wind direction to within 8° in winds up to 3 m/s, and to within 6° in higher winds up to 8 m/s. The wind speed measurements from the ship anemometers are being used to calibrate the hydrophones.

Future innovations

A wide variety of sensors may be attached to the SVP drifter so long as the casing is neutrally buoyant and does not significantly alter the drag area ratio. To date, SVP drifters have been fitted with SeaCats, barometers, hydrophones, and wind vanes as already described. They have also been equipped with radiometers to measure radiance and irradiance for biological productivity assessment, as well as thermistor chains at various depth intervals down to as much as 120 metres (Fig. 5). Many other parameters of physical, chemical, and biological interest can be imagined.

Currently, the SIO development laboratory is engaged in calibrating the wind speed measurements of the Minimet and improving confidence in quality control. Another recent development is an attempt to increase the lifetime of the tether through elimination of the subsurface buoy from the original SVP design. Although the subsurface buoy is effective at decoupling wave motions from TRISTAR drogues, holey socks have been observed to twist and fold in three dimensions regardless of its presence (Niiler et al., 1995). This advance will sacrifice minimal hydrodynamic advantage for substantial reductions in cost and drogue failure.

From sporadic use of various drifter designs in the past, to the present day global array of standard SVP drifters, obtaining accurate Lagrangian measurements in the upper ocean has become an affordable, reliable, and predictable endeavour. With the advent of globally inferred sea surface winds and ocean colour from satellite scatterometers and radiometers, SVP drifters further present the opportunity to directly test models of wind forced currents and biological influences in the Lagrangian frame. This can be attempted with unprecedented confidence because unlike its predecessors, the SVP exhibits easily modelled behaviour under various wind conditions.

Acknowledgements

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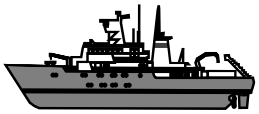
Lowered ADCP Development and Use in WOCE



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During the past eight years of WOCE field work, the lowered acoustic Doppler current profiler (LADCP) has evolved from an experimental instrument used only on selected stations to a standard tool of the WOCE Hydrographic Programme (WHP). The first LADCP velocity profile was made in 1989 on a WOCE project: the Hawaii Ocean Time series. The first WHP Pacific cruise with an LADCP was the P17 section on 135°W in 1991. The LADCP was used only within 3.5° of the equator, where direct velocity measurements were deemed most important. Use became increasingly common on later Pacific cruises. By the start of the one-time Indian Ocean WHP survey on the RV Knorr, near the end of 1994, the LADCP was securely strapped into the rosette frame for the duration, to be used on all CTD stations.

How the LADCP works

An LADCP is a self-contained ADCP that is lowered and retrieved with a hydro wire, usually as part of a CTD/rosette package. The ADCP pings as fast as possible, typically about once per second, yielding a large number of overlapping velocity profiles, each with a range of 100–200 m from the instrument, and each relative to the unknown velocity of the instrument. These unknown velocities are removed by differentiating the profiles in the vertical. The resulting overlapping shear profiles are then interpolated to a uniform depth grid and averaged to give a composite shear profile. Integrating this shear profile in depth gives a velocity profile relative to a single unknown constant of integration. If the vertical mean of the relative velocity profile is subtracted out, then the constant that remains to be determined is just the depth-averaged velocity. This can be calculated by a method closely analogous to that used in shipboard ADCP work (Fischer and Visbeck, 1993). The depth-averaged absolute water velocity is the time-average of the velocity of the water relative to the instrument, plus the time-average of the ship velocity as calculated from the position difference between the start and end of the cast, minus a small correction (usually less than 1 cm/s), calculated from the time-integral of the relative velocity profile. If the vertical velocity were a constant during the downcast, and another constant during the upcast, then the time-integral would be equivalent to a depth-integral – which is of course zero for the de-meaned relative velocity profile. Hence the calculation of the depth-averaged velocity is very insensitive to the accuracy of the relative velocity profile.

What is it good for?

The most obvious "WOCE-type" information that one may wish to derive from LADCP measurements is a picture of the large-scale geostrophic circulation and transports. The primary strength of the LADCP for this purpose is probably its ability to accurately measure the depth-averaged velocity. Weaknesses of the LADCP are its inclusion of ageostrophic as well as geostrophic velocities, and its point-sampling in space and time. Unlike geostrophic calculations, there is no along-track averaging inherent in LADCP measurements, so transports estimated from LADCP profiles alone are limited in accuracy by the degree to which horizontal current structures are resolved by the sample spacing, and by a random-walk accumulation of errors that are, at best, independent from one profile to the next. Horizontal resolution is also a critical factor when using the point LADCP measurements, vertically-averaged, to reference geostrophic currents averaged between stations. Particularly at high latitudes, an entire current jet sometimes fits between a pair of stations, so that it is missed by the LADCP. Despite these limitations, LADCP profiles have proven useful in identifying locations of strong abyssal currents and indicating their circulation patterns. An example is the extensive deep westward flow just offshore of the Kuroshio on the WHP P10 line (Fig. 1; Wijffels et al., 1998).

