FEATURES OF WIND FIELD OVER THE SEA SURFACE IN THE COASTAL AREA BASED ON SAR OBSERVATIONS

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"Wind-shadowing" effects in the Gulf of Finland coastal zone are analyzed using high resolution Envisat Synthetic Aperture Radar (SAR) measurements and model simulations. These effects are related to the internal boundary layer (IBL) development due to abrupt change the surface roughness at the sea-land boundary. Inside the "shadow" areas the airflow accelerates and the surface wind stress increases with the fetch. Such features can be revealed in SAR images as dark areas adjacent to the coastal line. Quantitative description of these effects is important for offshore wind energy resource assessment. It is found that the surface wind stress scaled by its equilibrium value (far from the coast) is universal functions of the dimensionless fetch Xf/G. Wind stress reaches an equilibrium value at the distance Xf/G of about 0.4.

Key words: wind transformation in coastal area, internal boundary layer, SAR, wind energy, Gulf of Finland

I. INTRODUCTION

When the air flow crosses the land-sea boundary, its characteristics change significantly due to abrupt changes of the underlying surface roughness and temperature. Adjustment of the air flow to the new surface characteristics takes place within the so-called internal boundary layer (IBL), the height of which increases with the fetch.

The IBL development is basically determined by the abrupt change of the following parameters at the land-sea boundary: (i) the aerodynamic surface roughness, (ii) surface temperature, and (iii) the air temperature above IBL. An overview of IBL models for the different conditions of their development is given in [1] (see also earlier papers [2-4] for more details).

Stages of the IBL development are generally divided into small-scale and meso-scale stages. During the former stage the IBL develops within the surface ("logarithmic") boundary layer, and during the latter one, the IBL extends beyond the logarithmic layer and evolves inside the Ekman part of the planetary boundary layer. Transition of the IBL development from small- to meso-scale stage takes place at fetches of few kilometers.

According to [1], for small-scale stage the IBL height, h, increases linearly with the fetch, x:

$$h\left[\ln\left(h/z_0\right)-1\right] \approx \kappa x, \qquad (1)$$

where z_0 is the roughness scale of surface over which the IBL develops, $\kappa = 0.47$ is the von Karman constant.

According to the measurements (see [1,2] for example) equation (1) is a quite good approximation of the IBL height at the initial (small-scale) phase of development. On the mesoscale stage the IBL depth develops as $\propto x^{1/2}$ for both neutrally and stably stratified IBL. In [3, 4] the following expression for growth of unstable stratified IBL had been proposed:

$$h^2 = C_D \gamma^{-1} \left(\theta_s - \theta_l \right) x, \tag{2}$$

where C_D is the surface drag coefficient, γ is the vertical temperature gradient above IBL, $\theta_s - \theta_l$ is the temperature difference between sea and land. For the stable stratified IBL the following expression was suggested [1]:

$$h^2 = \alpha^2 u^2 \left(g \Delta\theta / \theta \right)^{-1} x, \tag{3}$$

where α is the empirical constant, which value is in the range 0,014 – 0,024, g is the acceleration of gravity, u is the wind speed at the top of the IBL, $\Delta\theta = \theta_l - \theta_s$ is the temperature difference between land (temperature of background atmosphere) and sea. A simplified model of IBL, which is applicable for any stratification and stage of the IBL development, was proposed in [5].

Studies of wind field in coastal area are important for the wind energy assessment and development. If one is installing wind turbines in the coastal areas, he should take into account the effects of wind shadowing and IBL development with fetch. Wind above the IBL corresponds to the characteristics of the airflow above the land and, therefore, has a lower energy potential.

The main goal of this study is investigation of coastal area wind field features, associated with effect of wind acceleration in the developing IBL. The research is based on the measurements from synthetic aperture radar (SAR) ASAR (Advanced SAR) onboard Envisat satellite.

II. Study area and data

SAR measurements are the “ideal” tool for studies of wind field in the coastal area. The main advantages of SAR data are high spatial resolution (about 10 meters) and independence on presence of clouds. Examples of wind field studies using SAR measurements can be found in [6,7].

In total 10 SAR images of the Gulf of Finland was selected for this study. Each of the images represents typical scenario of the IBL development in the “homogeneous” incoming flow of different speed and atmospheric stratification.

