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ISSN: 2642-9020

Short Communication

Journal of Marine Science Research and Oceanography

How to Obtain a SAR Image of the Ocean Surface That Is Actually Free from The Impact of Orbital Velocities

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Submitted: 01 July 2021; **Accepted:** 05 July 2021; **Published:** 12 July 2021

Citation: *Mikhail Kanevsky (2021) How to Obtain a SAR Image of the Ocean Surface That Is Actually Free from The Impact of Orbital Velocities. J Mari Scie Res Ocean, 4(2): 220-222.*

As is known, the main problem in interpreting images of the ocean surface formed by microwave synthetic aperture radar (SAR) is the distortions introduced by the orbital movements of the small-scale (centimeter and decimeter) ripples in the field of large waves. The point is that the standard aperture synthesis procedure is a matched filtering operation aimed at extracting from the reflected signal a part that has a phase that changes according to a known scenario corresponding to a stationary reflecting surface. The movement of the ripples responsible for microwave backscattering violates this scenario, which mainly manifests itself as cut-off of the high-frequency part of the image spectrum, which in turn leads to a loss of azimuthal resolution and false indication of the direction of wave propagation. The theory of this phenomenon is presented in or, in a simplified form, in where detailed calculations are omitted [1, 2].

In this work, we propose a sensing method aimed at reducing the effect of orbital velocities on the SAR image of the ocean surface. The method involves the use of two synchronized SARs, which look across the track line and illuminate the same area of the surface (Figure 1).

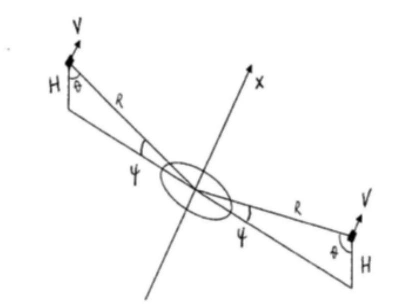

Figure 1: Probing geometry

It is assumed that the incidence of beams from both sides is fairly gentle, so that the horizontal component of the radial orbital velocity is much greater than the vertical one. In this case, the radial velocities relative to these beams will be close in magnitude, but mutually opposite in sign, which is the basis of the proposed method.

The aperture synthesizing operation is performed using the following transformation:

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

where a and a_{SAR} are, respectively, the complex amplitudes of the backscattered microwave electromagnetic field and the synthesized signal, Δt is the integration time.

Assuming the size of the SAR resolution cell in the horizontal range to be small in comparison with the characteristic wavelength on the surface, we will consider one row of the image in the azimuthal direction x. For the complex amplitude of the backscattered field, we write:

$$a(t') \propto \int_{\Delta x} dx'\, p(x',t') \exp\left[i\frac{k}{R}(x'-Vt')^2\right] \qquad 2$$

Where w is the azimuthal size of the physical resolution cell of the SAR, and p (x′, t′) is the complex reflection coefficient of the surface. Let the reflecting element of the surface be a point scatterer moving with a velocity, the radial component of which with respect to one of the SARs is

$$v_{rad}, \text{ i.e. } p(x',t') = p_0\delta(x'-x_0)\exp(-2ikv_{rad}t').$$

Obviously, with respect to another SAR, the radial velocity will have the opposite sign and close, although different from v_{rad} magnitude $-v_{rad} + \Delta v_{rad}$. (This difference is due to the presence of a small vertical component of the radial velocity, and from geometric considerations it follows:

$\Delta v_{rad} = 2v_{rad}\sin^2\psi$, where ψ is the depression angle.) Then for two SARs:

$$a_1(t') \propto p_0 \exp\left\{i\left[\frac{k}{R}(x_0 - Vt')^2 - 2kv_{rad}t'\right]\right\} \quad 3\text{ a}$$

$$a_2(t') \propto p_0 \exp\left\{i\left[\frac{k}{R}(x_0 - Vt')^2 + 2k(v_{rad} - \Delta v_{rad})t'\right]\right\} \quad 3\text{ b}$$

Let's write a_1 and a_2 in real form and then multiply them:

$$a_1(t')a_2(t') \propto \cos\left[\frac{2k}{R}(x_0 - Vt')^2 - 2k\Delta v_{rad}t'\right] + \cos[2k(2v_{rad} - \Delta v_{rad})t'] \quad 4$$

Let us apply the operation of matched filtering to the first term on the right-hand side of (4), having previously written it down in the usual complex form; while taking into account the double frequency of the filtered signal:

$$|a_{SAR\ pair}(t)|^2 \propto p_0^4 \left(\frac{\sin u}{u}\right)^2$$
$$u = \frac{2kV\Delta t}{R}\left(x_0 - Vt + \frac{R}{V}v_{rad}\sin^2\psi\right) \quad 5$$

Applying matched filtering to the second term gives a negligible value, which is natural due to the absence of a filtering object.

