Preliminary Side-Scan ADCP Measurements across a Ship's Wake

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ABSTRACT

A preliminary study shows how a standard acoustic Doppler current profiler, tilted so two beams scan horizontally beneath the surface, can be used to map characteristics of a ship's wake. For example, the measurements appear to resolve the flow of surface water outward from the wake centerline. This centerline divergence and the resulting convergence along the edges of the wake help form bands of relatively calm water that often appear in radar imagery of the sea surface.

1. Introduction

Radar imaging of phenomena such as ships' wakes, internal waves, and fronts relies on the patterns produced as a spatially varying current interacts with surface waves and surface-active material (e.g., Ochadlick et al. 1992). In the particular case of the wake of a surface ship, images show two distinct signatures having low levels of radar backscatter compared to ambient (corresponding to relatively calm water): a dark, trailing centerline wake, which is several ship beams wide and may extend for several tens of ship lengths aft, and a nearly parallel pair of much narrower dark bands, which may persist for over an hour and extend tens of kilometers (e.g., Reed et al. 1990; Griffin et al. 1992; Peltzer et al. 1992). An hypothesis to account for these signatures relies on twin vortices shed by a ship's hull that move surface water away from the centerline and toward the edges of the wake. This diverging flow can block and refract waves, leading to the calm centerline region. Further, the diverging flow will advect surface films, foam, and bubbles toward convergence zones along the two edges of the wake, where the material will collect and films will be compacted; this will act to lower the surface tension and damp small-scale surface waves, giving rise to the pair of narrow bands of calm water.

A test of these ideas requires knowing the surface flow field associated with the wake, especially the transverse velocity component; but, to our knowledge, direct current measurements have never been made in the field, though the flow has been inferred from drifters dispersed within a ship's wake (Kaiser et al. 1988; Meadows et al. 1994). While extensive numerical and model studies of ship hydrodynamics are available (e.g., Reed et al. 1990; Meadows et al. 1994), we believe it useful to have a technique for measuring the currents across an actual wake that would lend itself, ultimately, to a coordinated study of the velocity, surfactant, and surface wave fields.

One way to make the surface velocity measurements is to adapt acoustic Doppler current profilers (ADCPs), which have proven so useful in measuring currents in vertical profile, by tilting an instrument so two beams scan horizontally just beneath the ocean surface. While horizontally scanning acoustic Doppler measurements have been made in the open ocean from the *Floating Instrument Platform* (*FLIP*) (e.g., Smith 1992) and with success from a bottom-mounted rig near the shore (Smith 1993), the instruments used are specialized and not readily accessible to the general research community.

In this paper, we report the results of an attempt to use a standard, commercially available ADCP in a side-scan configuration to measure near-surface currents across the wake of a target ship. The ADCP is deployed in an instrument package towed on the water's surface parallel to the target wake. This geometry should be well suited to measuring the transverse flow, which is of especial interest. The measurements were made in the shallow, protected waters of Chesapeake Bay. As the reader will see, the data are limited and working in shallow water had drawbacks; nevertheless, we believe the results are encouraging and suggest additional applications, and it is in that spirit we are reporting these preliminary results.

2. Instrumentation

Measurements were made with an RD Instruments, Inc., 600-kHz broadband ADCP, standard except that

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the transducer head is attached with a right-angle adapter and rotated 45°. The ADCP is mounted lengthwise beneath a 3-m-long cylindrical float (Fig. 1a). A conductivity–temperature–depth (CTD) instrument is mounted below the ADCP, aft of the acoustic transducers. The ADCP, CTD, and float are supported between twin vertical keels. A mechanical tow cable is attached to the port keel and float with a three-point bridle so that the instrument package kites off to the starboard side and samples water undisturbed by the wake of the research ship. The kiting results in a small angular offset (about 5°) from the forward tow direction (Fig. 2). This combination of instruments and towbody is called TOAD (for towed acoustic Doppler). TOAD has been used previously with the ADCP in its usual down-looking configuration (Andrews and Trump 1994; Trump et al. 1995).

