Performance and Calibration of an Acoustic Doppler Current Profiler Towed below the Surface

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ABSTRACT

A towed acoustic Doppler current profiler (ADCP) system was tested. The instrument was deployed from ships of opportunity and towed at depths between 5 and 25 m. The towed system carries upward- and downward-looking ADCPs. The instrument platform is stable in most operating conditions at ship speeds up to 4.5 m s^{-1}. Large discrepancies are found, however, between the ship's velocity obtained from bottom-tracking ADCP pulses and that from navigational data. These are explained with a magnetic compass bias that varies with the ship's heading direction. Both the ship and the tow platform induce magnetic fields that bias the ADCP compass. An in situ compass calibration scheme is thus necessary and requires accurate navigational data. In our main study area, it is found that the Global Position System provides absolute and relative positions to within 88 and 4 m, respectively. These accuracies are sufficient for calibration purposes. With our calibration scheme the towed ADCP system performs as well as vessel-mounted systems. The ease of deployment from ships of opportunity and the capacity of the tow system to carry additional instruments makes it a valuable research tool. Furthermore, the capability of our system to profile the water column above and below the platform with different frequencies and thus different vertical resolutions enhances its flexibility and usefulness, especially to study surface and bottom boundary-layer processes.

1. Introduction

Towing an acoustic Doppler current profiler (ADCP) system offers an attractive alternative to vessel-mounted ADCPs. A towed system can be used from ships of opportunity, allows easy maintenance, and remedies several problems of vessel-mounted systems. Kaneko et al. (1990) first introduced a towed ADCP. They obtained detailed velocity measurements of the Kuroshio Current with an ADCP mounted inside a sled. The sled was towed behind the ship about 7 m beneath the surface. Internal ADCP sensors measured the heading, pitch, and roll of the sled. A trailing buoy attached to the sled stabilized the system, much as a tail stabilizes a kite. We describe here a towed ADCP system that differs in design, construction, and operation from that of Kaneko et al. (1990, 1993). Furthermore, we thoroughly test our instrument platform, which contains both an upward- and a downward-looking ADCP. We used this system from a small coastal research vessel off the coast of California and from a large icebreaker off the coasts of Alaska and Siberia. We find that a careful in situ calibration is essential in order to obtain accurate velocity measurements. Previous studies generally omitted such a calibration.

Vessel-mounted ADCPs are becoming a standard tool on many research vessels. Their operation has been studied by Kosro (1985), Didden (1987), Chereskin et al. (1987), and Joyce (1989). Beyond limitations inherent in the ADCP system itself (Chereskin et al. 1989; Chereskin and Harding 1993), air bubbles near the transducer heads and compass biases (King and Cooper 1993) often degrade shipboard ADCP observations. New (1992) reports that as the ship heaves, a cloud of air bubbles entrains under the hull of the ship. The bubble cloud then sweeps past the transducer heads in a layer about 1 m thick. This layer degrades ADCP current estimation as air bubbles have different acoustic properties than the seawater below. New (1992) found that the problem can be overcome when the transducer heads extend 1.5 m beneath the hull of the ship. A completely submerged towed ADCP system cannot entrain bubbles.

Vessel-mounted ADCP systems utilize the ship's inertial or gyro compass. A misalignment generally exists between the reference direction used by the Doppler system and that of the ship's gyro. Joyce (1989) details a calibration routine to determine this constant misalignment. Abrupt changes of the ship's course cause yet another compass error as the turn excites persistent

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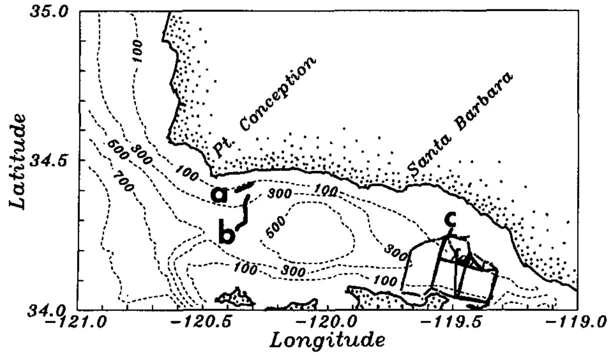

FIG. 1. The Santa Barbara Channel study area. Labels a, b, and c refer to different ship tracks. Dashed lines are bottom contours.

Schuler oscillations that bias the compass readings (Pollard and Reed 1989). While a calibration routine can resolve the misalignment problem, no recourse is available for the Schuler oscillations. Towed ADCP systems exhibit neither of these problems as they generally rely on a magnetic compass. The ship's hull and the tow platform, however, induce magnetic variations that can be large and must be removed through a calibration routine. Hence, both ship-mounted and towed ADCP systems require careful in situ calibration to account for compass biases.

We collected ADCP and navigational data on several cruises off California and in the Arctic Ocean. Most of our studies, however, took place in the Santa Barbara Channel. This channel is about 150 km long and 40 km wide and consists of a 600-m-deep central basin, a 200-m-deep eastern entrance sill, and a 450-m-deep western entrance sill (Fig. 1). The continental shelf areas to the north and south of the channel are about 100 m deep and vary in width between 5 and 20 km. The gaps between the southern Channel Islands are generally less than 40 m deep. The wind and wave conditions vary spatially in the study area. To the west, near Point Conception, winds and swell are from the northwest; however, high mountainous terrain shelters much of the northern shelf. In contrast, the southern shelf often experiences high winds (25 m s^{-1}) and rough seas. Our main study area thus represents a good region to test our tow system under different environmental conditions.