For the analysis and interpretation of SAR measurements, the following data characterizing background conditions were used. Global Odyssea Sea Surface Temperature Analysis (http://satin.rshu.ru/) data were used for the sea surface temperature assessment. Land surface roughness lengths were defined from Global Land Use 2000 with a spatial resolution of 250 meters (http://bioval.jrc.ec.europa.eu/products/glc2000/products.php). The vertical temperature profile data from NCEP reanalysis (http://rda.ucar.edu/datasets/ds083.2/) were used as information about

background atmosphere stratification. The land surface temperature was also taken from NCEP reanalysis. Table 1 summarizes the background parameters for the considered cases of PBL transformation in the Gulf of Finland coastal zone.

Table 1. Observation data: U1000 is wind at 1000 meters, θ1000 is potential temperature at 1000 meters, θS is water surface potential temperature, θL is land surface potential temperature, z0 is roughness length.

№	U1000, м/с	θ1000, °C	θS, °C	θL, °C	z0, м
1	32	3	3.4	-2	0.8
2	27	3	3.4	-2	0.8

For retrieval of wind speed from SAR data we used empirical geophysical CMOD5.N [8] function, which relates normalized radar cross-section (NRCS) to equivalent neutral wind vector at 10-meter height as function of incidence angle. As the wind direction we used direction of wind shadows visible in SAR images, as well as wind direction from NCEP GFS model (0.5 degree) data (http://rda.ucar.edu/datasets/ds084.6/).

By definition, wind speed obtained with CMOD5.N model is equivalent neutral wind speed at 10 meters. In this paper we consider evolution of wind stresses as the most explicit indicator of PBL transformation in the coastal area. Wind surface stress, τ_s, is calculated from measured equivalent neutral wind speed, U_{10}, as:

$$\tau_s = \left[\kappa / \ln\left(10 / z_0\right)\right]^2 U_{10}^2, \tag{4}$$

where z_0 is sea surface roughness, calculated from Charnock formula [9]:

$$z_0 = C_z \frac{u_*^2}{g}, \tag{5}$$

with $C_z = 0.018$ as the Charnock constant.

Calculation of wind fields from SAR measurement includes the following steps: a) the original SAR images are smoothed using the Wiener filter [10] with averaging window of 525 meters; b) wind direction field is defined from NCEP reanalysis; c) equivalent neutral wind field is calculated from ASAR data using CMOD5.N model; d) wind stress field is calculated using (4-5).

Example of wind field calculated from SAR data is shown in Fig. 1. Remarkable changes of the brightness on SAR image (from west to east) are caused by dependence of NRCS on incidence angle. This feature disappears after applying the wind speed retrieval algorithm. Instead, dark local features related to the wind transformation under land-sea transition do appear. In particular, it is clearly visible dark area along the north shore of the gulf which corresponds to low values of wind speed. With increasing off-shore distance, the wind speed increases due to acceleration of the atmospheric boundary layer over new smoother (as compared to the land) sea surface. Elongated wind shadows behind leeward side of the islands are also well visible. As it follows from Fig1b

shading effect may extend to tens of kilometers from the coastline, which may affect the wind energy potential in these areas.