In this work, the ADCP was used in side-scan configuration. This configuration was achieved by rotating the ADCP about its lengthwise axis until the two starboard beams were aimed horizontally at a depth of about 0.3 m (Fig. 1b) and with an angular separation of 41.4° (Fig. 2). As this rotation put the internal ADCP pitch-and-roll sensors off scale, auxilliary angle sensors were attached to the ADCP. These were monitored on a computer and recorded separately with a sampling rate of 6.3 Hz. For the data of interest here, TOAD rode with its bow up slightly (a mean pitch of 2.9° and a standard deviation of 0.9°). There was a mean starboard roll of 0.3°, though this small an angle is within the error of our determining a true horizontal in a laboratory reference frame. More significant is the roll standard deviation of 1.4°. As the acoustic beamwidths are 1.5°, the measurements can be expected to show some sensitivity to roll.

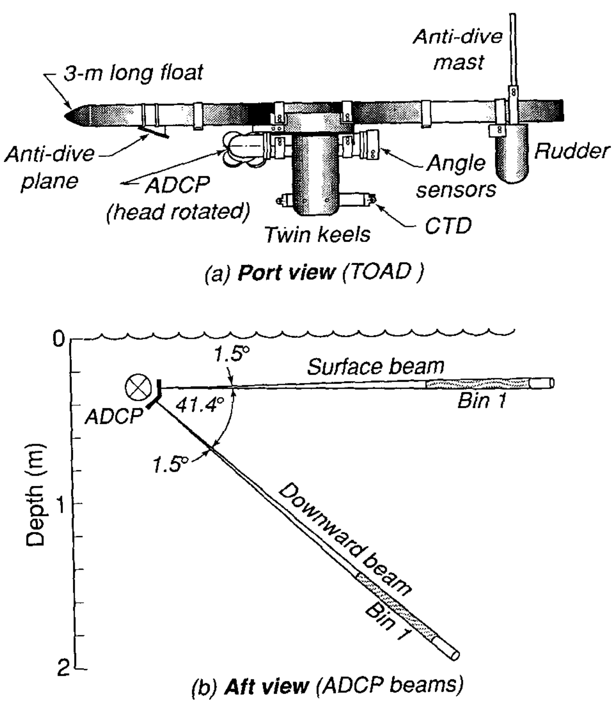

FIG. 1. Instrument schematic. (a) Port view of TOAD shows 3.05-m-long surface float with attached ADCP, externally mounted pitch-and-roll sensors, and CTD. (b) Aft view shows surface and downgoing acoustic beams extending to starboard.

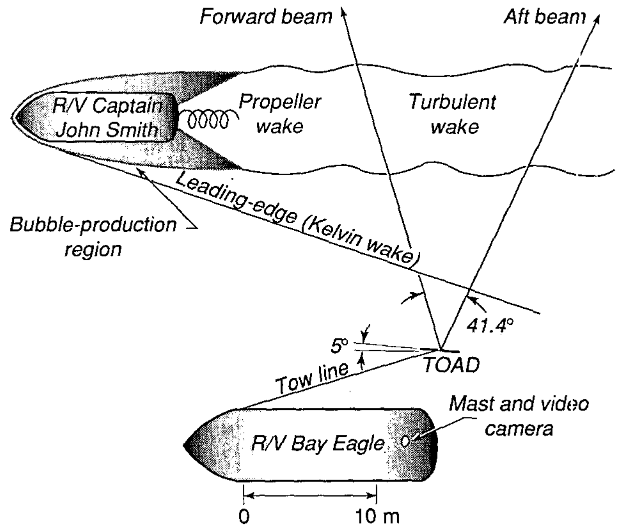

FIG. 2. Sampling scenario showing surface acoustic beams scanning across the target ship and wake. The sketch is approximately to scale and shows conditions at 1354 EDT, when the stern of the target ship (R/V *Captain John Smith*) was abreast of the bow of the measurement ship (R/V *Bay Eagle*).

The ADCP data were collected using a radial bin size of 0.60 m, a total of 80 bins, 63 pings per minute (using a data transfer rate of 38 400 baud), and an internal mode setting of one (using RDI firmware version 3.40). The distance from the transducer to the center of the first bin is 1.93 m (Fig. 1b). We did not muffle the two downward-looking acoustic transceivers, so that all four beams recorded data just as in the usual downlooking ADCP configuration.

Values of radial velocity and acoustic backscatter strength were calculated for each bin in each beam for every ping. The expected rms error in radial velocity is 3.2 cm s^{-1} (RDI 1993). Velocity components along and perpendicular to the tow direction (calculated from the two surface beams) have rms errors of about 8 and 5 cm s^{-1}. The backscatter strength was calculated from the recorded "echo intensity" (RDI 1989). We also make use of recorded values of "correlation," which is an internal diagnostic calculated as part of the velocity estimation. Low correlations result from relative movement of scatterers within or through the boundaries of an insonified volume; hence, low values may indicate large current fluctuations and strain rates.