2. System description

Our towed ADCP system consists of a hydrodynamic body, a conducting tow cable, and two independent ADCP systems manufactured by RD Instruments. The ADCPs are mounted inside an Edo Western, Inc., model 1019 hydrodynamic body. The body is about 1.5 m long and has a wing span of 1.5 m. The instrument's cavity is 0.5 m high and 0.8 m wide and includes a 400-kg lead weight forward. The ADCP electronics pressure cases are placed horizontally inside the cavity of the tow body. The transducer heads are coupled to

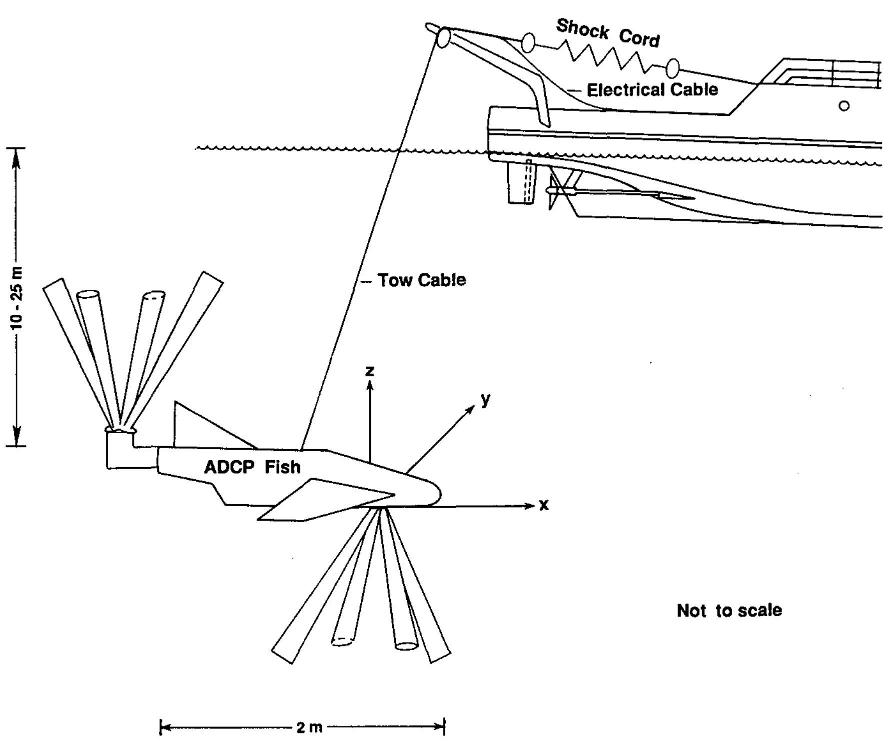

FIG. 2. Sketch of the tow.

the case through 90° adapters so that the 153- and 614-kHz transducers are oriented downward and upward, respectively (Fig. 2). Tilt sensors measure the pitch and roll, while a KVH fluxgate compass model LP101 measures the heading. Apart from the ADCPs, the cavity of the platform usually includes an Ocean Sensors CTD and a pressure case that contains a gimbaled KVH model C100 compass. All our measurements utilize the ADCP bottom-tracking capability, the firmware version 17.07, and the TRANSECT software version 1.0.

The upward-looking 614-kHz ADCP is self-recording and provides velocity observations of the water column above the towed body. The downward-looking 153-kHz ADCP is connected to a shipboard computer through the seven-conductor torque-balanced tow cable with 22 inner steel wires and 42 outer steel wires. The nominal outer diameter of the cable is 0.025 m. Added zipper tubing cable fairing minimizes strumming. The cable is rolled onto one of the winches aboard the towing vessel and paid over the stern or the side through a 0.52-m-diameter block on the aft A frame or side crane. A shock cord assembly, consisting of ten strands of 0.02-m-wide and 3-m-long bungee cord, is fastened to the cable using Yale Minigrip Kevlar braid grips. The shock cord takes the load of the tow between the winch and the block (Fig. 2) in order to reduce peak loads on the cable due to the differential motion between the towed body and the heaving ship. We have towed the ADCP system astern of a small coastal research vessel, the R/V *Robert Gordon Sproul,* and off the side of a large icebreaker, the CCGS *Henry*

TABLE 1. Pitch, roll, and pressure statistics.

Leg ship's speed (m s^{-1})	A 2.5	B1 3.0	B2 4.0	C 2.5
Mean pitch	6.6	6.4	6.4	5.3
Standard deviation pitch	±1.20	±3.69	±3.95	±0.59
Mean roll	1.6	1.4	1.6	1.6
Standard deviation roll	±0.95	±1.88	±13.42	±0.43
Mean depth	14.9	15.2	11.3	4.7
Standard deviation depth	±0.19	±0.38	±0.53	±0.13

