accurately, according to [2],

$$L_x = \left[\Delta_{SAR}^2 + \pi^2\left(\frac{R}{V}\right)^2 \sigma_{orb.rad}^2\right]^{1/2},$$

where $\sigma_{orb.rad}$ is the r.m.s. of $v_{orb.rad.}$ In practice, one can confine oneself to the second term in square brackets. (Note that in the particular case shown in Figure. 1, this segment combines three intersections, i.e., there is an overlap of three sub-images.)

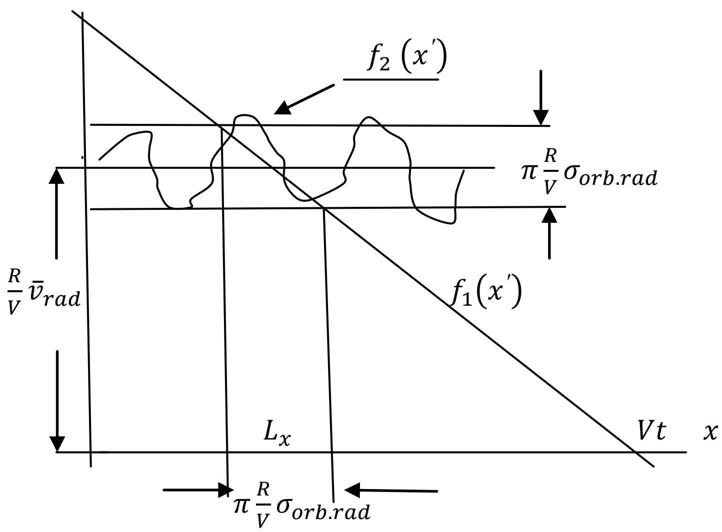

Fig.1

In the SAR image, the image of given segment is shifted from its real location, showed in Figure.1, to traverse point Vt, i.e., forward in the direction of movement of SAR. It corresponds to the case of positive $\bar{v}_{rad}$, when the total current is directed to the locator. In the case of the opposite $\bar{v}_{rad}$, the significant segment will be located under the x –axis, and its image will be shifted against the movement of SAR. Consequently, in SAR imagery, the pattern of currents is distorted.

Thus, having the values $\bar{v}_{rad}$ obtained through the Doppler centroid with an average accuracy of $\boldsymbol{f}_{STD}/2k$, where $\boldsymbol{f}_{STD}$ is the Doppler centroid standard deviation, one can determine the shift (R/V) $\bar{v}_{rad}$ at each image point, and then to shift it to its real place, i.e., to restore the real picture of currents with average accuracy of $(R/V)(f_{STD}/2k)$. The issue of f_{STD}, taking into account also other factors besides the orbital velocities, was considered in detail in [3], where, by means of numerical simulation, an estimate was obtained at SAR working frequency 9.6 GHz and a wide range of near-surface wind speeds: $f_{STD} \approx 3Hz$.

Note that it is generally possible to determine the current velocity and perform the procedure for reconstructing the real pattern of currents on the ocean surface without resorting to the Doppler centroid. As stated above, the integrand of (3) is concentrated in a relatively narrow segment size L_x shown in Figure.1. By the distance between the point x= Vt and midpoint $x' = Vt'$ of this segment, one can find the current velocity:

$$\bar{v}_{rad} = \frac{V}{R}\left(Vt - x_0'\right) = \frac{V^2}{R}\left(t - t_0'\right)$$

The measurement accuracy of v_{rad} on average will be determined by the value $\{R/V\}\sigma_{orb,rad}$ whence for the average error $\delta\bar{v}_{rad}$ it follows: $\delta\bar{v}_{rad} = (\pi/2)\sigma_{rad}$

Knowing the current velocity in the mentioned segment, as well as the magnitude and sign of the shift of its image, one can 'return' this segment from Vt to its real place and thus obtain an undistorted picture of the currents.

The main question remains: how to determine the location of the surface area that makes a decisive contribution to the SAR signal? Obviously, in the practical implementation of the matched filtering (1), one should select a segment with in the time interval $t - \Delta t/2 \leq t \leq t + \Delta t/2$ that makes the main contribution to the SAR signal and find its midpoint t_0'.

If this procedure is included in the SAR imaging algorithm, then simultaneously with the pattern of surface elevations an undistorted map of surface currents will be constructed. Note that this procedure works with the local value of the SAR signal, and a fairly extended signal realization is required to construct the Doppler spectrum.

Finally, let us estimate the considered effects numerically. So, for $R/V > 100s$, $v_{rad} = 2\ m/s$, and $\sigma_{orb.rad} = 0.5\ m/s$ the shift will exceed 200 m, and the average error of its determination will exceed 80 m.

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