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On remote sensing of vertical shear of ocean surface currents by means of a single-frequency VHF radar

Victor I. Shrira

Department of Mathematics, Keele University, Keele, United Kingdom

Dmitry V. Ivonin

Shirshov Institute for Oceanology, Russian Academy of Sciences, Moscow, Russia

Pierre Broche, and Jean C. de Maistre

LSEET, Université de Toulon et du Var, La Garde, France

Abstract. We propose and test experimentally a new way of probing vertical shear of ocean surface currents by means of a single frequency VHF radar. The key idea is to use additional information provided by the so called secondary peaks in radar echo spectra which appear due to nonlinearity. Results of the field experiment carried out in the Rhône's delta show that the new method does enable one to probe the vertical shear with a reasonable accuracy and has potential for further development.

Introduction

Processes in the upper few meters of the ocean are the key ones in controlling ocean-atmosphere exchange. One of the most informative characteristics of this uppermost layer of the ocean would be the vertical profile of the drift current which implicitly gives the turbulence intensity distribution and through this the parameters of heat and momentum flux exchange at the air/water interface. However, no adequate technique to measure or even to estimate the current vertical profile in the upper meter has been found yet. In the present work we propose and test experimentally an idea of how to estimate subsurface shear by means of a VHF radar. The idea is based upon a well established technique of remote sensing of surface currents employing single-frequency radars operating in the HF ($5-30\,MHz$) and VHF ($\simeq 50\,MHz$) ranges [*Barrick*, 1972; *Broche et al.*, 1987; *Paduan and Graber*, 1997]. In this range scattering occurs in the Bragg regime, i.e. the frequency spectra of radar echo reflected from the sea surface exhibit two pronounced peaks corresponding to the so-called Bragg lines (see fig.1). The discrepancy between the observed frequency of the Bragg lines and the linear dispersion relation for resonant surface gravity waves is attributed to the Doppler shift of the frequency of resonant waves due to the presence of shear current. Indeed, this Doppler shift of the surface wave frequency is well resolved by radar. The technique was further advanced by employing either two or more radars with different frequencies simultaneously or the so called multifrequency radars: two or more frequencies emitted by such radars select correspondingly two or more Bragg waves which feel shear current differently, thus allowing one to estimate the current vertical shear [*Stewart & Joy*, 1974; *Teague*, 1986; *Fernandez et al.*, 1996].

We propose a new way of probing current vertical shear using a *single-frequency* radar. We employ the fact that the backscattered radar echo often has at least one more pair of smaller peaks, primarily due to contribution of the second harmonics of the *two times longer* water waves propagating along the radar beam. These peaks being less pronounced (about $20\,dB$ smaller) are often still discernible and by means of a signal processing technique, which we report in detail elsewhere, can be reliably resolved (see fig.1). This enables us to obtain one more parameter of the current, and, thus, to specify the shear. We tested the idea in the field experiment, the results we report show its feasibility.

Theoretical Foundations

Theory of VHF sea-echo Doppler spectra in terms of ocean wind wave spectra and currents is well established (e.g.[*Barrick*, 1972]). The main peaks in the echo spectrum are due to the resonant Bragg waves of the length half of the radar wavelength propagating along the radar beam (see Fig.1). The second order echo, obtained as a perturbation in wave slope and smallness of rms wave height compared to the radar wave length, is characterized by two distinct pairs of peaks at frequencies near $\pm\sqrt{2}\omega_{Bragg}$ and $\pm 2^{(3/4)}\omega_{Bragg}$. It is known that a continuum of waves of different wavelengths and directions contributes to the energy spectrum at these frequencies. The central point our study is based upon is the dominance of the contributions of particular combinations of wave vectors, namely $(\pm k_{Bragg}/2, 0)$ and $(\pm k_{Bragg}/\sqrt{2}, \pm k_{Bragg}/\sqrt{2})$ corresponding respectively to the *second harmonic* and *corner reflection* peaks. This allows us to neglect the contribution of the continuum and interpret the Doppler shifts of the corresponding peaks as associated with the particular wave scales, $k_{Bragg}/2$ and $k_{Bragg}/\sqrt{2}$, and thus infer new information on the surface current profile. The present paper reports experimental testing of this idea for the second harmonics peak. Some preliminary results inferred from the corner reflection peak are also mentioned in the discussion of possible further development.