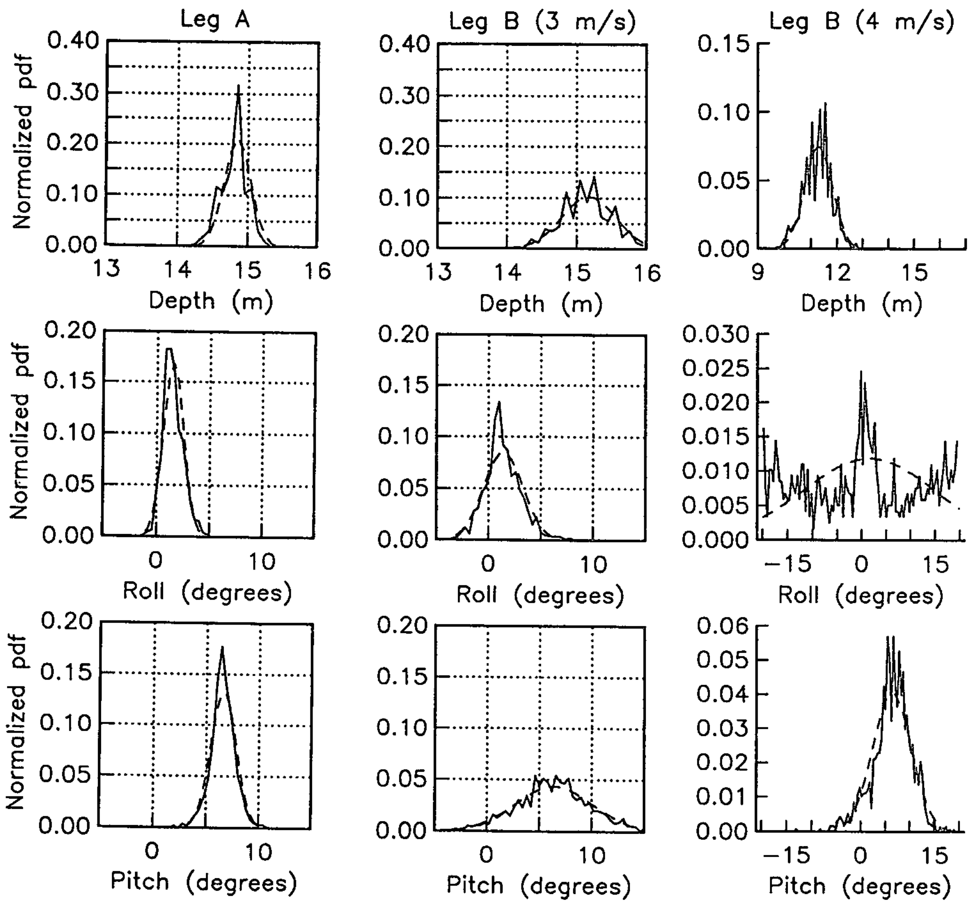

FIG. 3. Normalized histograms (solid) and Gaussian probability density functions (dashed). Shown are data of pitch, roll, and instrument depth. Scales on the *x* axis are not the same. Leg A and B refer to ship tracks shown in Fig. 1.

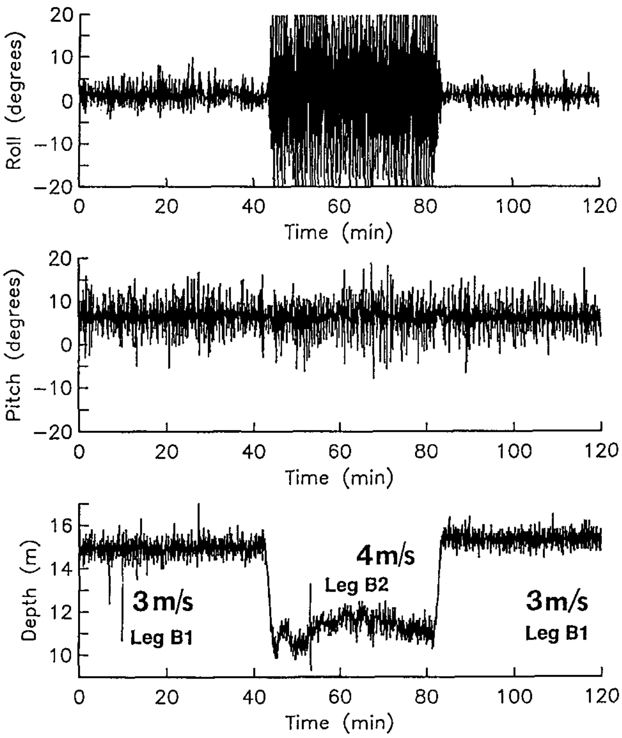

FIG. 4. Time series of pitch, roll, and pressure of leg B. Notice the decrease in instrument depth at the time of off-scale rolling motion.

Larsen. Deployment and recovery procedures are straightforward and take about 20 min. The remainder of this paper describes the operating condition, the stability, and the calibration of the tow system.

3. Motion and stability

We refer to rotations about the x, y, and z axes of a coordinate system fixed to the platform (Fig. 2) as roll, pitch, and heading, respectively. We measure pitch and roll angles with pendulums fixed to the ADCP while the heading angle is measured with two KVH fluxgate compasses, one ungimbaled and the other gimbaled. The ungimbaled compass is part of the ADCP while the gimbaled one is not. We also added a pressure sensor to indicate the vertical displacements of the platform. Sampling frequencies for all these instruments are higher than 0.5 Hz, high enough to resolve motion induced by surface gravity waves.

