A Practical Assessment of the Errors Associated with Full-Depth LADCP Profiles Obtained Using Teledyne RDI Workhorse Acoustic Doppler Current Profilers

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ABSTRACT

Lowered acoustic Doppler current profilers (LADCPs) are commonly used to measure full-depth velocity profiles in the ocean. Because LADCPs are lowered on hydrographic wires, elaborate data processing is required to remove the effects of instrument motion from the velocity measurements and to transform the resulting relative velocity profiles into a nonmoving reference frame. Two fundamentally different methods are used for this purpose: in the *velocity inversion method*, a set of linear equations is solved to separate the ocean and instrument velocities while simultaneously applying a combination of velocity-referencing constraints from navigational data, shipboard ADCP measurements, and bottom tracking. In the *shear method*, a gridded profile of velocity shear, which is not affected by instrument motion, is vertically integrated and referenced using a single constraint. The main goals of the present study consist in estimating the accuracy of LADCP-derived velocity profiles and determining which processing method performs better. To this purpose, 21 LADCP profiles collected during four surveys are compared to velocities measured simultaneously by nearby moored instruments at depths between 2000 and 3000 m. The LADCP data were processed with two slightly different publicly available implementations of the velocity inversion method, as well as with an implementation of the shear method that was extended to support multiple simultaneous velocity-referencing constraints. Regardless of the processing method, the overall *rms* LADCP velocity errors are <3 cm s^{-1} as long as multiple velocity-referencing constraints are imposed simultaneously. On the other hand, solutions referenced with a single constraint are associated with significantly greater errors. The two primary instrument characteristics that influence data quality are range and sampling rate. Dependence of the LADCP velocity errors on those two parameters was determined by reprocessing range-limited subsets and temporal subsamples of the LADCP data. Results indicate an approximately linear increase of the velocity errors with decreasing sampling rate. The relationship between velocity errors and instrument range is much less linear and characterized by a steep increase in velocity errors below a limiting range of $\approx$60 m. To improve the quality of the velocity data by increasing the instrument range, modern LADCP systems often include both upward- and downward-looking ADCPs. The data analyzed here indicate that the addition of a second ADCP can be as effective as doubling the range of a single-head LADCP system. However, in one of the datasets the errors associated with the profiles calculated from combined up- and down-looker data are significantly larger than the corresponding errors associated with the profiles calculated from the down-looker alone. The analyses carried out here indicate that the velocity errors associated with LADCP profiles can be significantly smaller than expected from previously published results and from the uncertainty estimates calculated by the velocity inversion method.

1. Introduction

Eulerian measurements of ocean velocities are used in many different contexts. Examples include transport estimation of oceanic currents, as well as the study of physical oceanographic processes such as mesoscale eddies, internal waves, etc. Acoustic Doppler current profilers (ADCPs) are particularly useful for sampling the oceanic velocity field because they yield velocity profiles, rather than the point samples recorded by traditional current meters. ADCPs obtain velocity profiles by transmitting acoustic pulses (called pings) and measuring the Doppler shift of sound energy reflected in the water column. The velocities are sampled in fixed-size "depth cells" or "bins," with the distance of a particular bin from the transducer being determined by the time delay between a ping and its echo return. The maximum distance from the transducer where valid velocity measurements are obtained is called

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the "instrument range" and depends both on instrument properties (transmit power and acoustic frequency) and on the spatially and temporally varying acoustic scattering properties of the ocean.

Most ADCPs are either permanently installed on ships, where they sample the velocity field in the upper ocean along the ship's track, or deployed on moorings and bottom mounts, where they collect Eulerian time series measurements. Because of the limited range of ADCPs, full-depth velocity profiles in the deep ocean cannot be obtained with single instruments deployed in this manner. This has led to the development of methods for processing data from ADCPs that are lowered on hydrographic wires, usually in conjunction with CTD systems. The primary instruments that are currently used for lowered ADCP (LADCP) work are 3000-kHz broadband ADCPs from the "Workhorse" product family manufactured by Teledyne RD Instruments (RDI). In the open ocean below the biologically productive surface layers, the typical range of these instruments varies between a few 10s of meters and $\approx$200 m.

When used in LADCP systems, the ADCPs measure velocity profiles relative to the moving instrument platforms. To derive full-depth, absolute (i.e., in the earth's frame of reference) velocities from the short, relative velocity profiles, the effects of the instrument motion must be removed before the overlapping velocity profiles can be combined. There are two fundamentally different methods that have been developed for processing LADCP data:

1) Shear method: Because of the geometry of ADCP measurements, translational instrument motions affect the velocities in all bins equally, whereas rotational motions around the center of the transducer (pitch, roll, and heading changes) do not affect the along-beam velocity measurements. Therefore, instrument motion does not affect vertical-shear profiles, which can be combined in overlapping averages to span the full water depth. The horizontal velocity profiles obtained by vertically integrating vertical-shear data are relative to unknown integration constants, which can be determined, for example, by tracking the seabed near the bottom of a profile or from ship drift estimated using navigational data (Firing and Gordon 1990). The first successful application of the LADCP shear method to derive full-depth absolute velocity profiles is reported by Fischer and Visbeck (1993), who find rms errors of $\approx$5 cm s^{-1} when comparing a handful of deep LADCP casts in the Tropical Atlantic to simultaneously obtained velocity profiles obtained with acoustically tracked Pegasus dropsondes.
2) Velocity inversion method: In its current implementations, the shear method does not allow multiple velocity-referencing constraints (e.g., both from navigational and bottom-tracking data) to be applied simultaneously. Therefore, Visbeck (2002) developed an alternative method for processing LADCP data based on the fact that every ADCP velocity measurement is the sum of ocean and instrument-package velocities (as well as noise). For each LADCP cast the velocity measurements define a system of linear equations, with ocean and platform velocities as unknowns. Although the resulting equation systems are singular, velocity-referencing constraints can easily be added as additional equations. The most widely used velocity-referencing constraints are derived from ship-drift data, from bottom tracking, and from velocities measured by hull-mounted shipboard ADCPs. The resulting overdetermined linear equation systems can be solved with standard inverse techniques (e.g., Wunsch 1996) to yield estimates of ocean and instrument-platform velocities.