A ship's wake has elevated values of acoustic backscatter because of bubbles created by the ship's drag and wave wakes and by the propeller (e.g., NDRC

1946; Reed et al. 1990). While a range of bubble sizes exists in the near wake (e.g., Miner and Griffin 1987), the backscatter at high frequency will be dominated by the high density of resonant bubbles, since these have scattering cross sections on the order of 1000 times their geometrical cross sections (Clay and Medwin 1977). The resonant bubble diameter at 600 kHz is about 11 μm (McCartney and Bary 1965). Bubbles of this size rise at a negligible rate (millimeters per second) and serve as tracers of the turbulence and any larger-scale organized motions in the wake. The mixture of air bubbles and water may reduce markedly the sound speed in the wake (King 1973), but we ignored this in calculating range.

The measurements were made from the 19.8-m-long R/V *Bay Eagle* (Virginia Institute of Marine Sciences). A mast-mounted video camera imaged the starboard-side ocean surface and TOAD, providing a permanent time-stamped record of the sampling. Local time (eastern daylight) is used.

3. Procedure

The measurements were made near the mouth of the York River, Virginia, in unstratified, 14-m-deep water. The salinity was 20 (in practical salinity units). Tows were made at 3 m s^{-1} toward the east into a 2.5 m s^{-1} wind. The target wake was made by the R/V *Captain John Smith* (Virginia Institute of Marine Sciences). This vessel has a length of 12.8 m, a draft of 1.5 m, a beam of 4.3 m, a displacement of 14 tons, and maximum power of 350 horsepower. Its single propeller (69-cm diameter, 71-cm pitch) rotates clockwise, as viewed from astern. The ship has a dry-exhaust, closed cooling system: combustion gases go up a stack and have minimal impact on the water surface, and, as only heat is exchanged with the seawater, there is no discharge to affect wake development. Likewise, minor oil leaks are contained in the ship's bilge to minimize contamination. The speed of the target ship was incrementally higher than that of the measurement ship, about 3.25 m s^{-1}. This gives a Froude number of about 0.3, which is typical of other full-scale and model ship wake measurements (Reed et al. 1990). The Froude number is defined as ship speed divided by the square root of the product of ship length and the acceleration of gravity.

Three runs were done with the target ship sailing a parallel course to starboard. The acoustic beams scanned the target wake from very near the ship to a distance of up to five ship lengths behind (see Fig. 2). All three runs showed similar wake development, but we inadvertently crossed into the wake during the middle of run 2, so a detailed analysis was done only on runs 1 and 3. Two additional kinds of experiments were done. These had the target ship approach the measurement ship at its maximum speed (14 kt) on either a reciprocal course or, once, on a (very!) close perpendicular course. Because of the short sampling time in the near wake, analysis of these data was not pursued.

4. Results

Figure 3 shows 7 min of backscatter and radial velocity data for the aft- and forward-looking surface beams from run 1. The wake appears clearly as a band of elevated acoustic backscatter. The plot begins with the target ship still aft of the forward beam, so initially the wake signal appears only in the aft beam. [Close examination does reveal a weak expression of the wake in the forward beam identical in shape to the aft beam's. This suggests scatter from a forward-beam sidelobe or cross talk with the aft beam. (See below.)] The wake first clearly appears in the forward beam at 1351:15 EDT; it quickly increases in width, consistent with an initial spreading region immediately astern of the ship (Fig. 2). There is no high return from the ship itself, perhaps because the acoustic beam is reflected off the hull, away from the transducer. The wake appears wider in the aft beam because of the viewing geometry (Fig. 2) and because, at a fixed time, the aft beam samples an older wake. The forward beam shows some scatter at near range and more along-wake variability, possibly the result of TOAD's mean upward pitch. Likewise, there is evidence of a power loss in the forward beam when the wake is close to the transducer. A narrow region of reduced backscatter occurs along the wake centerline (e.g., in the aft beam at 1355:30 EDT). The wake meanders in range and finally crosses TOAD's track. This may have been caused by differential wind drift or small differences in heading of the two ships. The times of intersection with the wake edges in Fig. 3 agree with visual observations of TOAD crossing foam lines that presumably lie along each edge of the wake. When TOAD lies inside the wake (such as at 1357 EDT), a separate examination of the downward beams shows, in the first data bin only, intermittent, 10-s-long periods of high backscatter (between −80 and −70 dB), consistent with wake returns. This indicates that the first bin of the downward beams was occasionally in the wake and, so, the mean wake depth was less than 1.7 m (Fig. 1b).