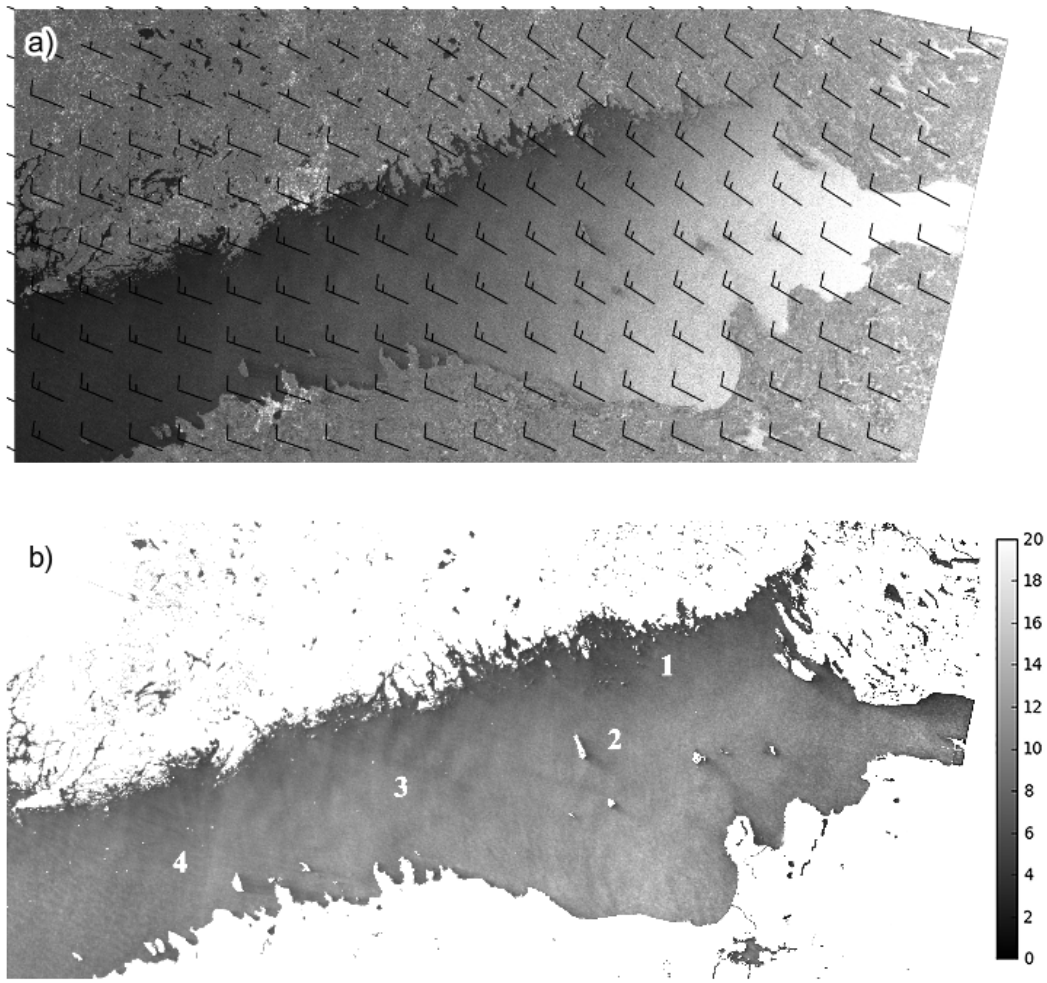

Fig. 1. (a) Fragment of ASAR Envisat image at 08.11.2011 08:51 UTC for eastern part of the Gulf of Finland: arrows indicate wind speed and direction from NCEP GFS model; (b) Wind field reconstructed from SAR data. Numbers in image indicate: 1 is shading area, 2 is island wakes, 3 is fingerprint of atmospheric internal gravity waves, 4 is cluster of ships.

The northern coast of the Gulf of Finland is a skerry-type with many rocky islands of various sizes and the straits between them that complicates analyze of the IBL development at the northern direction of the wind. Therefore, further we consider only cases of the southern winds.

III. Results

Fig. 2 shows a fragment of wind field derived from ASAR on the 2 January 2012, using NCEP wind directions, Fig. 3(a). According to the NCEP GFS data wind direction over the Gulf of Finland was mostly southeast. Long wind shadows of the islands and wind shadow along the southern coast are clearly seen on this image. Note that the width of the shadow along the normal to coastline depends on wind direction relative to the shore. It is clearly seen that the width is maximal

where wind blows perpendicular to the coastline and minimal where wind blows along coastline. These features indicate that the development of IBL can be described by the one-dimensional model.

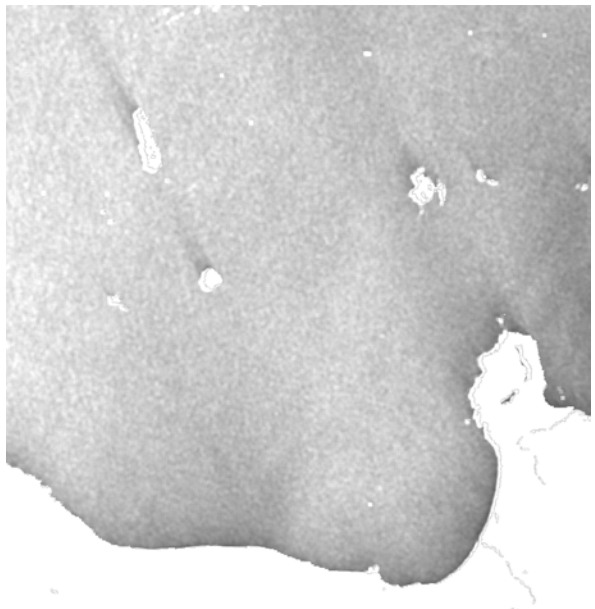

Fig. 2. Wind field reconstructed from ASAR Envisat image at 02.01.2012 08:33 UTC;