Much of the early experience with LADCP systems was gained during the second half of the World Ocean Circulation Experiment (WOCE; King et al. 2001). Processing of the WOCE LADCP data was carried out primarily with an implementation of the shear method developed by Eric Firing at the University of Hawaii. This software uses navigational data, usually from a GPS stream, to reference the relative velocity profiles, although at least one group carried out experiments with bottom tracking as an alternative (Cunningham et al. 1997). A particular shortcoming of LADCP velocities derived with the shear method is the lack of information about uncertainty, which has been estimated to be "a few cm s^{-1}, except when backscattering is very low, or something else goes wrong." (King et al. 2001). In contrast, the velocity inversion method provides formal uncertainty estimates (Visbeck 2002), which are, however, scaled semi-empirically—that is, it is not a priori clear, how accurate they are. Interpretation of the formal inversion uncertainty estimates is further complicated because LADCP uncertainties are the combined effects of different error sources with different vertical correlation scales (Firing and Gordon 1990; King et al. 2001; Visbeck 2002).

The only fully satisfying method for assessing uncertainties associated with LADCP-derived velocities consists of comparing the data to independent measurements, such as Pegasus profiles (e.g., Fischer and Visbeck 1993). Although shipboard ADCP (SADCP) velocities can be used for the same purpose (e.g., Cunningham et al. 1997), this is not ideal because SADCP data also provide useful velocity-referencing constraints for the LADCP solutions. The purpose of the present study is to assess the uncertainties associated with LADCP-derived velocities obtained with 300-kHz Teledyne RDI Workhorse ADCPs. To this effect, LADCP data collected during four surveys are compared to nearby velocity measurements obtained with moored instruments (section 2a). The data are processed using two different versions of the velocity inversion method, with an implementation of the shear method, as well as with a new inverse technique that permits multiple simultaneous constraints to reference the relative velocities obtained with the shear method (section 2b). Although rms errors of $\approx$3 cm s^{-1} can be achieved when using all available velocity-referencing constraints (section 3), the errors increase significantly when subsets of the constraints are applied (section 4). The performance of dual-head LADCP systems is usually, but not always, better than that of down-looker-only systems (section 5). Effects of instrument range and sampling rate are explored in section 6. Finally, it is shown that velocity profiles derived from three-beam LADCP data are associated with significantly increased velocity errors (section 7). The main findings are discussed in section 8. The appendix describes how the error estimates of the current implementations of the velocity inversion method are calculated.

2. Datasets and processing methods

a. Datasets

In August 2006, a CTD–LADCP survey was carried out during the *GRAVILUCK* cruise to the crest of the Mid-Atlantic Ridge near 37°N 32°W (Thurnherr et al. 2008). The LADCP system employed a single Teledyne RDI Workhorse 300-kHz ADCP installed as a down-looker on a CTD rosette. The ADCP was programmed to record single-ping velocity "ensembles" in beam coordinates. The bin length for the casts used here is 8 m, the blanking distance was set to 0 m, and data from the first bin are excluded from processing. To minimize the effects of previous-ping interference from the seabed, alternating ping intervals of 1 and 1.6 s were used (staggered pinging; King et al. 2001). Four of the LADCP profiles were taken less than 1 km from a bottom-mounted ADCP (also a Teledyne RDI Workhorse) that was deployed at a depth of 2080 m and recorded 10-ping velocity ensembles once every minute.

In November 2006, another CTD–LADCP survey was carried out during the *LADDER-1* cruise to the crest of the East Pacific Rise near 10°N 104°W (Thurnherr et al. 2010, manuscript submitted to *Deep-Sea Res.*). Throughout most of this survey, two Teledyne/RDI Workhorse ADCPs were installed on a CTD rosette, although, because of instrument failures, some casts were carried out with a single ADCP installed as a down-looker. The ADCP setup was identical to the one used during the *GRAVILUCK* survey, except for slightly longer pinging intervals of 1.5 and 2 s. During the *LADDER-1* cruise, five physical oceanography moorings with 15 Aanderaa RCM-11 acoustic current meters were deployed. Additionally, a bottom-mounted ADCP (another Teledyne RDI Workhorse) was deployed less than 1 km from one of the moorings. Eight of the LADCP profiles (five with a dual-head configuration) were taken less than 1 km from one of the moored instruments, all of which sampled the oceanic velocity field every 20 min at depths between 2430 and 2930 m.

In December 2006–January 2007, a second CTD–LADCP survey was carried out in the same region near the East Pacific Rise during the *LADDER-2* cruise (Jackson et al. 2009). The LADCP system employed two Teledyne RDI ADCPs installed on a CTD rosette. The ADCPs were programmed the same way as during *LADDER-1*. Five of the LADCP profiles were taken less than 1 km from one of the moored instruments deployed there in November 2006. A third CTD/LADCP survey was carried out in the same region during the *LADDER-3* cruise in November 2007 (Thurnherr et al. 2010, manuscript submitted to *Deep-Sea Res.*). Again, two Teledyne RDI ADCPs were installed on a CTD rosette and the same instrument setup was used. Four of the LADCP profiles from this survey were taken less than 1 km from one of the moored instruments deployed there during *LADDER-1*.

Combining the four datasets, there are 40 pairs of simultaneous nearby velocity samples from LADCP casts and moored instruments. Because of the configuration of the moorings, 34 of these velocity samples were obtained within 150 m of the seabed, whereas the remaining ones were measured between 400 and 600 m above the bottom (Fig. 1).

b. Data processing

Currently, there are three main publicly available software packages used for LADCP data processing: 1) an implementation of the shear method developed and maintained by Eric Firing's group at the School of Ocean and Earth Science and Technology (SOEST) of the University of Hawaii; 2) the original implementation of the velocity inversion method developed by Martin Visbeck and now maintained by this author at the Lamont-Doherty Earth Observatory (LDEO); 3) a cleaned up implementation of the velocity inversion method maintained primarily by Gerd Krahmann at the Leibniz Institute of Marine Sciences (IFM-GEOMAR, or IFMG) in Kiel, Germany. For simplicity, the processing