Figure 3 depicts histograms of pitch, roll, heading, and pressure data for three different cases. Legs A and B (see Fig. 1 for locations) represent observations from two 2-h-long tracks in the presence of heavy seas and winds. Figure 3a represents observations collected on leg A, when the ship steamed at 2.5 m s^{-1} in the swell direction. Deviations from the mean pitch, roll, and vertical position of 6.6°, 1.6°, and 14.9 m are about 1.2°, 1.0°, and 0.2 m, respectively; the platform is stable. The variations about the mean appear to be normally distributed as the dashed lines in Fig. 3 indicate. A few hours later the ship changed the steaming direction by 90° when heavy seas perpendicular to the track induced a heavy rolling motion. As a result, the range of pitch and roll variations increases by a factor of 2–3 (Fig. 3b; Table 1). We depict observations from this leg (B) as a time series in Fig. 4. Initially (leg B1), at speeds of about 3 m s^{-1} the platform is stable at 15-m depth. As we increase the towing speed beyond 4 m s^{-1} (leg B2), the platform is raised by about 4 m. The new vertical position coincides with rolling motion in excess of 20° (Figs. 3c and 4). The platform has become unstable as it rolls violently. Table 1 summarizes all statistical results, including those from legs C, on a different cruise, when wind speeds and wave heights were below 5 m s^{-1} and 0.2 m, respectively.

The compass commonly supplied with the ADCP is not gimbaled, and we compare this compass with

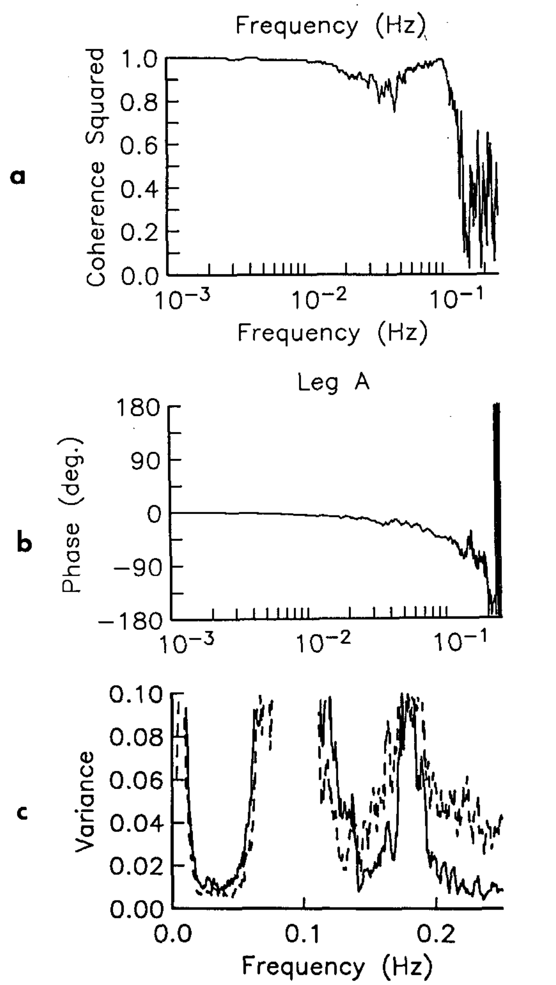

FIG. 5. Frequency domain analysis of the two compass time series. (a) Coherence, (b) phase, and (c) variance (solid line represents the ungimbaled ADCP compass and the dashed line represents the gimbaled external compass).

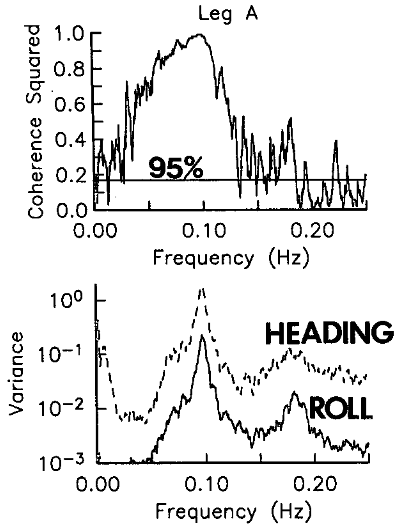

FIG. 6. Frequency domain correlation of the roll and heading time series. The dashed curve in the lower panel represents the data from the ADCP compass, the solid line the data from the roll sensor.

one that is. We compute cross-spectral estimates from the two compass time series and conclude from the coherence (Fig. 5a) and phase (Fig. 5b) that at frequencies smaller than 0.02 Hz the agreement of the two instruments is almost perfect. At higher frequencies, however, the two compasses do not correlate. From Fig. 5c we estimate noise levels at these frequencies of about 0.1° and 0.2° for the ungimbaled and the gimbaled compass, respectively. At low frequencies, smaller than 0.15 Hz, the variance of the ADCP compass is about 10% higher than the variance of the gimbaled compass.

We speculate that this additional variance of the ADCP compass is caused by the rolling motion of the platform at gravity wave frequencies. In Fig. 6 we show both autospectral and coherence estimates of the ADCP heading and roll time series. Two spectral peaks at about 0.1 and 0.2 Hz represent heading variations which are coherent with the rolling motion of the platform. About 0.5° of roll cause almost 2° of heading change at the swell period of about 10 s. This result is significant at the 99.9% confidence level and the 2° change in heading is well above the noise floor (Fig. 5c). From our interpretations of Figs. 5 and 6 we conclude that the compass data should be averaged for at least 2 min in order to remove random variations introduced by wave-induced platform motion.

