SAR Imaging of Ship Wakes and Inverse Ship Wake Problem

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Airborne Synthetic Aperture Radar (SAR) images of sea surface often reveal ship wakes, which appear in a form of bright and dark streaks. It is believed that some of them pertain to the ship generated Kelvin wave system and some to the ship turbulent wake (Reed et al., 1990). The streaks in SAR images are sufficiently narrow to consider them as straight segments. Assuming that the location and orientation of the straight segments representing the ship wake in SAR images are defined, a related question arises: do these images contain sufficient information to extract from it certain ship characteristics, e.g. its speed and some principal geometric parameters?

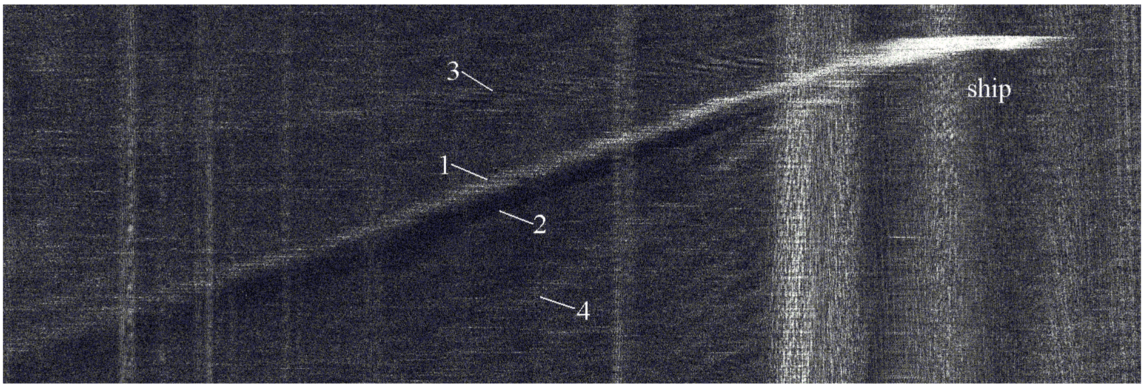


Fig. 1. Airborne ship wake image presented here was obtained by employing an X-band SAR in the course of experiments carried out in the eastern Mediterranean during light breeze. Several straight segments can be clearly identified: 1. bright wake presenting one of the two arms of the narrow V-wake; 2. long dark turbulent wake; 3-4. boundaries of the Kelvin wave-wake.

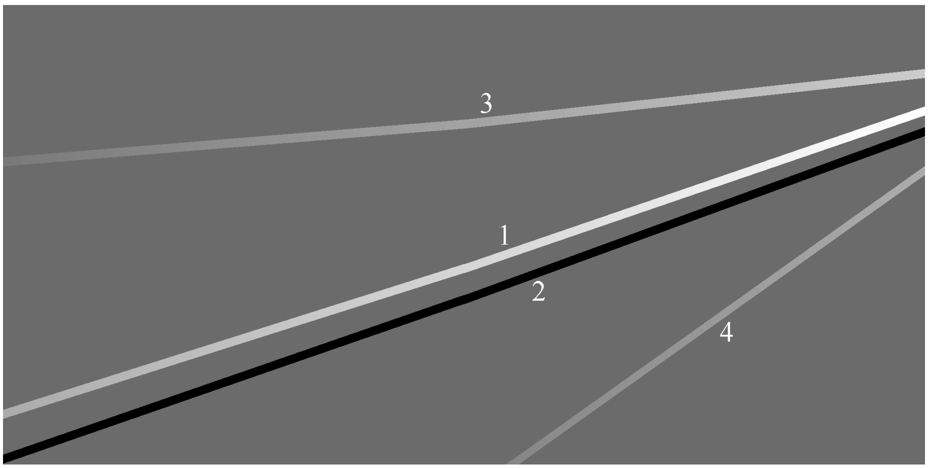
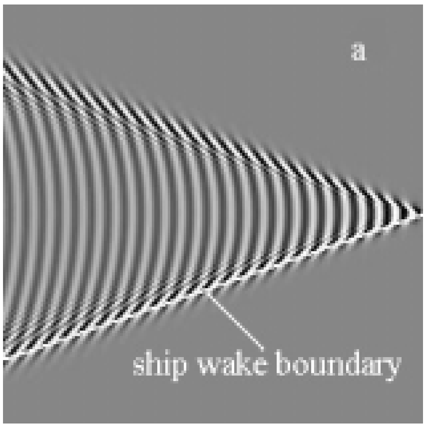


Fig. 2. Processing of SAR image by the fast discrete Radon transform.