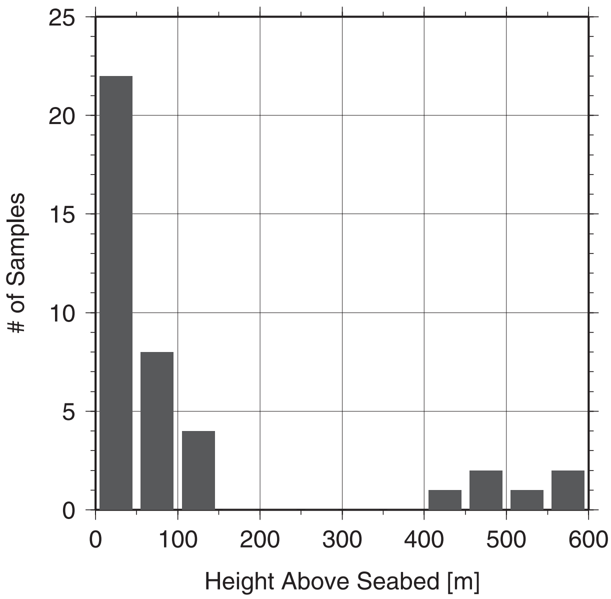

FIG. 1. Distribution of LADCP–mooring velocity pairs with height above the seabed.

packages will be referred to by the institutional abbreviations where they are maintained, that is, SOEST, LDEO and IFMG. It should be noted that the IFMG and the LDEO implementations are derived from (and share much of) the same original code, that is, they are expected to yield similar results.

The official versions of all three software packages available in July 2008 are used for the present study, that is, LDEO version IX_5 and IFMG version 10.6—the SOEST software does not use version numbers. During processing, several bugs in the LDEO software had to be fixed to allow all possible combinations of the velocity-referencing constraints to be used (section 4); the bug fixes, which have been incorporated into version IX_6, do not affect the default solutions derived using all three constraints in any way. All three software packages have ''free'' parameters that can be modified by the user, although there are many more in the LDEO and IFMG velocity inversion implementations than in the SOEST shear method software. Recommended values are used throughout for all processing parameters. For the SOEST and IFMG software packages, these are the default values, but for the LDEO software the recommendations of the ''how to'' (Thurnherr 2009) were followed.

During the course of this investigation, it was found that the profile quality is affected significantly by the number of simultaneously applied velocity-referencing constraints (section 4). To allow for a fair comparison between the shear and the velocity inversion methods, a new *shear inversion method* was implemented as follows. For each velocity component of an LADCP profile a set of linear equations is constructed relating the gridded shear u_z obtained with the SOEST software to the velocities u, that is,

$$\frac{u(z^{i+1}) - u(z^i)}{z^{i+1} - z^i} = u_z\left(\frac{z^{i+1} + z^i}{2}\right). \tag{1}$$

The velocities from the shipboard ADCP u_{SA} and from bottom tracking u_{BT} define additional sets of equations that reference the relative velocity profiles in the upper ocean and near the seabed, respectively:

$$u(z^i) = u_{\mathrm{SA}}(z^i) \quad \text{and} \tag{2}$$

$$u(z^i) = u_{\mathrm{BT}}(z^i). \tag{3}$$

Finally, the ship-drift (GPS) constraint is written as a single equation

$$\frac{1}{n}\sum_i u(z^i) = \langle u \rangle, \tag{4}$$

where $\langle u \rangle$ is the depth-averaged velocity taken from the SOEST solution, and n is the number of velocity samples in the profile. Expressions (1)–(4) define a set of linear equations for the unknowns $u(z^i)$ that can be solved with standard linear inverse techniques (e.g., Wunsch 1996). For consistency, the bottom-tracking velocities are taken from the solutions of the LDEO processing software, although it is also possible to extract bottom-tracked velocity profiles from LADCP data without running a full velocity inversion.

3. Fully constrained down-looker solutions

For many applications, the most fundamental diagnostic of the quality of LADCP data is the accuracy of individual (i.e., at a given depth) velocity estimates. Here, this quantity is estimated from comparisons with velocity measurements from nearby (<1 km horizontal distance) current meters and bottom-mounted ADCPs. Although bottom-mounted ADCPs measure velocity profiles, the LADCP velocity errors at different depths cannot be considered statistically independent. Therefore, each bottom-mounted ADCP profile is vertically averaged and the resulting velocity estimate is treated the same way as a single current-meter sample. For standard LADCP processing with any of the methods described in section 2b, the down- and upcast data are combined, which assumes that the ocean velocities do not change significantly during a cast. Therefore, the velocity measurements from the moored instruments are also

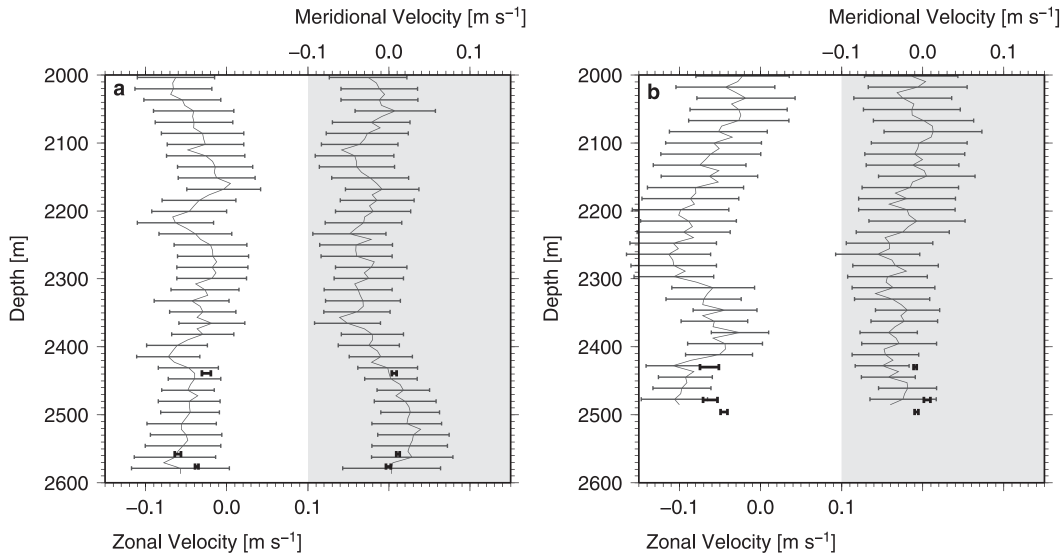

FIG. 2. LADCP profiles from LDEO-processed down-looker data constrained with bottom-tracking, GPS, and shipboard ADCP data, as well as simultaneous current-meter velocities. LADCP data are plotted with thin lines; error bars show the processing-derived error estimates see the (appendix). Current-meter data are plotted with thick error bars given by the standard errors estimated during time averaging and assuming independent sample errors. (a) Profile with overall best agreement (0.8 cm s^{-1} rms discrepancy) and (b) profile with overall worst agreement (4.6 cm s^{-1} rms discrepancy).

averaged over the durations of each LADCP cast. Figure 2 shows the LDEO-processed LADCP down-looker profiles associated with the smallest and largest discrepancies with the simultaneously measured current-meter velocities. In both cases, the agreement between LADCP and current-meter velocities is significantly better than that indicated by the processing-derived errors—that is, the uncertainties estimated by current implementations of the velocity inversion method see the (appendix) are overly conservative.