4. Compass bias and calibration

Joyce (1989) suggested a calibration scheme for vessel-mounted ADCPs that provides a scaling and a misalignment constant. One obtains these calibration coefficients by correlating velocities measured by the ADCP with those inferred from navigational data. We follow this scheme but extend it in order to resolve compass variations induced by the steel of the ship's hull and the tow. First, however, we test the ADCP compass on a magnetically quiet cliff near San Diego before calibrating data from ADCP tows at sea. We will adopt a calibration procedure suggested by the U.S. Naval Oceanographic Office (1969) in order to correct magnetic compass variations that are induced by the ship's or the tow's magnetism. A compass deviation D due to the ship's own magnetic field is given as

$$D = a + b\cos(\phi) + c\sin(\phi) + d\cos(2\phi) + e\sin(2\phi);$$

where a represents a misalignment between true north and the north indicated by the compass; ϕ is the biased compass heading; and b, c, d, and e are coefficients that explain fore–aft and athwart ship components of the ship's permanent and induced magnetic fields. We find a–e from least-squares fits to the data. Table 2 summarizes the coefficients and their uncertainties for two calibration tests on the cliff and two calibrations at sea. The uncertainties in Table 2 are the 95% confidence limits of rejecting the null hypothesis in multiple linear regression (Fofonoff and Bryden 1972).

In the first test we horizontally rotate the ADCP pressure case through 360° and compare the expected orientation with the compass reading. The test reveals that all coefficients are zero to within the uncertainty of the least-squares fit, that is, no bias is present in the absence of both the ship and the tow body. We observe a large bias, however, when we place the ADCP pressure case together with all other instrumentation inside the tow body and repeat the above procedure. In contrast to the first test, we find calibration coefficients that are significantly different from zero. They imply a compass bias that varies with the orientation of the tow. The bias reaches up to 15° (Fig. 7a) and must be caused by steel components and structural elements of

TABLE 2. Calibration coefficients.

Experiment	Depth	a	b	c	d	e	Uncertainties in a, b, c, d, e
ADCP, no tow	n/a	n/a	0.1	0.4	0.6	0.2	n/a, 0.7, 0.7, 0.7, 0.7
ADCP, with tow	n/a	n/a	13.3	−1.0	−0.6	−1.8	n/a, 0.6, 0.6, 0.5, 0.5
December 1993	24 m	−2.9	12.9	5.1	0.9	−1.6	0.3, 0.5, 0.4, 0.4, 0.6
May 1993	5 m	−2.2	15.0	1.4	1.3	−2.7	0.3, 0.5, 0.5, 0.4, 0.7

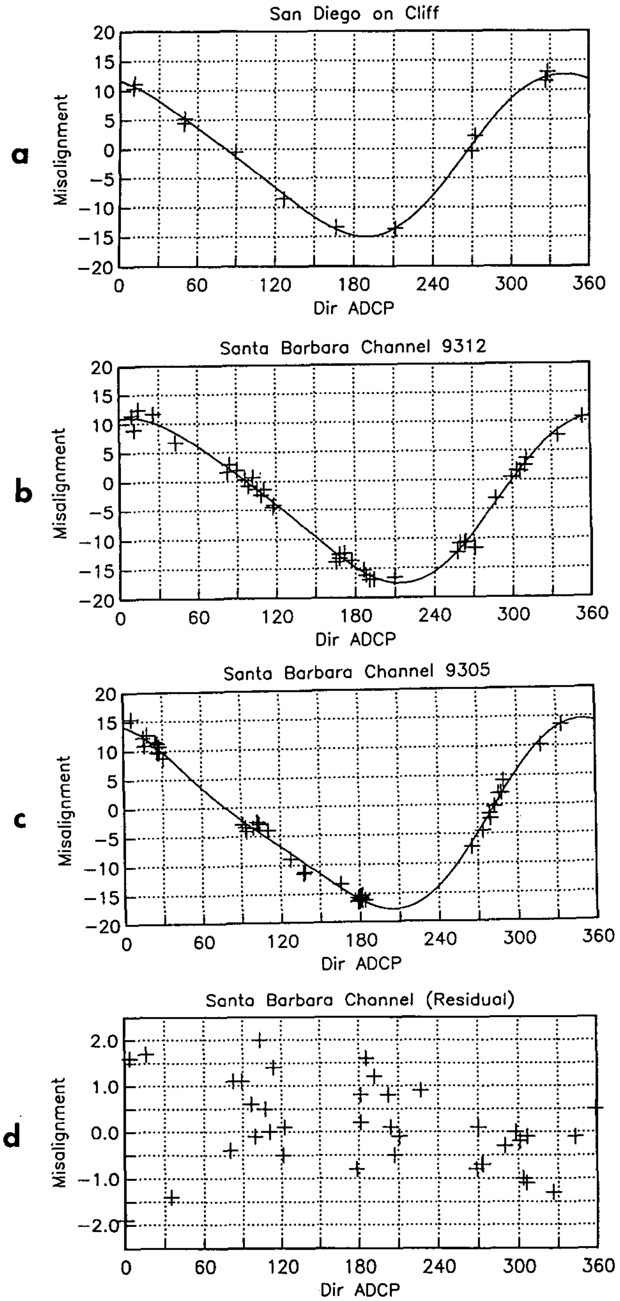

FIG. 7. Misalignment angle (symbols) and predicted compass bias (solid line) as a function of the compass heading. The predicted compass bias is determined from the calibration coefficients in Table 2. (a) Compass calibration of the tow on the cliff, (b) compass calibration of the tow at 24 m (December 1993) before the compass correction, (c) as (b) but for a tow at 5-m depth (May 1993), (d) after compass correction (data from May 1993), note the different scale.

the tow. We thus anticipate similar coefficients when we tow the instrument platform in the ocean. There, however, the steel of the ship's hull induces further magnetic compass biases. As we will see next, the effects of the ship's hull are small during our application off California; however, they are large in our application in the Arctic Ocean. We first discuss the results from two tows off California.