The inverse ship wave-wake problem was discussed by Newman (1991) and Griffin et al. (1996). These works are based on an assumption that the Kelvin waves are fully observable and that their spectra can be calculated precisely. Scrutiny of used by us SAR images shows that it is rather difficult to extract from them the heights of the ship generated waves and to distinguish many important details of the Kelvin wave system. We do not assert that such a situation is typical for SAR imagery of ship wakes (albeit it is not unlikely) but admit the results of observations made by us and previously by many other researchers: in SAR images the turbulent wake and the Kelvin wave cusp-lines are the most robust and reliable manifestation of the entire ship wake pattern.

The classical Kelvin wave-wake consists of two different wave families, namely, the transverse and divergent waves. The Kelvin wave-wake is bounded by two cusp-lines at an angle $\theta = 2\arctan\sqrt{1/8}$. Along the cusp-lines, the wave-number K_θ of the Kelvin waves and the ship speed U are related as $K_\theta = \sqrt{3}g / 2U^2$, were g is the acceleration of gravity. Close to the cusp-lines the wave amplitudes decay with the distance x aft the ship as $x^{-1/3}$, whereas inside the Kelvin angle the decay is much faster, i.e., $x^{-1/2}$. Possibly for these reasons the boundaries of the Kelvin wave-wake are typically more distinguishable than the entire wave-wake. An example of a simulated Kelvin wave-wake is shown in Fig. 3a. Since a ship generates on the cusp-lines a narrow band wave spectrum, Tuck et al. (1971) proposed to estimate the ship speed according to the spectrum peak. An example of a simulated surface velocity spectrum calculated along the cusp-line is shown in Fig. 3b.



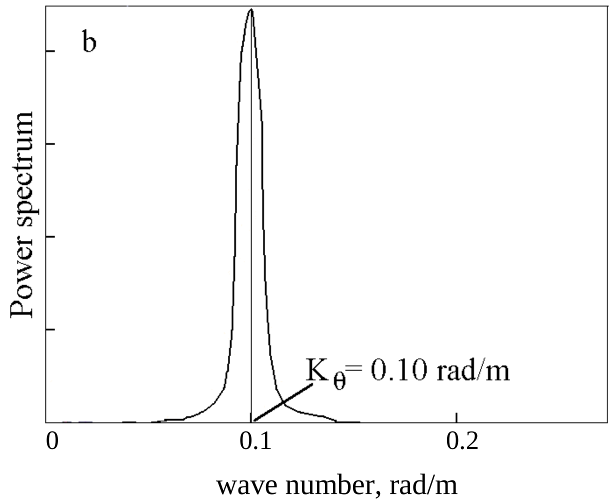


Fig. 3. Simulated longitudinal surface velocity for a ship with length L = 52.0 m, beam B = 5.70 m, draft T = 3.5 m and speed U = 9.2 m/s: a) surface velocity component; b) normalized power spectrum along the ship wake boundary.

An experimental wave spectrum obtained by processing of the SAR image along the cusp-line (see Figs. 1 and 2) is presented in Fig. 4. The wave-number of the spectrum peak corresponds to the estimated ship velocity $\hat{U} = 8.7$ m/s.

One of the most remarkable features of the far Kelvin wake is that a small boat and a supertanker moving with equal velocities may generate on the Kelvin arms waves of almost of the same length. Under such circumstances it is difficult to estimate the ship dimensions by processing of the Kelvin arms solely. To estimate at least one of the ship dimensions (its beam) we suggest here at the first time to explore the properties of the ship turbulent wake.

The expansion of the turbulent wake aft a self-propelled ship with zero axial net momentum was predicted by Birkgoff and Zarantonello several decades ago. Recently their asymptotic relationit was verified experimentally for full scale self-propelled vessels (Milgram et al., 1993). Although the qualitative agreement between the theory and experiment is striking, Birkgoff's formula cannot be used directly for estimating of the ship dimensions since it does not include ship parameters explicitly.

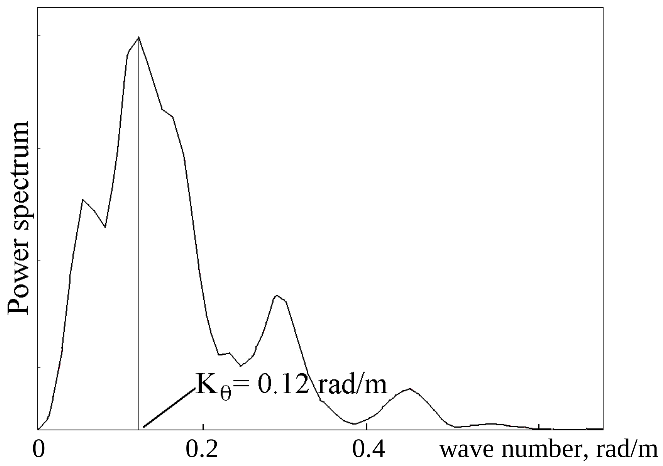


Fig. 4. Normalized power spectrum of SAR image intensity along the Kelvin cusp-line 3.