To obtain a statistical measure of the quality of LADCP velocity samples, the individual velocity components of the entire dataset are compared to the corresponding values from the moored instruments (Fig. 3). These and all following comparisons are based on the LADCP samples (at $\approx$8 m vertical resolution) closest in depth to the corresponding moored measurements, without any extrapolation of the LADCP profiles below the maximum depths. The overall rms discrepancies between the LADCP and the moored-instrument velocity components (2.6–3.4 cm s^{-1}) are significantly smaller than the processing-derived velocity error estimates of 4–5 cm s^{-1}, confirming that the latter are overly conservative. The data furthermore indicate similar velocity discrepancies for the samples from the bottom 150 m and for those taken 400–600 m above the seabed (Figs. 3a–c). The distributions of the velocity discrepancies are similar for all three processing methods (Figs. 3d–f). The velocity discrepancies associated with the different processing methods are linearly correlated, although with rather large rms misfits ($\approx$2.3 cm s^{-1}; not shown).

In addition to LADCP measurement and processing errors, the rms discrepancies between the LADCP and the moored-instrument velocities also include measurement errors of the moored instruments, as well as temporal and spatial oceanic variability. To quantify the effects of these velocity uncertainties that are not caused by LADCP errors, two of the moored-instrument records are used: between 9 November and 15 December 2006 a bottom-mounted ADCP deployed at a depth of 2570 m recorded velocity profiles every 20 min less than 200 m from a moored current meter recording velocities at the same frequency and in the depth range of the bottom-mounted ADCP measurements; averaging the data over the typical duration of a CTD/LADCP cast (2 h) yields rms velocity differences between the two moored records of $\approx$2 cm s^{-1}. Interpreting this value as the uncertainty associated with an individual LADCP velocity error estimate and assuming that the LADCP velocity errors from different casts are statistically independent allows the uncertainties associated with rms velocity discrepancies calculated from sets of LADCP profiles to be estimated. For example, the rms velocity discrepancies of the entire dataset (21 profiles) listed in the caption of Fig. 3 are associated with uncertainties of 0.4 cm s^{-1} that are unrelated to LADCP measurement and processing errors. This implies that the three rms velocity discrepancies resulting from the different

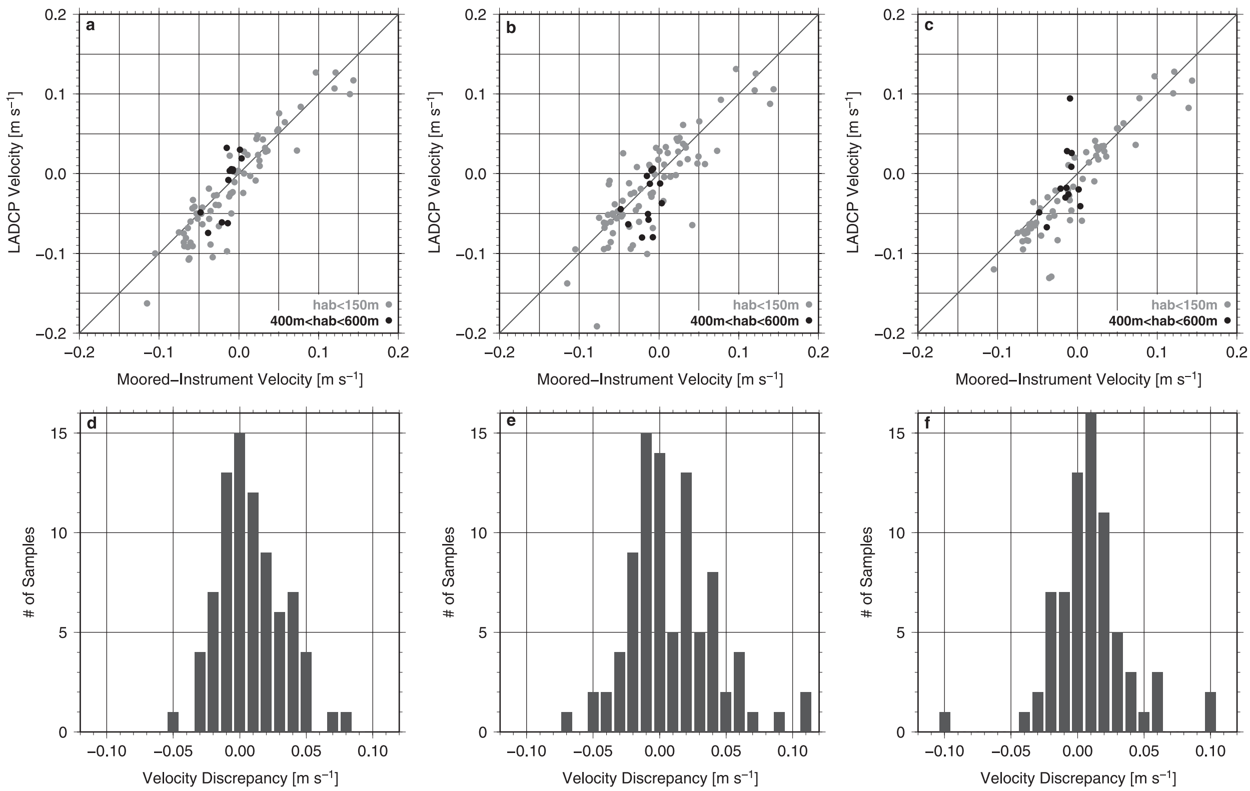

FIG. 3. Down-looker LADCP data vs current-meter velocities: (a)–(c) scatterplots of velocity components; (d)–(f) corresponding histograms of velocity discrepancies; (a),(d) LDEO-processed solutions, 2.6 cm s^{-1} rms velocity discrepancy; (b),(e) IFMG-processed solutions, 3.4 cm s^{-1} rms velocity discrepancy; and (c),(f) shear inverse solutions, 3.0 cm s^{-1} rms velocity discrepancy.

processing methods overlap within their uncertainties, that is, the solutions are of similar quality. The discrepancies between the LADCP velocities and the moored-instrument measurements are significantly greater than the uncertainties that are unrelated to LADCP measurement and processing; therefore, in the following they will simply be called LADCP velocity errors.