During our experiments in the Santa Barbara Channel, we collected navigational data with both the standard Global Position System (GPS) and its differential variant (DGPS). DGPS is designed to partly remove noise that is purposely introduced to degrade position accuracy. We quantify the accuracies of both systems by applying boot-strapping methods to data collected while the ship docked in San Diego harbor. From this analysis (not shown) we infer a mean position error of about 88 m (4 m) for GPS (DGPS) data that has been averaged for 3 min. Computing vessel speeds from two such averaged positions T seconds apart, we obtain a speed error δu due to a position error of δx as $\delta u = 2\delta x / T$, which is about 1 and 22 cm s^{-1} for $T = 20$ min for DGPS and GPS data, respectively.

In December of 1993 we towed our upward- and downward-looking ADCPs at about 24-m depth in the Santa Barbara Channel. For over five days we collected ADCP data under at a variety of different sea states. We then selected all pieces of ship track between 20 and 30 min long for which the ship sailed along a steady course at a constant speed. The ADCP tracked the bottom at all times and collected data at 0.1 Hz in the ADCP beam coordinates. We screen our data both before and after averaging it. As preaveraging criteria, we require the estimated signal-to-noise ratio in Doppler velocities to exceed 6 dB for all four beams. The data from these four beams provide three velocity components and a redundant so-called error velocity. The latter is the difference between two independently determined vertical velocities and ideally equals zero. We reject all data for which this error velocity exceeds 20 cm s^{-1} for a bottom-tracking ping. As post-averaging screening criteria, we require that the standard deviation of the compass heading during the ensemble does not exceed 10° for each minute of averaging interval. This requirement assures that we average data in beam coordinates only while the ship's heading variations are sufficiently small within the averaging interval. Additionally, we require that the ship does not change speed or direction by more than 0.2 m s^{-1} and 2°, respectively, for each minute of averaging interval. This screens out data while the ship turns, accelerates, or decelerates, factors that generally degrade ADCP data quality. We finally reject all ensembles for which less than 20% of the bottom-tracking pings are valid. We use directional statistics (Mardia 1972) to average the pitch, roll, and heading data. We use these averaged quantities to transform the data from beam to earth coordinates (Kosro 1985). The uncertainty due to random noise of the ADCP is less than 0.5 cm s^{-1} as each ensemble contains more than 400 acoustic pings.

In Figure 8a we compare the ship's velocity components from the ADCP without compass correction with those that we obtain from GPS. The agreement

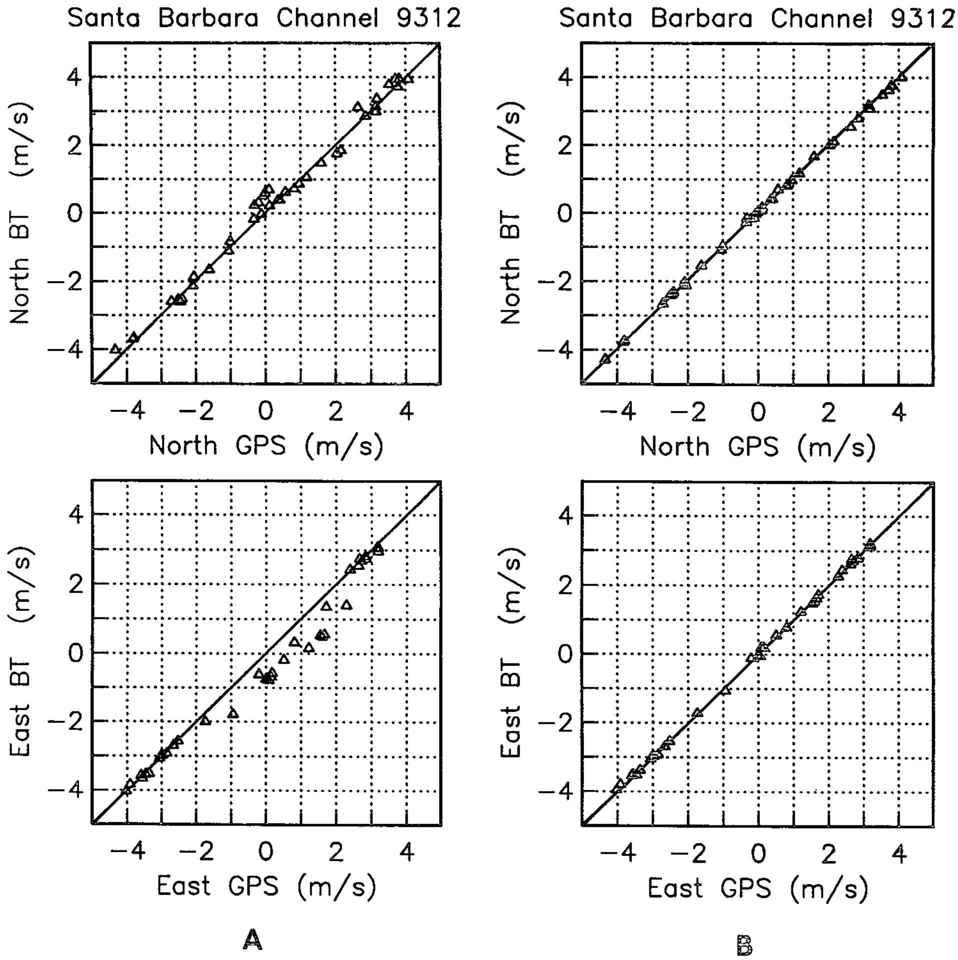

FIG. 8. Comparison of the ship's velocity components over ground from the ADCP bottom tracking (BT) and the navigational data (GPS) for the December 1993 experiment. (a) Data prior to the compass calibration; (b) data after compass calibration.