The width *W(x)* of the turbulent wake of a self-propelled ship grows with the distance x aft the ship as $W(x) = (AxB^{\alpha-1})^{1/\alpha}$, where α may vary between 4 and 5, and the constant of proportionality A can be obtained on the basis of experimental measurements; unfortunately, they are still rather rare. Assume that on some distance $x = \bar{x}_0 L$ aft the ship the wake width $W = \bar{w}_0 B$ is known. In such a case the width of the turbulent wake can be expressed as:

$$W(x) = \bar{w}_0 B\left(\frac{x}{\bar{x}_0 L}\right)^{1/\alpha}. \qquad (1)$$

For the ship observed by Milgram et al. (1993), the relation (1) is in a good agreement with the results of experimental observations if $\bar{x}_0 \approx$ 4.0 and $\bar{w}_0 \approx 5.0$. Once the measured values of the ship turbulent wake are known, the parameters α and B can be also evaluated. Examples of processing of the ship turbulent wake are shown in Figs. 5 and 6.

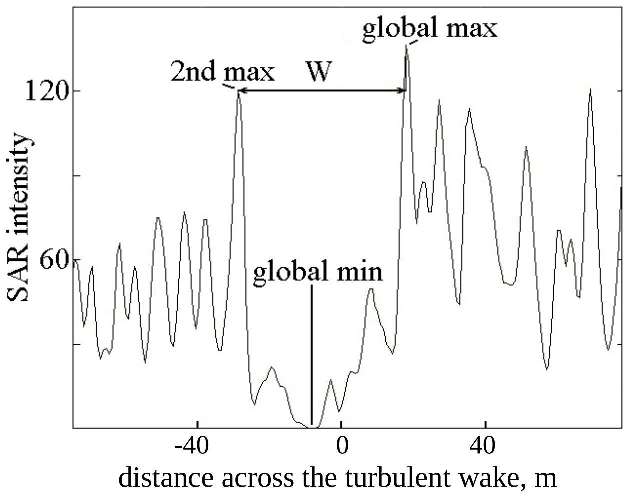


Fig. 5. SAR intensity variation in pixel brightness across the turbulent wake at some distance aft the ship (Fig.1).

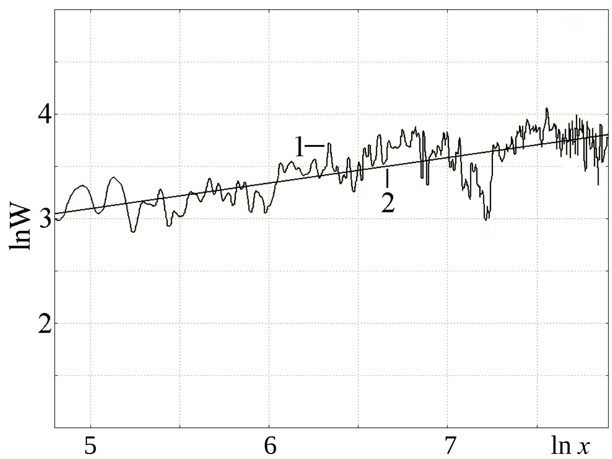
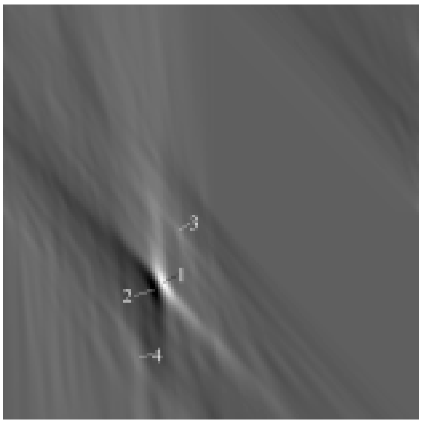
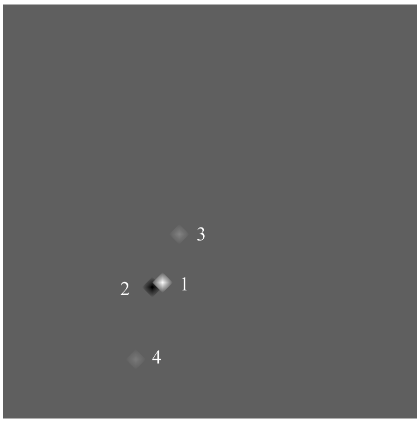


Fig. 6. Width of the turbulent wake: 1-measurements; 2-fitting by the least square method (α = 4.03, B = 5.5 m).

The processing of the ship wakes is feasible only if one knows their location in SAR images. Several authors have considered the long streaks in SAR images of ship wakes as straight lines and have used for their detection the discrete Radon transform (Copeland et. al., 1995). For the same purpose we use here the fast discrete Radon transform (Fig. 7).



a



b

Fig. 7. Radon space of the SAR image (Fig. 1): a) raw Radon space; b) refined Radon space. Restored lines see in Fig. 2.

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