4. Velocity-referencing constraints

In the datasets analyzed here, the discrepancies between the fully constrained LADCP velocities and the corresponding measurements from the moored instruments are similar, regardless of the processing method used (section 3). This observation is not particularly surprising given the fact that 85% of the velocity measurements from the moored instruments were made within 150 m of the seabed (Fig. 1), that is, in the depth range where the package motion is directly constrained by bottom tracking. Consistent with this consideration, the LADCP velocity errors of the profiles constrained with bottom tracking alone are similar to the corresponding errors in the fully constrained solutions, and the LADCP velocity errors from the different processing methods constrained only by bottom tracking again agree within their nominal uncertainty of 0.4 cm s^{-1} (Table 1).

Whereas bottom tracking constrains the package motion near the seabed, shipboard ADCP data directly constrain the LADCP velocities in the upper ocean (the top 600–900 m in the datasets analyzed here). The constraint that has traditionally been most widely used in LADCP processing, however, is based on ship drift inferred from navigational (GPS) data (Fischer and Visbeck 1993). In contrast to bottom tracking and shipboard ADCP measurements, both of which directly constrain the LADCP velocities in particular depth ranges, ship drift constrains the temporally and vertically averaged ocean velocities. If the LADCP velocity errors are dominated by uncorrelated single-ping errors of constant magnitude, the LADCP velocity errors resulting from using a constraint for the integrated velocities are smallest in midwater and increase both toward the sea surface and toward the seabed (Firing and Gordon 1990).

Consistent with these considerations, the rms LADCP velocity errors in the datasets analyzed here increase significantly for all processing methods when the velocities are constrained by ship-drift (GPS) data alone (Table 1). At first sight somewhat less expectedly, the

TABLE 1. Rms LADCP velocity errors (cm s^{-1}) from down-looker data. The rms error of the SOEST solutions is identical to that of the shear inversion solutions constrained by GPS data alone, that is, 6.4 cm s^{-1}.

Velocity-referencing constraints	LDEO	IFMG	Shear inversion
BT	2.8	2.6	3.0
BT, GPS, and SADCP	2.6	3.4	3.0
GPS and SADCP	3.3	4.2	5.3
GPS	5.0	4.1	6.4

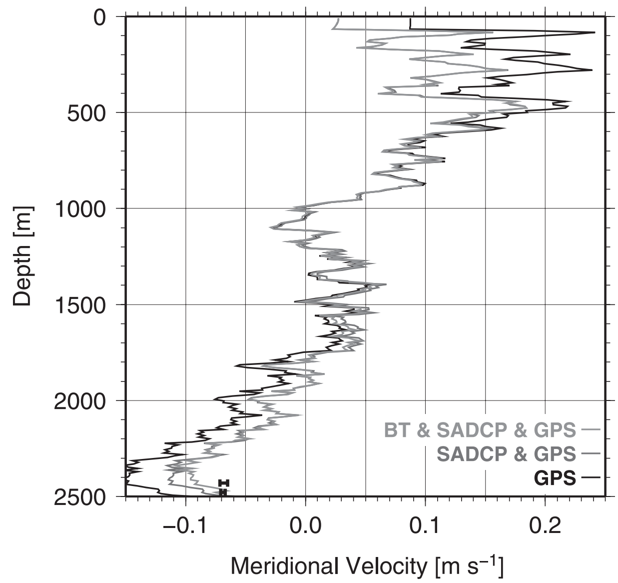

FIG. 4. LDEO-processed example profile illustrating the effects of applying different combinations of the available velocity-referencing constraints: from bottom tracking (BT), SADCP, and GPS. The error bars between 2400 and 2500 m show current-meter measurements.

LADCP velocity errors near the bottoms of many profiles are significantly smaller when constrained both with shipboard ADCP and GPS data, compared to the solutions constrained with GPS data alone. This fact is immediately apparent from the tabulated LADCP velocity errors corresponding to the LDEO- and shear inversion–processed data. (In the case of the IFMG-processed profiles, two out of the four datasets show the same behavior.) This implies that the LADCP velocity errors in the upper and lower halves of the profiles are anticorrelated, as illustrated with an LDEO-processed example profile in Fig. 4. Without multiple velocity-referencing constraints (darkest-shaded profile), the vertically integrated shear between 100 and 2400 m is $\approx$40 cm s^{-1}, which is significantly greater than the best estimate of $\approx$25 cm s^{-1} derived from the fully constrained solution (lightest-shaded profile). Applying both the shipboard ADCP and the ship-drift velocity-referencing constraints (intermediately shaded profile) corrects the shear between the sea surface and the middle of the profile near 1200 m. Because the ship-drift data constrain the vertically averaged velocities, any change in large-scale shear in the upper half of a profile must be balanced by a corresponding change of opposite sign in the lower half, which improves the velocities near the seabed.

5. Single- versus dual-head LADCP systems

Three out of the four LADCP datasets analyzed here were collected with dual-head LADCP systems, which consist of both downward- and upward-looking ADCPs (section 2a). To determine whether there are significant differences between the performance of upward- and downward-looking instruments, statistics of the ADCP error velocities[1] were calculated (Fig. 5)—the down- and upcasts are treated separately because of possible package-wake effects. Apart from contamination caused by transducer "ringing" affecting the bins closest to the instruments, the error velocities are unbiased and the mean values (Figs. 5a,b) show no indications for package-wake effects, which would be expected to affect the up-looker data during the downcasts and the down-looker data during the upcasts. Although the mean error velocities are similar for upward- and downward-looking instruments, the up-looker standard deviations are consistently and significantly greater than the corresponding down-looker standard deviations (Figs. 5c,d). This observation is likely related to the presence of the hydrographic wire, which can affect the up-looker data via sidelobe interference and/or wire-wake effects. Furthermore, close inspection reveals that the up-looker error velocity standard deviations of the downcasts are consistently greater than the corresponding upcast standard deviations. These differences are likely caused by package-wake effects that are, however, much smaller than the up-looker versus down-looker differences. A similar observation holds for the down-looker error velocity standard deviations but here the presumed package-wake effects are even more subtle and restricted to the *LADDER-2* and *LADDER-3* datasets. Finally, the error velocity standard deviations suggest that the data from the upward-looking ADCP used during *LADDER-3* are of somewhat inferior quality than the data from the *LADDER-1* and *LADDER-2* up-lookers.