The wake signature is less clear in the plots of radial velocity (the lower two panels in Fig. 3). This is because of contamination at far range from multiple scattering effects, which we believe arise primarily from bottom- and wake-reflected signals. To emphasize the wake's velocity signal, we superimpose outlines of the wake determined from the backscatter plots. With the outlines as guides, underlying patterns in radial velocity become clearer: positive values (flow toward the ADCP) occur along the near edge of the wake, negative values occur near the far edge of the wake, and near-zero values occur near the wake centerline. Also visible in the aft beam velocity is the target ship's Kelvin wave wake (Fig. 3,

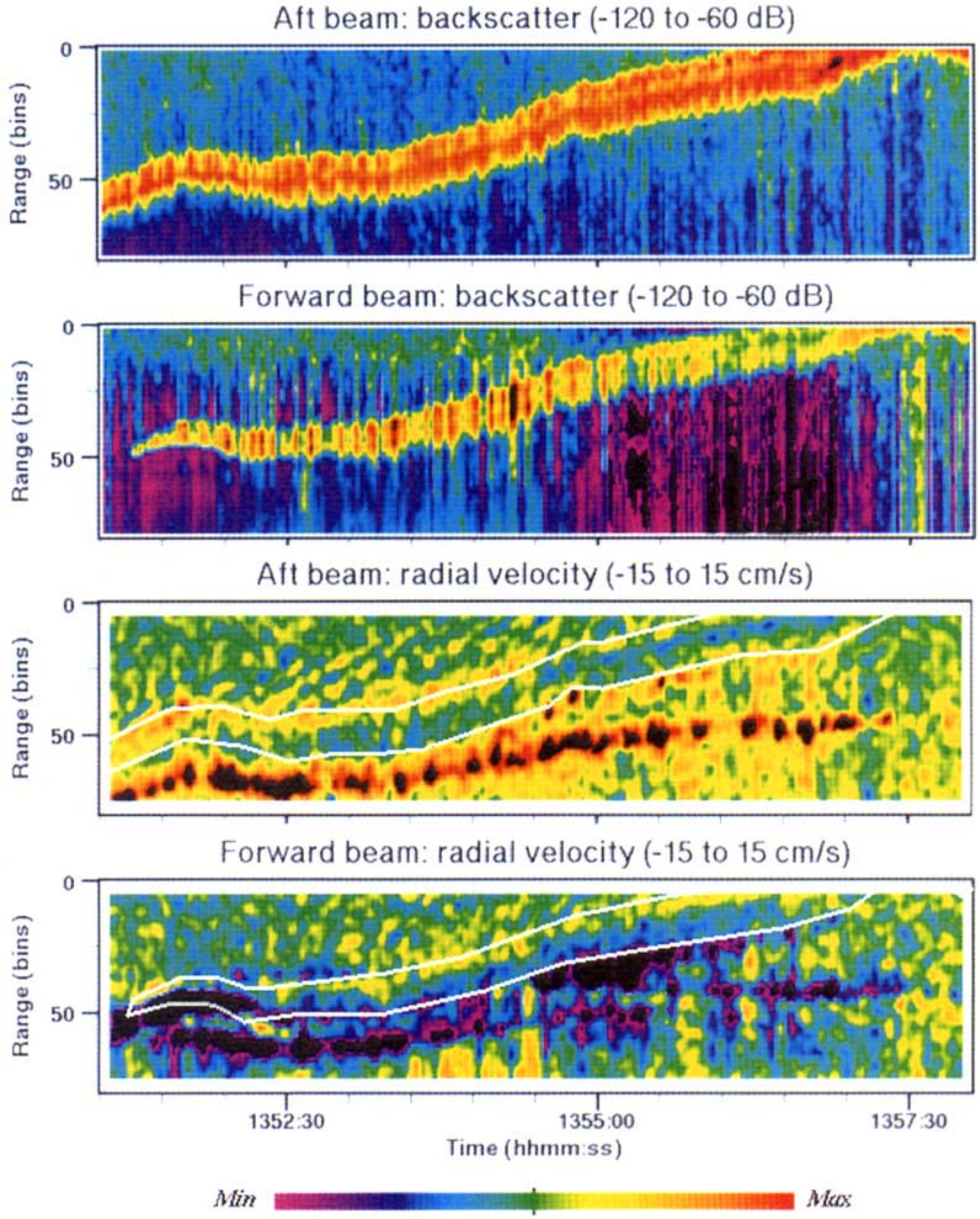

FIG. 3. ADCP data from the two surface beams during run 1. Top panels show backscatter strength; bottom panels show radial velocity. Color bar shows data ranges. Black indicates data values outside the indicated ranges. Backscatter data are smoothed over single adjacent pings and bins; velocity data over six adjacent pings and bins. Velocity data at far range are contaminated by multiple scattering. (See text for details.)

1352:30–1354:30 EDT). The waves are separated by about 4 m in range; this is consistent with the video records, which show a wavelength of about 3 m. The wave orbital speed from Fig. 3 is about 5 cm s^{-1}, which will be less than the actual value on account of resolution and data smoothing. [A plausible value for actual wave orbital speed is $u = a\omega \exp(-kz) \approx 20$ cm s^{-1}, where the wave frequency $\omega \approx 4.5$ s^{-1}, the wavenumber $k \approx 2\pi/(3\text{ m})$, the amplitude $a \approx 8$ cm, and the measurement depth $z \approx 30$ cm.] The Kelvin wake is not apparent in the forward beam presumably because it scans the waves at an oblique angle (cf. Fig. 2). Since there is no Kelvin wake signal in the backscatter data of either beam,