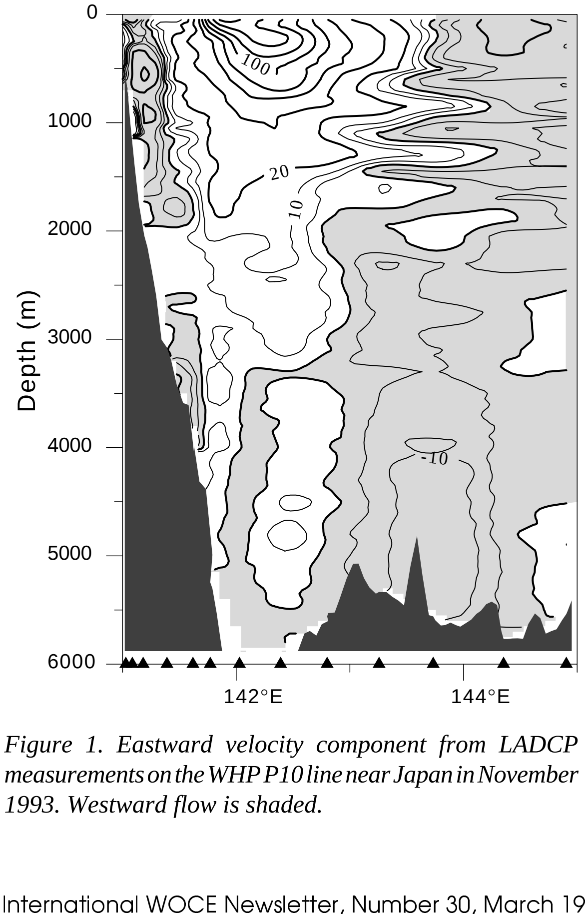

Figure 1. Eastward velocity component from LADCP measurements on the WHP P10 line near Japan in November 1993. Westward flow is shaded.

A particular concern when trying to use vertically-averaged LADCP currents for geostrophic referencing is the amplitude of the barotropic tide. Measurements of open-ocean barotropic tidal currents are rare; depth-averaged LADCP measurements provide a means of checking tide models, which may in turn be useful in estimating the tidal component in LADCP datasets. In Fig. 2, an example from the Indian Ocean shows unusually large tidal currents in the LADCP data (P. Hacker, personal communication) but indicates that they are systematically overestimated by the tide model of Egbert et al. (1994). It remains to be determined from additional LADCP-model comparisons whether the overestimation is specific to this time and place or is more widespread.

The LADCP's lack of inherent horizontal averaging can be an advantage rather than a liability. Consider, for example, the submesoscale feature sampled at 62°S, 103°W, on the WHP P18S line. The 30 cm/s westward jet at 3000 m in Fig. 3 is much faster than indicated by geostrophic calculations (G. Johnson, personal communication). Similar but weaker features have appeared in LADCP profiles from at least two other Southern Ocean sections.

High vertical resolution, and the ability to measure ageostrophic as well as geostrophic currents, makes the LADCP good for measuring near-equatorial currents – an important part of the original motivation for its development – and also for looking at internal waves. Polzin and Firing (1997) show how LADCP profiles may provide information about the geographical distribution of diapycnal mixing. In addition to this statistical approach, one may study particular examples of energetic small-scale structure such as the packet of wiggles between 500 and 2000 m in Fig. 1, on the south-east flank of the Kuroshio.

How well does it work?