As is known (see, for example, [1]), in the case of a traditional survey using a single SAR

$$|a_{SAR}(t)|^2 \propto p_0^2 \left(\frac{\sin u}{u}\right)^2$$
$$u = \frac{kV\Delta t}{R}\left(x_0 - Vt + \frac{R}{V}v_{rad}\right) \quad 6$$

If we consider the ocean surface as a continuum of moving scatterers, whose velocities correspond to the spectrum of orbital velocities, and compare (5) and (6), then we can conclude that the results of the theory [1] are applicable to the pair with the only difference that k and v_{rad} should be replaced by $2k$ and $v_{rad}\ \sin^2\psi$. Since the depression angle ψ is assumed to be small, it can be expected that the influence of orbital velocities will be significantly reduced. In addition, as can be seen from (5), the nominal azimuthal resolution of the pair is twice as high as compared to the traditional SAR.

As shown in the theory, the presence of orbital velocities in most cases leads to the fact that images of different parts of the surface are randomly shifted and superimposed on one another. The fact that each point in the image plane is formed by different parts of the surface means a loss of resolution or, equivalently, the appearance of a spectral cut-off. The number of these parts, depending on the state of the surface, is random, and its fluctuations, along with fluctuations of the radar cross section, form the SAR image of the surface.

If the number of the parts is equal to one, then the disturbances introduced by the orbital velocities are not so significant and there is no spectral cut-off. From the theory [1], as applied to the pair, the condition for the absence of overlaps follows:

$$\Delta\sigma_{rad} \le \frac{0.3\Lambda_v}{R/V} \quad 7$$

where $\Delta\sigma_{rad}$ is the root-mean-square value Δv_{rad} and Λv is the characteristic wavelength in the spectrum of orbital velocities. Thus, for a sufficiently small value of $\Delta\sigma_{rad,}$ we obtain a wave pattern that is practically not perturbed by the orbital velocities. At the same time, it should be borne in mind that if for a conventional survey we consider the intensity of the SAR signal to be proportional to the surface elevations, then in this case the values of the obtained wave field turn out to be proportional to the square of the elevations.

We point out that to form a row of the image spaced at a distance d from the flight line shown in Figure. 1, one should use the transformation

$$a_{SAR\ pair}(t) \propto \int_{t-\Delta t/2}^{t+\Delta t/2} dt'\, a_1(t')\, a_2(t') \exp\left[-i\frac{2k}{R}\left(1 + \frac{d}{R}\cos\psi\right)V^2(t'-t)^2\right] \quad 8$$

In order to understand which sounding scheme can be applied for this method, some evaluations have been performed. As the initial data, we took H - the flight altitude of the SAR carrier and ψ - the depressing angle of the probe beam near the ocean surface. Then, taking into account the sphericity of the Earth, for the incidence angle ϑ and the slant range R we obtain

$$\sin\vartheta = \frac{a}{a+H}\cos\psi\,, \quad R = a\frac{\cos(\psi+\vartheta)}{\sin\vartheta} \quad 9$$

where a = 6371 km is the Earth radius. The estimates were carried out for ψ = 30° and the SAR carrier speed V= 8 km/s. For H= 200 km (low near-earth orbit), we get and ϑ = 57.10° R= 644.6$_{KM}$, and R/v= 80.6 s.

The value R/V ≈ 80 s with the traditional sensing method by no means guarantees the absence of spectral cut-off, while the proposed method, as shown below, can almost completely eliminate its probability.

Let us estimate the right-hand side of (7) for a given sounding scheme, which will give us $\widehat{\Delta\sigma}_{rad}$- an upper estimate of the value $\Delta\sigma_{rad}$, of at which the wave pattern obtained using the pair remains practically undistorted. For Λ_v ≈100 m, which corresponds to developed waves at a wind speed near the surface of about 10 m/s, we obtain $\widehat{\Delta\sigma}_{rad} = 0.37\ m/s.$ And then we give an estimate for the left-hand side of (7) for the same conditions, taking into account that $\Delta v_{rad} = 2v_{rad}\sin^2\psi$:

$$\Delta\sigma_{rad} = 2\sin^2\psi\,(\cos^2\vartheta + \sin^2\varphi\,\sin^2\vartheta)^{1/2}\sigma_{orb}$$
$$\sigma_{orb} \approx 6.8\cdot 10^{-2}U \quad 10$$

Here φ is the angle between the flight direction and the general direction of waves propagation, U is the near-surface wind speed. The second equality is an estimate of the root-mean-square value of the orbital velocity, following from the formula for the Pearson-Moskowitz spectrum.

Substituting in (10) the arbitrary value φ= 45° and the above values of all other quantities, we obtain $\Delta\sigma_{rad}$ = 0.27.

Thus, the considered sounding scheme provides a practically undistorted wave pattern with an increased resolution. It is possible to evaluate other schemes for the application of this method in space, although, of course, the initial tests should be carried out using airborne SARs.

References

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2. Mikhail Kanevsky (2020) Waves and noise in SAR imagery of the ocean. DOI:10.13140/RG.2.2.24416.71687.

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