[1] ADCP error velocities are a measure of the mutual (in)consistency of the four along-beam velocities (e.g., RD Instruments 1996).

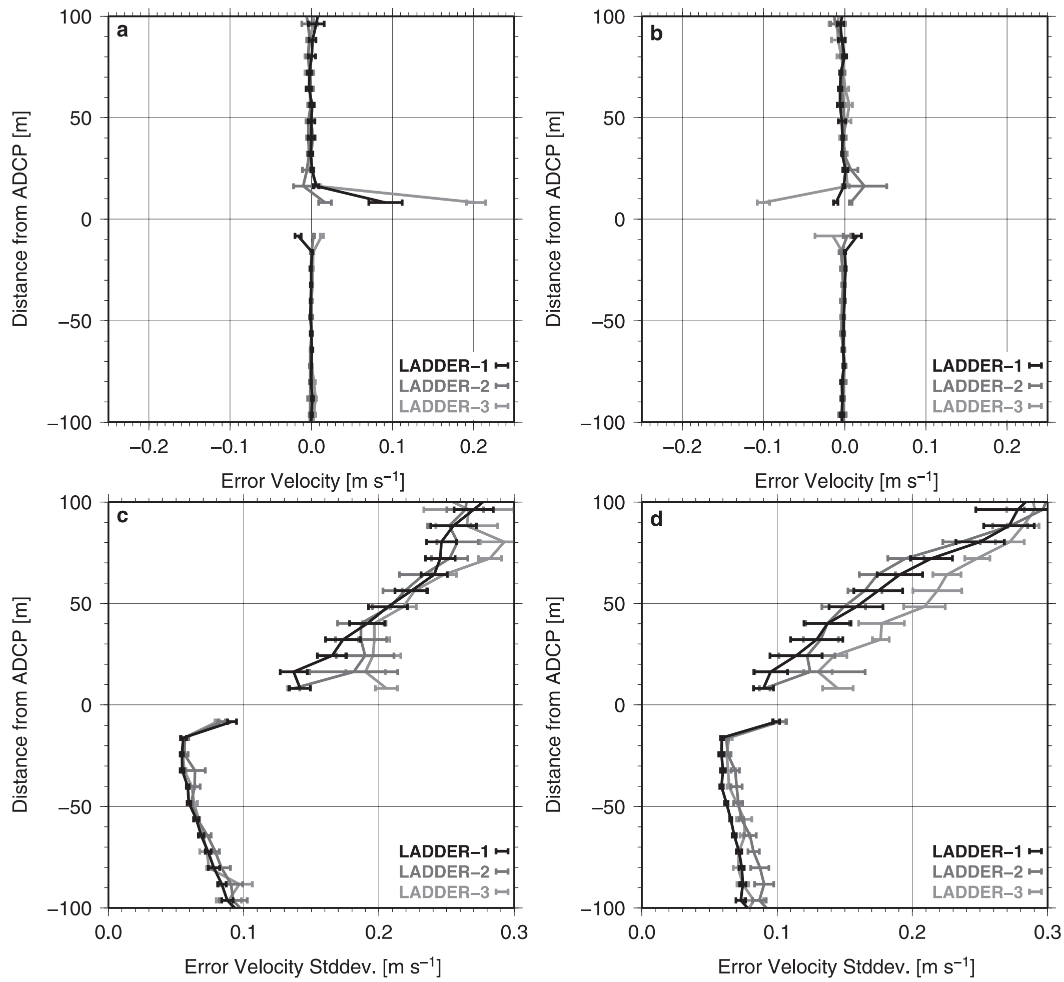

FIG. 5. Error velocities of the datasets collected with dual-head LADCP systems: (a),(b) cruise-averaged mean values; (c),(d) standard deviations; (a),(c) downcasts; and (b),(d) upcasts.

The accuracy of the processed velocity profiles is of much greater importance than error velocity statistics, of course. In the datasets analyzed here, the LDEO-processed up-looker-only solutions are of similar quality as the down-looker-only solutions, except in the case of LADDER-3 (Table 2). The *LADDER-1* and *LADDER-2* velocity profiles calculated from combined up- and down-looker data are associated with significantly smaller LADCP velocity errors than either of the single-head solutions, as expected from the increased effective range of dual-head systems (Visbeck 2002). In the case of *LADDER-3*, however, the addition of the up-looker data decreases the quality significantly when compared to the down-looker-only solutions. It is interesting to note that the apparent problems with the *LADDER-3* data are much more severe for the solutions constrained with GPS data alone. This observation indicates that the errors introduced by combining the *LADDER-3* up- and down-looker data manifest themselves primarily as biased shear.

6. Effects of instrument range and sampling rate

Instrument range is an important factor affecting the quality of LADCP data (Visbeck 2002), consistent with the observation that the velocities derived from dual-head LADCP systems can be associated with significantly smaller LADCP velocity errors than those from down-looker- or uplooker-only systems (section 5). Conversely, in regions characterized by weak acoustic backscatter the instrument range often becomes too small to calculate full-depth LADCP velocity profiles (e.g., King et al. 2001). Within a given profile, the instrument range is not a constant. In the case of the *LADDER* data, all instruments are associated with ranges exceeding 20 bins in the upper ocean and approximately constant minimum ranges of 10–12 bins below 1500 m or so. To quantify the relationship between instrument range and LADCP profile quality, the dual-head profiles from *LADDER-1* and *LADDER-2* were reprocessed several times by the

TABLE 2. LDEO-processed LADCP velocity errors (cm s^{-1}) from surveys carried out with dual-head instruments. The *LADDER-1* data include three profiles collected with a down-looker-only system (section 2a).