Several factors control LADCP profile accuracy. It is important to distinguish between the accuracy of the relative velocity profile as a function of vertical wavenumber, and the accuracy of the depth-averaged velocity. One must also distinguish instrumental errors, caused by the fundamental limitations of the hardware and software, from errors or shortcomings associated with the way the LADCP samples

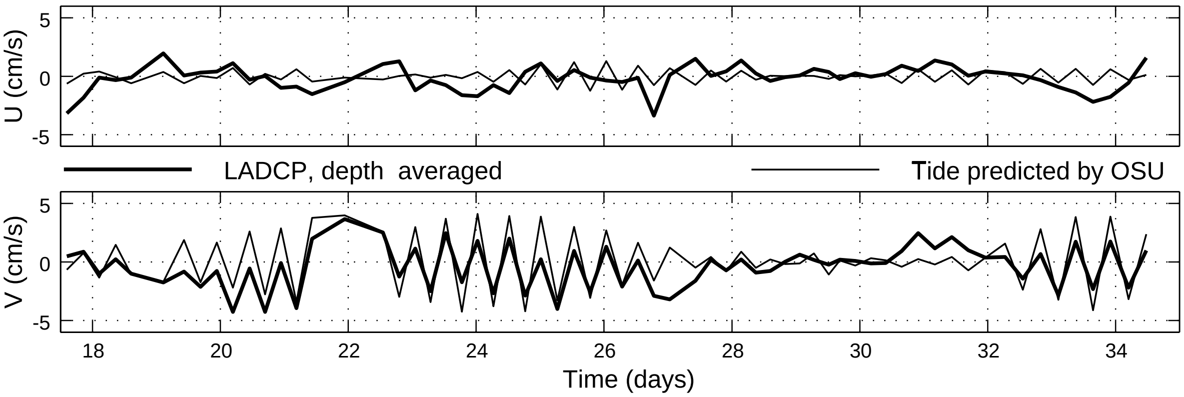

Figure 2. Depth-averaged currents (east component in the top panel, north below) from the LADCP on the second half of the WHP Indian Ocean I9 line, compared to the prediction of the OSU TOPEX/POSEIDON crossover global inverse solution version 3.0 (Egbert et al., 1994), averaged over the duration of each station. Time is in days from the first station of the cruise.

the ocean.

Because the relative velocity profile is calculated as the depth-integral of a composite shear profile, relative velocity errors between two depths tend to grow as the square root of the separation, as in a random walk. The velocity error wavenumber spectrum is red for scales larger than the depth range of each individual ADCP profile (from a single ping), and white for smaller scales (Firing and Gordon, 1990). The magnitude of the error increases with uncertainty in the raw ADCP velocity estimates, and decreases with increasing range of the individual profiles and with increasing numbers of profiles. This analysis assumes unbiased ADCP profiles. Unfortunately, the relative velocity profile is extremely sensitive to small shear biases in the individual profiles; however, such bias has been dominant only in a small fraction of the profiles that have been made. The reason for these occasional episodes of bias, which cause the downcast and upcast profiles to cross in a characteristic “X” on plots of velocity versus depth, has not yet been determined. The problem can often be reduced by rejecting data from more distant bins in each of the single-ping profiles.

Because the relative velocity profile accuracy depends on the accuracy and the range of the single-ping ADCP profiles, it decreases with reduced acoustic backscattering strength. Backscattering at the 150–300 kHz frequencies typical of LADCPs varies widely with depth and location. It generally decreases from the upper ocean to the abyss, often with a sharp change near 1000 m. Typical differences exceed 20 db. At all depths, scattering tends to be weak in the tropics and subtropics, increasing slightly at the equator (particularly in the eastern Pacific) and increasing greatly in subpolar regions. Consequently, it tends to be easiest to get good LADCP profiles at high latitudes; and in some low latitude regions, the relative velocity profiles have been rendered useless below about 1000 m.

Until recently, relative velocity profiles were subject to major interference from sound reflected from the ocean bottom. For each individual ping in the affected depth range, the bottom reflection of the previous ping overwhelms the signal scattered from the water. With a 1-Hz ping rate, for example, the interference would be centred at about 650 m off the bottom, and could contaminate a depth band up to 200 m thick. The velocity signature of this interference depends on the velocity of the package over the ground. When the velocity is small, the bottom-contaminated velocity estimates are similar to the surrounding uncontaminated estimates, and the interference is not visually evident in the calculated velocity profile. When the package velocity is larger than 10 cm/s or so, the interference shows up as velocity spike and/or offset in the processed LADCP profile, if no special editing is done. Editing out the contaminated depth range leaves a gap in the composite shear profile and therefore an uncertain offset between the parts of the velocity profile on either side of the gap. The problem can be avoided entirely by using a staggered ping sequence, so that the interference appears in two non-overlapping depth ranges on alternate pings. Editing out the interference then leaves no gap in the composite shear profile. The use of two ADCPs, one looking up and the other down (Visbeck, 1997), also solves the problem; the upward-looking profiler’s data remains uncontaminated.