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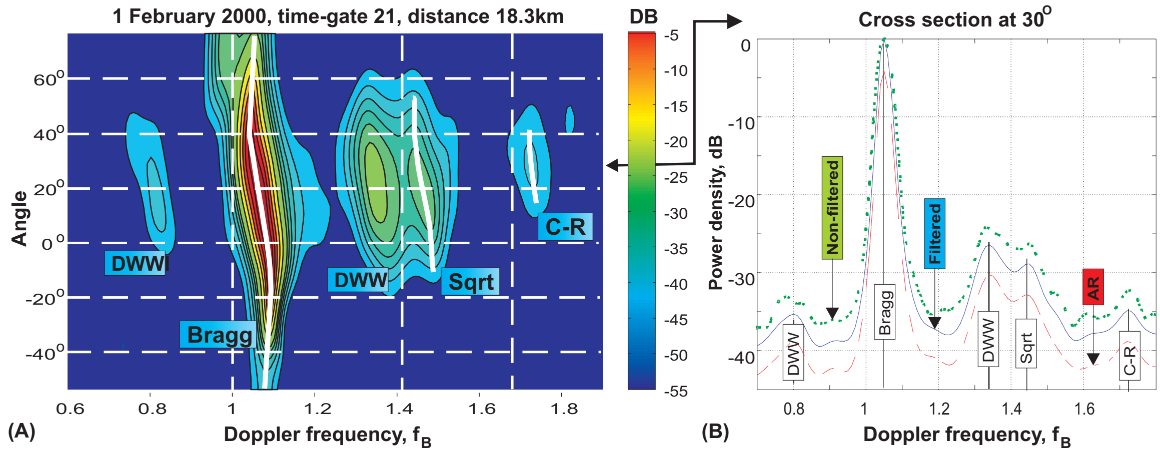

Figure 1. (a) An example of the positive part of the spectrum obtained by the prewhitening technique. Power density in dB is given by color scale. All the peaks, the Bragg one near $1.1f_B$, the second harmonic one near $1.41f_B$, two peaks near $0.8f_B$ and $1.3f_B$ due to dominant wind waves marked as DWW, and the corner reflection peak near $1.71f_B$ (marked C-R) are well discernible. The spectrum is for the time-gate 21, i.e for distance 19 km from the radar. 32 noncoherent samples were used. **(b)** The spectrum cross-section at the angle 30^o. The dashed line is non-prewhitened spectrum, the dotted one is autoregressive (AR(50)) spectrum, the solid line gives the prewhitened spectrum (50 autoregressive coefficients).

Experiment

The field experiment was carried out by *Laboratoire de Sondages Electromagnetiques de l'Environnement Terrestre, Université de Toulon et du Var* in the delta of Rhône (French Mediterranean coast) in February 2000. The site advantage is in the fact that it is well studied [*Broche et al.*, 1998] and is known to provide a wide range of values of vertical shear from very high, localized in the Rhône plume, to quite small, typical of wind induced currents, distributed in space in a constantly changing manner. A VHF radar operating at 45 MHz (the EM wavelength $\lambda \simeq 6\,m$ and the resonant water-wave wavelength is about $3\,m$) was situated at a sand beach 4 km to the East of the delta (see fig.2). The radar had 4 transmitting elements and the receiving phased array of 16 dipoles spaced by $3.33\,m$. The directional diagrams of both transmitting and receiving antennas were tested from a ship. The phase adjustment was done digitally in the data processing after the signals from each element had been separately recorded. To avoid often observed first peak splitting (e.g. [*Barrick*, 1972; *Forget et al.*, 1981; *Fernandez et al.*, 1996]) we applied the Welsh technique [*Marple*, 1987] to