is poor and the discrepancies are larger than the uncertainties in the measurements. Errors exceed 50 cm s^{-1} and thus are unacceptably large. The data therefore requires a careful in situ calibration routine. Applying the calibration of Joyce (1989) to each of the selected segments, we arrive at Fig. 7b where we plot the misalignment angle as a function of the ADCP compass reading and again find an unacceptably large compass bias that reaches 15°. The variation follows a similar trend as in Fig. 7a and implies that the dominant compass bias is induced by the tow not by the ship. As this magnetic perturbation is fixed to the tow, its effect on the ADCP compass varies with the tow's heading direction because the ADCP compass measures the direction of the vector sum of the earth's and the tow's magnetic field. Only the latter changes as the ship turns.

We next apply the above compass calibration to each recorded compass heading angle prior to screening and averaging, that is, we remove the bias as predicted by the calibration coefficients in Table 2 from the raw heading data. The resulting ship's velocity components are illustrated in Fig. 8b. The ship's velocity components estimated from the ADCP and the GPS systems now agree to within the errors of the measurements. Following Joyce (1989), we arrive at the two calibration constants by ensemble-averaging cross correlations of various velocity components from the ADCP and GPS. We find a misalignment angle of about 3° (our coefficient a) and a scaling constant of about 0.996; that is, the ADCP velocities are high by about 0.4%. Both these values are within instrument specifications.

How does the tow depth affect the compass bias? In our final test off California we towed our instrument at only 5 m below the surface. Over two days we collected ADCP data in the eastern part of the Santa Barbara Channel at calm sea states (leg C in Fig. 1). During this particular experiment we collected navigational data using the DGPS. The position accuracies during this experiment are thus an order of magnitude better

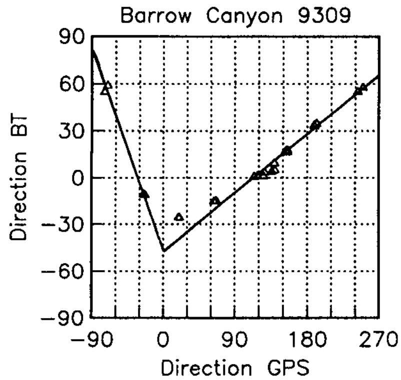

FIG. 9. Comparison of the ship's direction from navigational (GPS) and ADCP (BT for bottom track) data while the CCGS *Henry Larsen* completed a full circle during an 18-h calibration experiment off Barrow, Alaska. Note the small range of the ADCP compass data as compared with the range of the direction from GPS data. The solid lines are regression lines used to map the limited ADCP compass range into the full heading range.

than the standard GPS system. Despite this improvement and despite the different towing depth, we again find similar calibration coefficients (Table 2 and Fig. 7). We thus conclude that most of the 15° compass bias is caused by the tow body. This statement, however, applies only to our ADCP application from aboard the R/V *Robert Gordon Sproul* off the coast of California. As we discuss next, a different ship and a different study area cause a different magnetic compass bias.

In September of 1993 we deployed our ADCP tow system from the CCGS *Henry Larsen* off the coasts of Alaska and Siberia. The magnitude of the horizontal component of the magnetic field strength vector is about 11 000 nT near Barrow, Alaska, while near San Diego, California, it exceeds 24 000 nT. We thus expect a larger magnetic compass bias at high latitudes because the relevant part of the earth's magnetic field is weaker there. The expected larger bias is compounded by the large amount of steel in the icebreaker from which we tow our instruments. We thus specifically designed a calibration pattern off Barrow, Alaska. The icebreaker sailed for two hours along each of eight legs in different compass directions. We towed the platform at about 14-m depth, which is about 7 m below the hull of the icebreaker. Figure 9 shows the ship's direction as determined from the navigational and the ADCP systems. While the GPS correctly indicates the 360° range of the ship's heading during this experiment, the ADCP compass indicates a range of less than 120°. It is thus clear that in this specific case the ship's magnetic field dominates over both the earth's