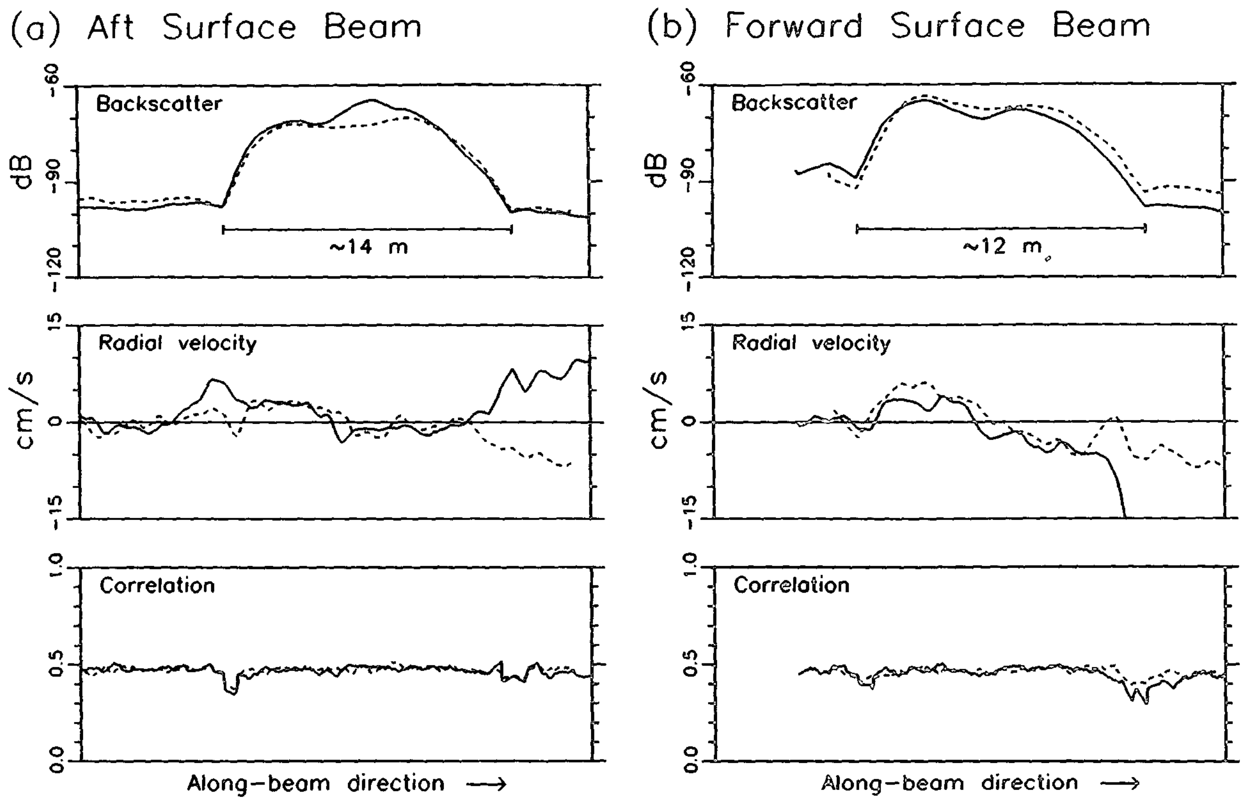

FIG. 4. Surface scans of backscatter, radial velocity, and correlation values for the (a) aft and (b) forward beams. Solid curves show results from run 1; dashed from run 3 made a half-hour later. Data have been averaged over a 1-min interval as described in the text. Indicated are along-beam wake widths based on the backscatter signals (assuming a constant value of sound speed across the wake). Velocities in each ping have been calculated relative to the near-range bins.

the velocity scatterers for the aft beam are likely ambient ones, such as bubbles from ambient breaking waves.

To improve signal to noise, we have averaged the data from run 1 over a 1-min period (63 pings) corresponding to an interval when each beam separately samples the wake at about the same position of two to three ship lengths behind the target. Thus, we choose the period 1353:30–1354:30 EDT for the aft beam but 1354:20–1355:20 EDT for the forward beam (a 50-s time lag). Also, because the wake does not occur at a fixed range, we scale the range positions in each ping of each beam with the instantaneous backscatter wake width and then form a composite average. Finally, to reduce the effect of platform motion on velocity, we use a reference layer for each beam consisting of the velocity data from bin 1 to the near edge of the wake (as determined from the backscatter data).

The resulting average profiles for each of the two surface beams are shown as the solid curves in Fig. 4. Clearly resolved now are two backscatter peaks, 20–30 dB above ambient levels, and a 2–5-dB depression between peaks. The minimum backscatter region would be consistent with surface flow diverging from the wake centerline and replenishment with deeper water containing fewer resonant bubbles. Thus, we will take the location of minimum wake backscatter to indicate the centerline (see below). Relative to this centerline the wake is asymmetrical, being wider on the starboard side. Asymmetry in this sense may result from the clockwise propeller rotation, from power loss through the wake, or from processing assumptions, such as