		GPS- and SADCP- constrained			GPS-constrained
Dataset	Number profiles	Down-looker	Up-looker	Dual head	Dual head
LADDER-1	8	3.2	3.1	2.5	4.3
LADDER-2	5	3.6	3.7	2.4	3.6
LADDER-3	8	2.8	5.0	4.4	10.4

LDEO software with artificially limited instrument ranges obtained by discarding data from the farthest bins (Fig. 6). The *GRAVILUCK* data are not used for this comparison because they were collected with a down-looker-only system and in a region characterized by a different scattering environment; and the *LADDER-3* profiles are not used because of the inconsistencies between the down- and up-looker data (section 5). Consistent with expectations, the LADCP velocity errors decrease with increasing instrument range up to the deep-water range determined by the scattering environment. In the data analyzed here, a minimum of seven 8-m bins are required to derive LADCP velocity profiles with errors <5 cm s^{-1}; restricting the instrument range to less than five bins results in numerous profiles that cannot be processed any more.

Inspection of Fig. 6 indicates close agreement between the dual-head and down-looker LADCP velocity errors for instrument ranges between eight bins (four from each instrument in the case of the dual-head LADCP) and the maximum effective instrument range of single-head systems (≈10 bins). At shorter instrument ranges, the dual-head LADCP velocity errors are larger, most likely because the first bin is always discarded (section 2a)—that is, at an instrument range of six bins, a dual-head single-ping profile consists of four velocities (bins 2 and 3 from each instrument), whereas the corresponding single-head single-ping profile consists of five velocities (bins 2–6). The agreement for instrument ranges of 8–10 bins implies that adding an upward-looking ADCP can be as good as doubling the range of a down-looker-only system.

In addition to increasing the effective instrument range by adding a second ADCP, increasing the sampling rate is also expected to improve the LADCP data quality (Firing and Gordon 1990). To elucidate the effects of the pinging rate on the LADCP velocity errors, the down-looker data from the three *LADDER* cruises were reprocessed by the LDEO software with different subsets of the recorded single-ping ensembles. The *GRAVILUCK* data are not used for this comparison because of the different sampling rate. Because staggered pinging was used to avoid data gaps caused by the previous-ping interference (section 2a), consecutive pairs of single-ping profiles were kept in the subsets used for processing; for example, the profiles with a mean sampling rate of 5.25 s were calculated by discarding single-ping profiles 1–4, keeping 5 and 6, discarding 7–10, etc. Within the explored range of sampling rates, the LADCP velocity errors increase approximately linearly with increasing sampling intervals (Fig. 7).

7. Three-beam solutions

Single-beam failures are a fairly common hardware problem of LADCP systems. In principle, such single-beam failures are not catastrophic because three beams are sufficient for determining the three components of the oceanic velocity field. To assess the degradation in data quality associated with three-beam solutions, the down-looker LADCP data were reprocessed 14 times with the LDEO software and constrained with shipboard ADCP and GPS data after discarding the velocities from a randomly chosen beam (a different one for each profile) of each instrument. Comparison with the solutions derived from all four beams indicates that the LADCP velocity errors associated with the three-beam solutions tend to be larger than the LADCP velocity errors associated with the four-beam solutions, except in the case of *GRAVILUCK* where the three- and four-beam solutions are of similar quality (Table 3). Except in the case of *LADDER-3*, there are three-beam solutions associated with smaller LADCP velocity errors than those of the four-beam solutions, however. Averaged over the four datasets, the mean three-beam LADCP velocity error is 4.2 ± 0.4 cm s^{-1}, which is significantly greater than the 3.3 cm s^{-1} associated with the the four-beam solutions. The reduction in data quality is therefore similar to the effect of halving the sampling frequency (Fig. 7).

Occasionally, LADCP data show evidence for contamination by instrument package wakes. Although no evidence for significant wake contamination was found in the data analyzed here (section 5), the profiles were nevertheless reprocessed with the LDEO software after discarding from each ensemble the velocities from the beam pointing in the instantaneous downstream direction. For all datasets considered here, the corresponding LADCP velocity errors lie within the range of the "3 random beams" solutions (Table 3), consistent with the prior

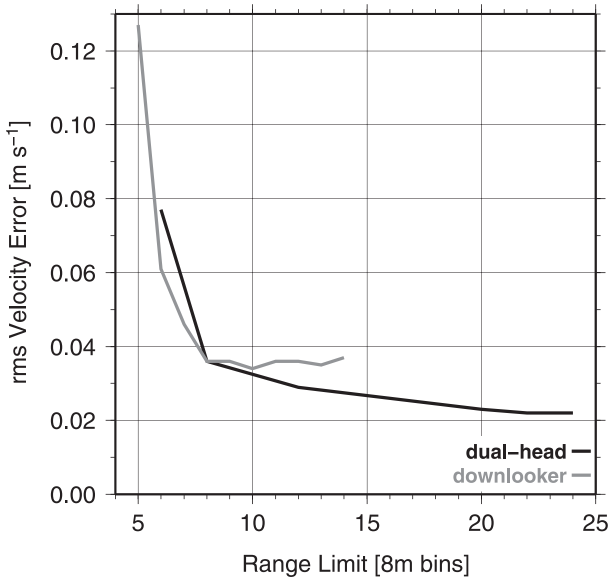

FIG. 6. LADCP velocity errors vs instrument range for the LDEO-processed dual-head profiles from *LADDER-1* and *LADDER-2*.

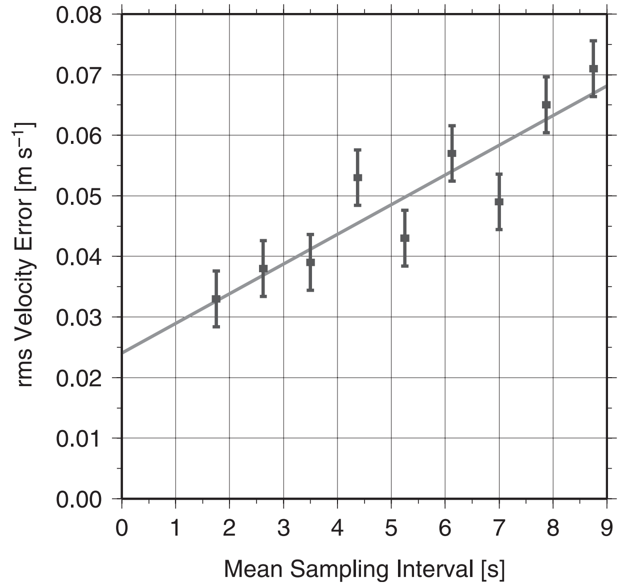

FIG. 7. LADCP velocity errors vs sampling rate for the *LADDER* down-looker datasets, processed with the LDEO software and constrained with GPS and shipboard ADCP data.

inference that package-wake contamination does not affect these velocity profiles significantly.