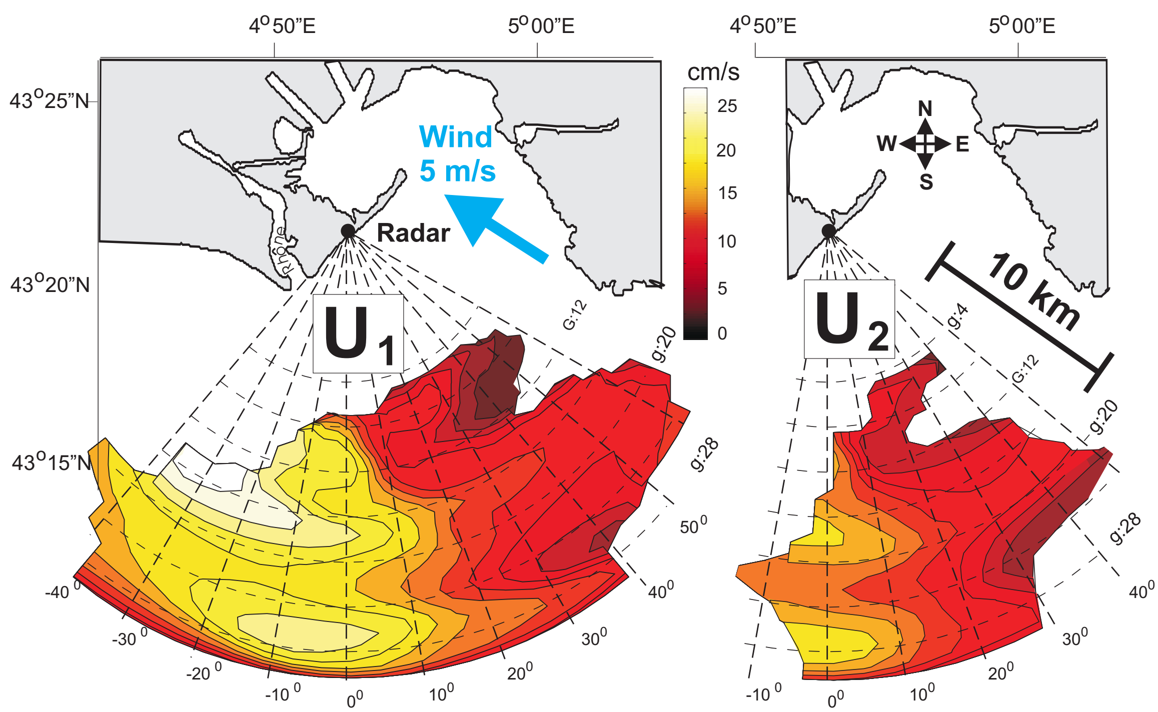

Figure 2. A sample of the velocity fields reconstructed from the shift of the first and second harmonic peaks. The radial velocity component is directed to the radar. The current velocity is given by color scale in cm/s.

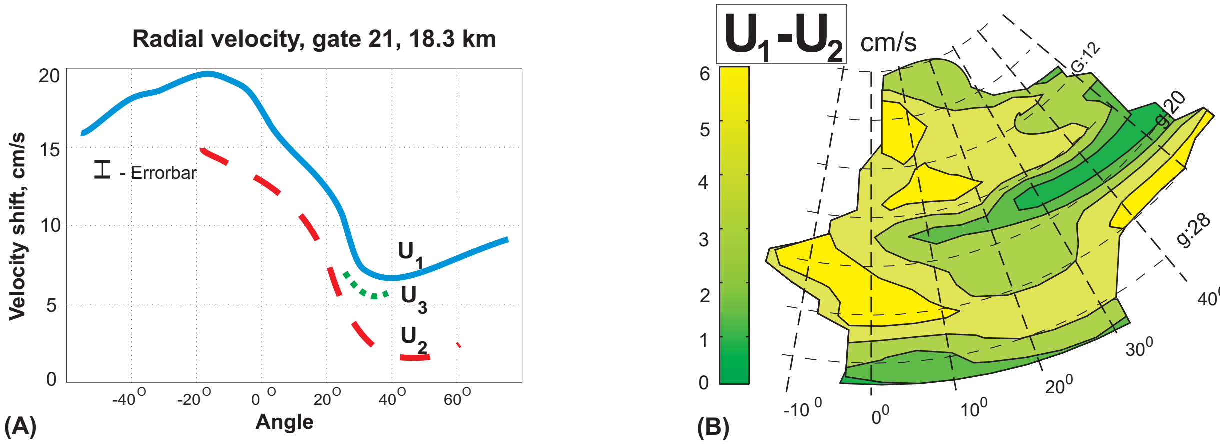

Figure 3. **(a)** Radial current velocity (in cm/s) at two characteristic depths obtained from the Bragg and the second harmonics echo. We also add plot of U_3 due to corner reflection (see Concluding Remarks). Gate 21, distance 19 km. **(b)** Map of radial component of vertical shear as the difference (in cm/s) between the currents at two characteristic depths obtained from the Bragg and the second harmonics echo.

the angle. We divided the array of 16 whips into 3 arrays of 8 whips overlapping by 4. Thus the bearing cell was 13^o. The along-ray resolution was $600\,m$. The radar peak power is $1.6\,kW$ enabling it to cover the range of up to $30\,km$ under reasonably good weather and wind wave conditions. As only one radar was used, only the radial component of the current velocity is studied hereafter.

We found out that for distances up to $20\,km$ both the first (Bragg) and the second ($\sqrt{2}$) peaks were well separated and resolved (see fig.1). The main problem was concerned with the two peaks symmetrical with respect to the Bragg frequency due to dominant wind waves or swell which are often observed on both sides of each of the Bragg lines. As in our case these peaks appear close to the second harmonic peak (see fig.1), the prewhitening technique [*Percival*, 1993] has been used to resolve them more accurately (fig.1b).