using a uniform sound speed in calculating range (section 3). The mean radial velocities are consistent with the pattern in Fig. 3: each beam indicates positive flow in the near-range part of the wake, a zero crossing near the presumed centerline position, and negative flow in the far-range part of the wake. Some of the fluctuations in these average scans may arise from coherent velocity structures within the wake (Meadows et al. 1994, Fig. 14). As in Fig. 3, signals are corrupted at far range where the curves tend toward either large positive or negative values. Finally, mean profiles for the beam correlations (Fig. 4) show abrupt decreases (by about 20%) at the near- and far-wake edges. This is consistent with large spatial gradients in bubbles, turbulence intensity, or currents at the edges of the wake.

An identical analysis was done for run 3 using data from about a half-hour later (1425:26–1426:26 EDT, aft beam; 1426:16–1427:16 EDT, forward beam). The results are shown as the dashed curves in Fig. 4. They indicate behavior similar to run 1's: a zero crossing in radial velocity occurring near the minimum in wake backscatter and anomalous behavior at the far edge of the wake.

Results from both runs are combined in Fig. 5 to give true cross-wake profiles. Data at far range are masked because of the anomalous behavior noted above. The wake half-width is about 5 m, slightly larger than the beam of the target ship. (The half-width is measured between the near edge of the wake backscatter signal and the centerline minimum.) The transverse flow in the wake is clearly resolved. Surface water diverges from near the centerline at about 3 cm s^{-1} in both the starboard and port directions. The centerline divergence is about 5 cm s^{-1} over 1.5 m, giving a strain rate of about 0.03 s^{-1}. The near-edge convergence is less well resolved but appears to have a comparable strain rate. The along-wake data are noisier, but the forward flow near the wake edges and aft flow near the wake centerline (about 5 and 3 cm s^{-1}) are consistent with flow in the hull drag wake and centerline thrust wake (e.g., Meadows et al. 1994).