Measured profiles were simulated using a simplified model of atmospheric boundary layer transformation over inhomogeneous surface [5]. The input parameters of the model are the temperature and wind speed at certain level in the background PBL, the surface temperature of the land and water and surface roughness parameter. The output of the model gives change of the boundary layer parameters including changes of the surface wind stress and IBL height with fetch.

The input parameters of the model listed in Table 1. In this case stably stratified airflow enters the warm sea surface leading to the rapid development of unstable IBL.

Model simulations were performed for transections AB and CD along the wind direction (Fig. 3b). Profiles of the surface wind stress along these transects are shown in Fig. 3b and Fig. 3c.

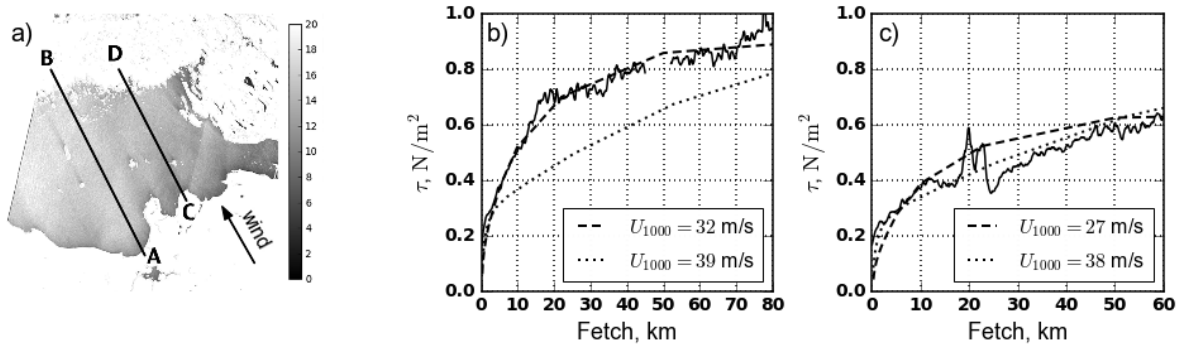

Fig. 3. (a) Wind field reconstructed from ASAR Envisat image at 02.01.2012 08:33 UTC for eastern part of the Gulf of Finland; (b) Wind stress profiles along transection AB from SAR data (solid line), from full model (dashed line) and from model taking into account only roughness change (dotted line); (c) The same as for (b) but for CD transection.

The model simulations are consistent with observations, describing the airflow acceleration and increase of wind stress in the course of the IBL development. For comparison, this Figure also shows the model simulations for the neutrally stratified IBL, when its evolution is due to abrupt change of the surface roughness across water-land boundary. In this case, wind accelerates more slower than observed.

All measured wind stress transections are plotted in Fig. 4a. Each of the wind stress profile is normalized by its equilibrium value u_{*eq}^2 and is presented as a function of dimensionless coordinate Xf/G , where X is fetch, f is Coriolis parameter, G is geostrophic wind speed. Value of u_{*eq}^2 was defined as steady-state value of surface stress far away from the coast, when IBL reaches its full development. Mean wind stress profiles and the standard deviations from the mean are shown in Fig. 4b. As it follows from the figure, surface wind stress reaches an equilibrium value at Xf/G about 0.3-0.4, which can be treated as the scale of the planetary boundary layer relaxation. .