The accuracy of the depth-averaged velocity depends almost entirely on the accuracy of the position fixes at the start and end of the cast, and on the accuracy of the time-integrated velocity of the water relative to the package. Fix accuracy is not a major concern, now that military GPS accuracy is widely available on US ships, and differential GPS (real-time or post-processed) and GLONASS receivers can provided similar accuracy on non-US ships. Even civilian GPS contributes an error less than 1.6 cm/s to 95% of all casts lasting 2.5 hours or longer. Of greater concern is the velocity integral, for which there are two types of error: that of the velocity measurement itself, and that due to gaps in the sampling. Long gaps, as opposed to occasional ping dropouts and the normal interval between pings, are caused primarily by interference from sound reflecting off the ocean bottom instead of the water. Although such gaps can last several minutes, this interval is short compared to the entire profile, and can be filled by interpolating a low-pass filtered time series of the water velocity relative to the package. Even if the interpolated velocity is in error by 10 cm/s on average, and the gap is 5 minutes, the contribution to the depth-averaged velocity error will be only 0.3 cm/s for a 2.5-hour profile. Therefore the most worrisome type of error is that which contributes a bias to the velocity measurement. Of the possible causes, I will discuss only one here: compass error.

Compass error affects both the relative velocity profile and the depth-averaged velocity calculation. The LADCP is much less sensitive to compass error than a shipboard ADCP because the magnitude of the velocity error is proportional to the magnitude of the velocity relative to the instrument, which is usually smaller for the LADCP by a factor of 10 or more. For example, if the velocity of the water relative to the LADCP is 20 cm/s, a 5° compass error will cause a 1.7 cm/s velocity error perpendicular to the mean velocity. Compass accuracy will vary with geographic position and instrument tilt, becoming increasingly problematic near the magnetic poles. Nevertheless, LADCPs seem to have performed well in such adverse locations as the Iceland basin, and the Southern Ocean south of Australia and New Zealand. Apart from one recent episode of major compass failure, compass errors have not been immediately obvious from inspection of the velocity profiles.

This brings up an important question: how do we evaluate LADCP performance in practice? And, how good or bad is it? There have been only a few comparisons between LADCP profiles and independent velocity profile measurements. Fischer and Visbeck (1993) showed the result of comparison with Pegasus profiles: rms differences of about 5 cm/s in each component, up to a factor of two larger than the rms difference between Pegasus up and down casts. Hacker et al. (1996) made a similar comparison, but compared only the depth-averaged velocity estimates from the two methods. Rms differences of the depth-averages were about 1.5 cm/s on a cruise in 1992, and under 1 cm/s on a 1993 cruise using a better LADCP. On the November 1997 cruise of RV Knorr, 18 XCP profiles were made during LADCP casts in collaboration with Eric Kunze and Kurt Polzin. The results are not yet available.

Given that direct comparisons between LADCP and other profiling methods are rare, and clouded by uncertainties in the alternative methods and by spatial and temporal differences in sampling, we are led to rely on other consistency checks. The most general one is the comparison between up and down casts. As noted above, this comparison sometimes shows obvious problems. A second useful comparison is between the top of the LADCP profile and simultaneous shipboard ADCP data. This comparison is made separately for LADCP up and downcasts; temporal differences are often substantial, as verified by on-station shipboard ADCP time series. Similarly, Send (1994) has shown that Pegasus up-down differences are roughly consistent with a Garrett-Munk type internal wave spectrum. A third type of comparison is between the bottom of the LADCP profile and the near-bottom velocity calculated by tracking the bottom in addition to the water. Cunningham et al. (1997) have shown cases where this method together with the shipboard ADCP comparison reveal a disturbing lack of consistency; the cause of the error is not yet clear.

As this discussion of error sources suggests, there is no good easy answer to the question, “What is the error in an LADCP profile?” A reasonable but vague answer would be, “A few cm/s, except when backscattering is very low, or something else goes wrong.” A better answer would point out that accuracy tends to be highest for the depth average, but lowest for the lowest non-zero vertical wavenumbers; that relative velocity profile errors are larger for deep profiles than for shallow ones, but the reverse may be true for the depth-averaged velocity; etc. More precisely quantifying the errors in existing LADCP profiles, and finding ways of reducing errors in future profiles, is an ongoing project.