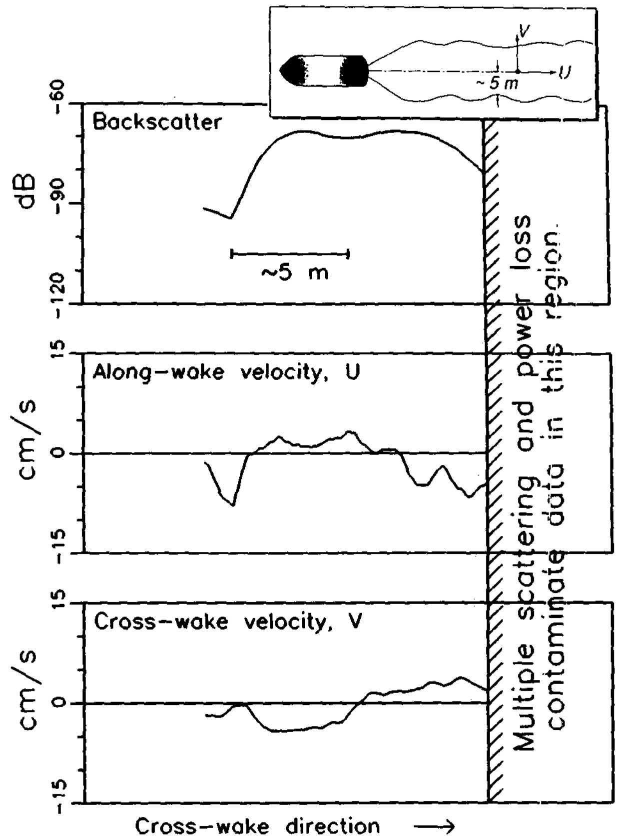

FIG. 5. Cross-wake backscatter and velocity distributions synthesized from the four surface scans in the previous figure. Coordinate system is defined in the inset. The indicated wake half-width extends from the near edge of the backscatter wake signal to a presumed wake centerline.

5. Summary and discussion

We have made a preliminary study of a ship's wake by using a standard acoustic Doppler current profiler deployed on a surface-towed platform so that two beams scan horizontally beneath the surface (at about 0.3-m depth). Measurements were made across the wake of a relatively small ship, 13 m long, moving at 3.25 m s^{-1}, and characterized by a Froude number of about 0.3, a value typical of other full-scale and model ship wake measurements.

As expected, the ship's wake appears clearly as a continuous region of elevated acoustic backscatter. The width of the acoustic wake is about 10 m, or 2.3 times the ship's beam, and consistent with other measurements of wake geometry (Griffin et al. 1992; Peltzer et al. 1992). The backscatter is reduced along the wake centerline, consistent with surface advection of bubbles away from the centerline and replenishment with deeper water with fewer resonant bubbles. Beam correlation values decrease at the edges of the wake, consistent with high spatial gradients between the wake and ambient water. Thus, the backscatter and correlation signatures are useful in interpreting the velocity data.

The current measurements made at a position of two to three ship lengths astern appear to resolve both the transverse flow and along-wake (drag and thrust) flow. The flow in the hull drag wake should be about 3% of the ship's speed based on model tow tests (Meadows et al. 1994), giving a forward flow of about 9 cm s^{-1}. Our measured values near the edges of the wake show forward currents of roughly 5 cm s^{-1}. The transverse measurements, expected to be more robust on account of viewing geometry, show currents of about 3 cm s^{-1} (1% of the ship's speed) diverging from the wake centerline. This compares favorably with model results (for a *twin-screw* ship) that show values of 0.85%–0.52% of the ship's speed at two to three ship lengths astern (Meadows et al. 1994). The symmetrically divergent surface flow supports the strong role played by hull-induced vortices. Surface strain rates associated with the diverging flow are about 0.03 s^{-1}. It is interesting that this is of the same order as strain rates associated with internal waves and fronts in littoral waters (Gasparovic and Apel 1988; Marmorino and Trump 1994), which, like a ship's wake, may exhibit bands of relatively calm water that derive from the effects of wave refraction and surface-film compaction.

We conclude that using a standard ADCP in this manner provides a useful technique for studying ship wake geometry and flow. Future measurements should be made in water deep enough to avoid bottom reverberation. An alternative in shallow water might be to cover the downgoing beams, but there is still the possibility of a strong scatter path from the wake to the bottom and back to the surface beams. To improve signal to noise, the target and measurement boats should use the same speed so that longer time averages can be made at a fixed distances behind the target. The technique should be applicable to the study of other phenomena such as small-scale surface fronts and internal waves. When observing natural phenomena, it may be advantageous to mount the ADCP directly off the side of an anchored ship and make time-evolving instead of towed measurements.

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