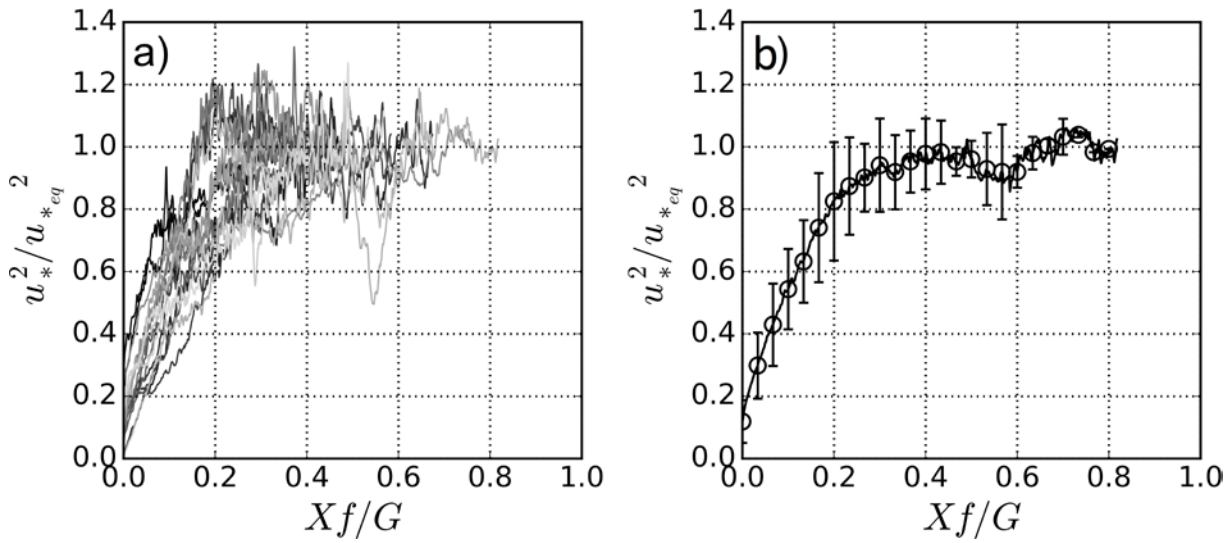

Fig. 4 The surface wind stress normalized by the equilibrium value of surface tension u_{*eq}^2 as a function of dimensionless fetch Xf/G: (a) all profiles, (b) mean wind stress profile and its standard deviations

There is a simple interpretation of this result. From the dimensional analysis, the height of the IBL h, during the stage of the mesoscale development is govern by the turbulent eddy-viscosity coefficient K_h in Ekman part of IBL:

$$h^2 \propto K_h X / G. \tag{6}$$

The eddy –viscosity coefficient also determines the depth of the equilibrium PBL H :

$$H^2 \propto K_h / f. \tag{7}$$

Therefore, combining (7) and (6), we arrive at:

$$(h/H)^2 \propto fX/G. \tag{8}$$

Development of the IBL terminates when its height attains depth of the equilibrium PBL prescribed by local characteristics of underlying surface and free atmosphere parameters. In this case, the wind stress increase with fetch is terminated. According to the measurements (Fig. 4), the proportionality coefficient in (8) is 0.3-0.4.

It should be noted, that equation (7) gives well-known asymptotic expressions for heights of neutral- and stable-stratified PBL, proposed earlier in [11]. To do this, we represent eddy viscosity coefficient in Ekman part of PBL as in [12]:

$$K_h = \kappa u_* \varepsilon H / (1 + \varepsilon H / L), \tag{9}$$

where ε is a constant of about 0.1. Substituting (9) in (7), we have the following expressions for dimensionless PBL thickness $\tilde{H} = Hf/u_*$:

$$\tilde{H} = \varepsilon\kappa / (1 + \varepsilon\mu\tilde{H}), \tag{10}$$

where $\mu = \kappa u_* / fL$ is dimensionless stratification parameter for PBL, $L = u_*^2 / \kappa\beta\theta_*$ is Monin-Obukhov length scale, $\beta = g/\theta$ is buoyancy parameter. From (10) the following asymptotic equations follow [11]: while $\mu \ll 1$ PBL height is $\tilde{H} \propto \text{const}$, while $\mu \gg 1$ PBL height is $\tilde{H} \propto \mu^{-1/2}$. With (10) IBL height (8) can be expressed as:

$$h \propto \tilde{H}\,(GX/f)^{1/2}. \tag{11}$$

Evaluating stratification parameter μ as $\mu \approx \kappa g\left(\Delta\theta/\theta\right)/(fG)$, equation (11) for very-stable stratified IBL becomes:

$$h^2 \propto G^2 \left(g\Delta\theta/\theta\right)^{-1} X, \tag{12}$$

which agrees with the equation (3).