Although far from perfect, the LADCP has made a substantial contribution to WOCE. Interest in the technique

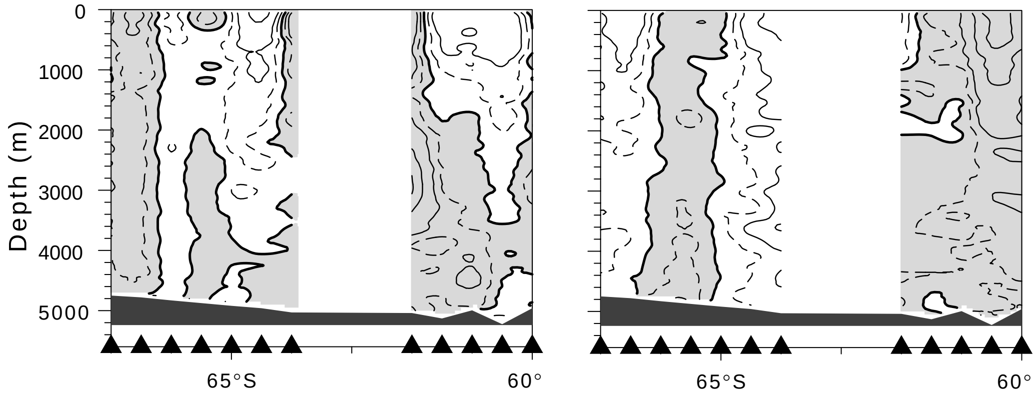

Figure 3. LADCP zonal (left) and meridional (right) velocity components from WHP line P18. Solid contours are at 10 cm/s intervals, negative components are shaded. Note the 30-cm/s westward jet at 3000 m, 62°S, in the left panel.

continues to grow, along with improvements and innovations such as Visbeck's (1997) dual upward and downward-looking system based on RD Instruments' compact "Workhorse" ADCP, and a new Sontek dual system with a high ping rate and other optimisations.

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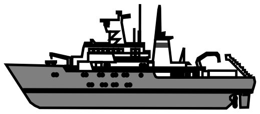
Bottom Pressure Measurements across the Drake Passage Choke Point



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Long-term measurements of sea level or the equivalent pressure variations at the sea bed have proved their value to the scientific community for the study of climate change. Sea level and its possible trends are of direct interest and its variations can be related to internal processes such as changes in ocean circulation. Sea level is at present measured by instruments in-situ or on a global scale by altimetric satellites such as ERS-1, ERS-2 and TOPEX/POSEIDON. The WOCE tide gauge network recently provided a basis from which long term drift in the TOPEX/POSEIDON altimeter was detected which was finally ascribed to a software error. In-situ sea level measurements have shown themselves to be complementary to altimetry and between the two we now have global measurements of ocean dynamics at the sea surface. Measurements of bottom pressure to study dynamics associated with deep flows and the thermohaline circulation are less widespread. They have been concentrated in areas of particular interest. One such area is the Southern Ocean which plays an important role in the global climate balance through the interchange of water masses between the major ocean basins.

ACCLAIM

A programme of measurements was started in the late 1980s in the South Atlantic and the Southern Ocean which became known as ACCLAIM, (Antarctic Circumpolar Current Levels from Altimetry and Island Measurements, Spencer et al., 1993), an acronym which omits the important contribution from Bottom Pressure Recorder (BPR) measurements to the programme. The programme was oriented towards a study of the circulation of the Antarctic Circumpolar Current (ACC) as one of the UK contributions to WOCE.

The principal objective was to study variations in the ACC over a range of time scales and to resolve the spatial scales of the variability. BPRs were positioned across the main filaments of the ACC to measure transport fluctuations in the region of the Drake Passage 'choke point'. A parallel investigation using altimeter data was undertaken (Woodworth et al., 1996b). The first BPR array was installed in 1988 in the Scotia Sea. In 1992 the work was relocated to concentrate on measuring across the Drake Passage between Burdwood Bank and Elephant Island where it has remained. The instruments were replaced annually to produce a long term data set.

POL sea level stations were installed on islands and at Antarctic mainland sites (Fig. 1), the latter through collaborative work with the British Antarctic Survey. With the development of improved instrumentation and modern microprocessor technology it became possible to construct autonomous sea level stations in remote areas and to have them run continuously (Woodworth et al., 1996a). The desire to obtain data in quasi real time and to monitor the operation of the stations led to daily transmission of the data through a telemetry link. Operational stations have been installed at Ascension, St Helena, Tristan da Cunha, Port Stanley (Falkland Islands), Signy Island (South Orkney), Faraday (now Vernadsky) and Rothera. These stations record sub-surface pressure, sea temperature, air temperature and barometric pressure from which sea level variations can be derived. Goal 2 of WOCE, which is to measure the long-term representativeness of any short term measurements, is satisfied to an extent by our BPR array and the sea