Results: Velocity Shear

The particular results given below are confined to the observations made on 1 February 2000, 13:00-14:00 GMT. The conditions were characterized by a moderate $5-6\,m\,s^{-1}$ SE (130^o) wind with gusts up to $10\,m\,s^{-1}$. We found from the radar measurements two integral parameters of the shear flow, which can be estimated using the Stewart-Joy formula [*Stewart & Joy*, 1974]:

$$U_1 = 2k \int_{-\infty}^{0} U(z) e^{2kz} dz, \;\; U_2 = k \int_{-\infty}^{0} U(z) e^{kz} dz, \qquad (1)$$

where $k = k_{Bragg}$ is the wavenumber of the Bragg water wave, $U(z)$ is the current vertical profile, and U_1 and U_2 are the velocities provided by processing the main and second harmonics peaks, respectively. The plots in fig.2 show velocity fields U_1 and U_2. They are consistent with each other. We estimated velocities U_1 and U_2 only for the angles where the peaks can be confidently resolved (see fig.1). The absence of the signal from the part of the plume area in fig.2 is due to its stronger attenuation over fresh water. The difference between the velocities obtained from the first and second harmonics peaks is plotted in fig.3b. The difference usually varies from about $20\,cm\,s^{-1}$ in the plume area (just $\simeq 7 cm\,s^{-1}$ in the presented example) to $2-4\,cm\,s^{-1}$ outside the plume. We provide a more detailed picture of U_1 and U_2 in fig.3a. The error in velocity estimation which is discussed later, is $\simeq\ 1\,cm\,s^{-1}$. This is about 20% of the difference $U_1 - U_2$ in the open sea. Thus, by means of our single frequency radar it proved possible to resolve confidently the difference in shear current velocity at two different characteristic depths.

To find the vertical shear or the characteristic vertical scale of the shear we should either know *a priori* the profile of the current near the surface or have a verified model of the surface current. As long as these options are not available, the only way is to make a learned-guess-type assumption on the profile. Since the outcome is not very sensitive to a particular model [*Broche et al.*, 1986], we take for an estimation the often used exponential shear model $U_e(z) = U_0\ e^{z/h}$ having the advantage of the ultimate simplicity. Then the vertical scale h varies from $0.5\,m$ to $4.5\,m$.

An improvement of the quality of the results was obtained due to use of comparatively long time series. The total length of the data set of $T = 3072\,s$ enables us to attain a very low theoretical error of $0.5-0.6\,cm\,s^{-1}$ [*Barrick*, 1980; *Broche et al.*, 1987]. Since the employed long data acquisition took about an hour we controlled the velocity variations with time. A conservative estimate of the error is $\simeq 1\,cm\,s^{-1}$. At present we do not have at our disposal a way to check directly the validity of our results by an independent method. The work on analysis of data obtained by independent means able to corroborate the results is in progress.

Concluding Remarks

In our view the presented analysis of a few samples of field data convincingly shows that the existing VHF radars can be used to probe the characteristic vertical scale of the currents, at least in the situations characterized by strong currents and high vertical shear. The questions of validation of the proposed method and establishing the range of its applicability remain open yet. The work is in progress. The main advantage and the main weakness of the proposed method stem out of the same basic fact: there is no reliable alternative way of measuring drift velocity profile in the upper meter or two in the presence of developed wind waves.

The method was tested in a specific coastal environment characterized not only by strong currents but also by their strong and capricious localization in space and variability in time. In this context the method can be applied for monitoring the coastal environment, it has an advantage of providing the picture of current and shear distribution in real time and enables one to catch both spatial and temporal variability of small-scale coastal processes of practical interest in comparatively large area (up to 20 km in radius). The situations typical of open sea are characterized by weaker shear but at the same time by much less variability in space and time, the currents are often almost steady uniformly plane-parallel in the range of scales we are interested in. This enables us to apply the method to such generic situations as well, since the resolution of the method can be noticeably enhanced as soon as the geometry of the currents is simple and *a priori* known.

The method can be also further extended to include processing of the corner reflection (CR) peaks linked to the pair of waves $\sqrt{2}$ times longer than the Bragg wave propagating at angles $\pm 45^0$ to the radar beam. The Doppler shift of the peaks results from the radial component of the current only, since the contributions of transverse components cancel each other. By providing a third integral equation of the type (1), this enables one to obtain a better approximation to the shear profile. We show in fig.3b (the green dotted curve) that the CR curve can be found indeed and it is consistent with the curves for the first and second harmonics. The figure also illustrates the principal limitations of the advance in this direction: the CR peaks are discernible only in the comparatively narrow range of angles.

We conclude that probing of the surface current shear by a single frequency VHF radar is indeed possible, and could provide extremely valuable real time information on air-sea exchange processes.

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V. I.Shrira, Department of Mathematics, Keele University Keele, ST5 5BG, UK. (e-mail: v.i.shrira@keele.ac.uk)

D.I. Ivonin, Shirshov Institute for Oceanology, Russian Academy of Sciences, 36 Nakhimovsky av., Moscow 117851, Russia. (e-mail: dima@wave.sio.rssi.ru)

P.Broche and J.C. de Maistre, LSEET, Université de Toulon et du Var, La Garde 83957, France. (e-mail: broche@lseet.univ-tln.fr; demaistre@univ-tln.fr)

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