A quantitative measure of the wind energy available at any location is called the wind power density, which is defined for a unit area and per second as:

$$Power = \frac{1}{2}\rho U_z^3 \tag{13}$$

where ρ is air density and U_z is wind speed at certain height.

Fig. 5 shows an example of model wind profile and wind power density for the case of multitransformation of the PBL caused by the transition from land to water surface and from water to land surface. The initial conditions for the model was: wind speed at 10 m is 5 m/s, neutral stratification; land surface roughness length is 0.8 m. Figure shows that the maximum of wind energy potential is achieved on the windward coast of the Gulf. And at the height of 50 meters (commercial wind turbines height varies from 40 to 170 meters) the maximum of wind power density is maintained above the land surface for about one kilometer from the coastline.

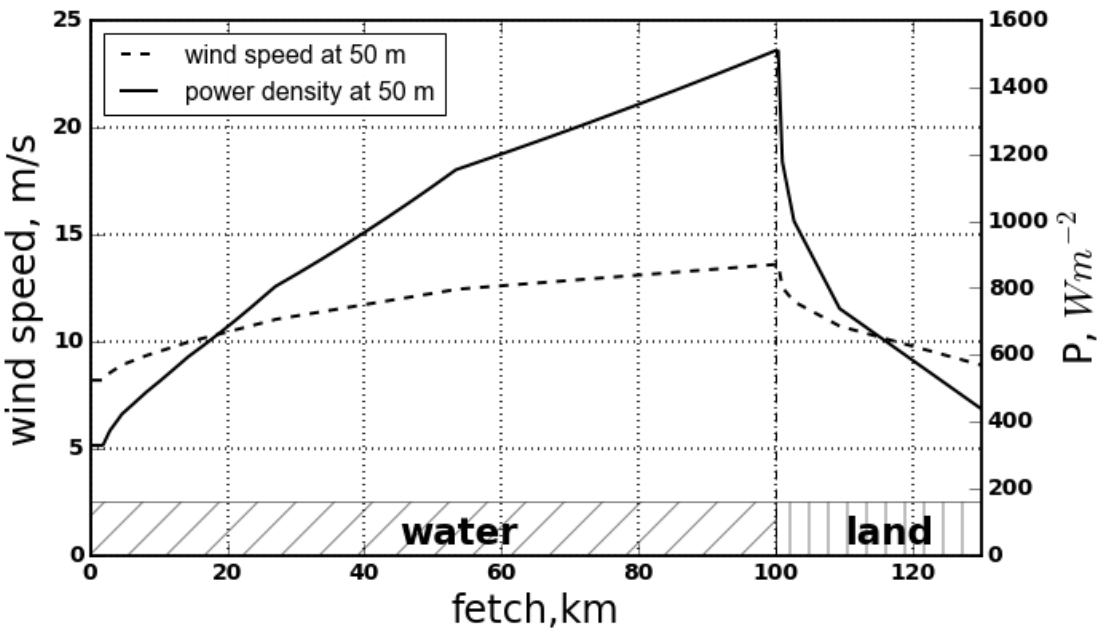

Fig. 5 Wind profile (dashed line) and wind power density profile (solid line) at height of 50 meters calculated with IBL model [5].

IV. Conclusions

Wind field features in the coastal zone of the Gulf of Finland were analyzed with use of high-resolution SAR measurements. In particular, the effect of “wind shading” as air flows from land to water surface was investigated. Such shading effects are caused by the fact, that atmospheric boundary layer initially adapted to the “rough” land surface, moves to “slippery” water surface, where it accelerates and surface wind stress increases with fetch. In SAR images areas of acceleration are seen as “dark” areas – areas of shading. Such features were observed in all analyzed here SAR images, either as shading areas along the coastline, or as wind “shadows” behind leeward side of the islands. Width of the "shadow" depends on the wind speed and atmospheric boundary layer stratification. Measurements showed that in the area of wind acceleration the surface stress, normalized to the equilibrium value (far from the coast) is universal functions of the dimensionless fetch. Surface wind stress reaches an equilibrium value at $Xf/G \approx 0.4$, which is the scale of the planetary boundary layer relaxation under the sea surface.

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