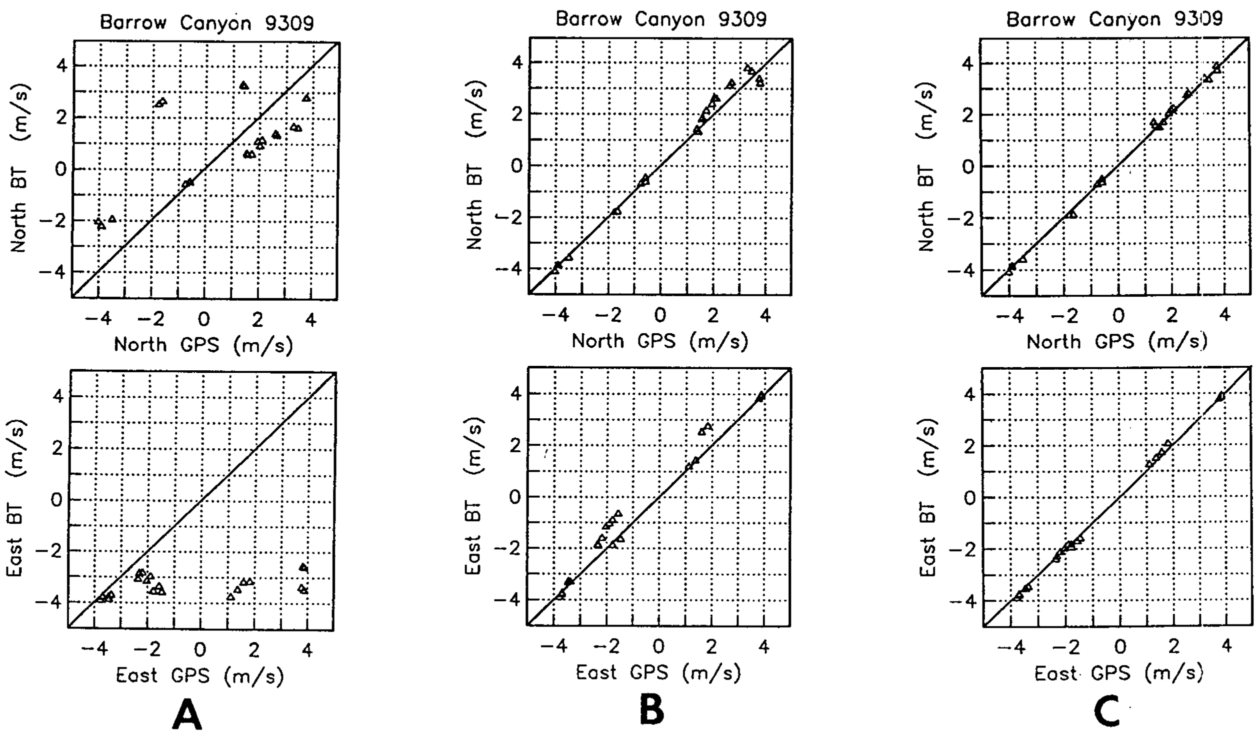

FIG. 10. Comparison of the ship's velocity components over ground from the ADCP bottom tracking (BT) and the navigational data (GPS). (a) Data prior to the compass calibration, (b) data after the compass mapping (see Fig. 9), and (c) data after compass mapping and compass calibration.

and the tow platform's magnetic fields. Hence we must first map the ADCP compass range into the full heading range before we can apply our above calibration routine. We define two linear regression curves from the data shown in Fig. 9. Figures 10a and 10b show the effect of this "mapping" upon the ship's velocity components as we compare the data before and after the "mapping." Discrepancies of up to 1 m s^{-1} still remain (Fig. 10b). The final magnetic calibration (Fig. 10c) brings the ship's velocity components from the GPS observations into close alignment with those that use the ADCP.

Any use of a towed ADCP system needs a careful in situ calibration of its magnetic compass. We recommend to tow the ADCP system as deeply as possible in order to minimize the effect of the ship's hull. The use of an upward-looking ADCP allows deep tows while still resolving the surface layer. An in situ calibration is still required as one must resolve the magnetic bias of the ADCP tow system. Previous studies did not perform any such calibration.

5. Discussion

We described a towed ADCP system whose stability characteristics and compass calibration we analyzed in detail. We identified two separate sources of error: surface gravity waves and compass biases. Surface gravity waves added noise into the compass record dominantly through the rolling motion of the platform. Other variables such as pitch and vertical displacement appeared unimportant. Under most operating conditions, however, variations in pitch, roll, and vertical position do not exceed 0.5°, 0.4°, and 20 cm, respectively. These variations are random and can thus be removed by averaging. Our towed ADCP system thus constitutes a very stable system. Only in the presence of very choppy seas at ship speeds exceeding 3 m s^{-1} does the platform become unstable and the data it returns become unusable. We presented data from one such event while the ship moved perpendicular to 25 m s^{-1} winds that generated short waves with large amplitudes. Such events are rare and reducing the ship speed to 3 m s^{-1} alleviated the problem. In calmer seas or from a larger vessel, however, we towed the ADCPs at ship speeds up to 4.5 m s^{-1} without problems.

A more serious problem relates to compass biases due to the magnetic field of the ship and the tow body. These biases must be calibrated out, and we combined the ADCP calibration technique of Joyce (1989) with a magnetic compass calibration. We found errors in excess of 50 cm s^{-1} in the absence of such a calibration and conclude that any application of a towed ADCP system relying on magnetic compasses requires an in situ calibration. It is important to apply the compass calibration in postprocessing prior to any averaging. We thus recommend collecting single-ping data in beam coordinates even though this increases the volume of data that needs to be stored during an experiment.

The towed and the vessel-mounted ADCP systems differ in two ways that affect their data quality. The first is that the towed system requires a magnetic compass while the vessel-mounted system commonly uses the ship's gyrocompass. Pollard and Read (1989) carefully calibrated ADCP observations that use a gyrocompass. They found that abrupt changes in the ship's heading introduce Schuler oscillations at periods of 20 and 80 min. The amplitude of these oscillations can reach several degrees. Magnetic compasses do not exhibit these oscillations; however, they are biased by the magnetic field of the ship and the tow. This bias can and must be calibrated out in order to achieve the same accuracy as gyrocompasses. The second difference between towed and vessel-mounted ADCP systems relates to clouds of air bubbles that are entrained under the ship as it moves through a surface gravity wave field. New (1992) describes an example of this effect in a vessel-mounted system. Bubbles near the transducer heads change the speed of sound and induce resonant interactions with the acoustic pulse. Both these effects can invalidate the data. Our tow is generally more than 5 m below the ship's hull and is thus little affected by the clouds of air bubbles. We thus conclude that our towed ADCP system returns data of at least the same quality as vessel-mounted ADCP systems do.

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