8. Discussion

a. Representativeness of the datasets analyzed here

The main purpose of the present study is to provide quantitative estimates of the uncertainties associated with LADCP-derived velocity profiles. The data analyzed here indicate that, in regions of sufficient scattering, LADCPs can be used to measure instantaneous velocities with rms uncertainties between 2 and 3 cm s^{-1}, although the LADCP velocity error distributions shown in Fig. 3 indicate that outliers associated with significantly larger errors are common. For a given profile, the smallest LADCP velocity errors are expected in the depth ranges where the velocity-referencing constraints directly affect the solutions, that is, near the seabed for bottom tracking, near the sea surface for shipboard ADCP data, and at mid-depth for the ship-drift (GPS) constraint. Consistent with this expectation, the LADCP velocity errors estimated here increase from 3.0 $\pm$ 0.4 cm s^{-1} when all constraints are used to 4.3 $\pm$ 1.0 cm s^{-1} without bottom tracking (Table 1). When only the ship-drift constraint is used, the LADCP velocity errors increase further to 5.2 $\pm$ 1.2 cm s^{-1}, which is similar to previously reported errors for GPS-only constrained profiles collected with different instruments in other regions (e.g., Fischer and Visbeck 1993; Cunningham et al. 1997). Therefore, the results derived here are considered representative for the LADCP data collected, for example, during the WOCE and Climate Variability and Predictability (CLIVAR) projects.

A potentially significant limitation of the datasets analyzed here is the fact that 85% of the moored velocity samples were recorded in the bottom 150 m of the water column, where the LADCP velocities are directly constrained by bottom tracking. It is reiterated, however, that the LADCP velocity errors associated with the remaining 15% of the samples, which were recorded 400–600 m above the seabed, are not significantly greater than the errors associated with the near-bottom samples (Fig. 3). Nevertheless, all tests of the effects of dual-headed systems (section 5), instrument range and sampling rate (section 6), and three-beam solutions (section 7) were carried out without using bottom-track data. The resulting velocities near the seabed are, therefore, vertically separated by more than 1000 m from the closest ''velocity-referencing level'' at middepth for the GPS constraint. This is similar to the maximum vertical distance of any LADCP velocity from the nearest velocity-referencing level for a 5000-m cast constrained by bottom tracking, shipboard ADCP data, and GPS measurements, again suggesting that the results derived here can be considered representative for full-depth LADCP profiles.

Acoustic backscatter is the most important environmental parameter affecting ADCP range and, therefore, the quality of the LADCP velocities. To put the scattering environment of the data analyzed here into a wider context, the minimum deep-water instrument ranges were

TABLE 3. LDEO-processed down-looker LADCP velocity errors (cm s^{-1}) for four- and three-beam solutions, constrained by GPS and shipboard ADCP data. The mean values and ranges (in parentheses) of the ''three random beams'' solutions are estimated from 14 reprocessing runs.

Dataset	No. of profiles	All beams	Three random beams	Three upstream beams
LADDER-1	8	3.2	3.6 (2.6–5.0)	3.8
LADDER-2	5	3.6	4.2 (3.2–5.2)	3.9
LADDER-3	8	2.8	4.8 (3.9–5.9)	5.8
GRAVILUCK	4	4.2	4.2 (3.3–5.5)	4.2

determined for all stations of a recent meridional section across the eastern Pacific between 20°N and 70°S (CLIVAR P18), where LADCP data were collected with a dual-head Workhorse-based system and an identical instrument setup to the one used here (Fig. 8). Although the instrument range of the LADCP data analyzed here (10–12 8 m bins in the deep water below 1500 m; Section 6) is somewhat above the average observed during CLIVAR P18, Fig. 6 implies that the expected LADCP velocity errors of most of the P18 profiles are nevertheless <4 cm s^{-1}.

b. *Obtaining high-quality LADCP velocity profiles*

In general, the errors associated with LADCP-derived velocities are caused by a combination of unbiased random measurement errors, shear bias, as well as velocity-referencing uncertainties. Previous analyses of LADCP velocity errors deal primarily with unbiased random errors (Firing and Gordon 1990; Visbeck 2002), although King et al. (2001) also discuss strong shear bias errors that contaminate a (small) subset of LADCP profiles to the point where the down- and upcast profiles are clearly inconsistent. It should be noted, however, that shear bias errors are difficult to distinguish from unbiased random errors—Firing and Gordon (1990) show that the velocity errors associated with vertically integrated LADCP-derived shear increase with increasing vertical wavelength even in the absence of shear bias, that is, the expected vertically averaged shear error does not vanish. Fortunately, applying multiple simultaneous velocity-referencing constraints reduces not just shear bias errors but also the LADCP velocity errors associated with unbiased random velocity errors (section 4).

In addition to applying multiple simultaneous velocity-referencing constraints to reduce the shear errors on large vertical scales, the primary method for improving the accuracy of LADCP velocities consists of increasing sampling by extending the instrument range and/or increasing the pinging rate. For a given ADCP the maximum achievable sampling rate is limited by the number of bins to be stored and the time required for data processing and storage. Besides lowering the acoustic frequency, which requires transducer modifications, the instrument range can potentially be extended by increasing the acoustic power transmitted into the water column. Recent tests carried out with a ''high-power'' 300-kHz Workhorse prototype instrument have not yielded noticeable improvements in data quality, however (Liang and Thurnherr 2009). Given the lack of currently available ADCPs with acoustic frequencies below 300 kHz and suitable for LADCP work, the only remaining option for increasing the instrument range consists of using dual-head LADCP systems. The results from *LADDER-1* and *LADDER-2* indicate that the data quality obtainable with dual-head systems can be as good as doubling the range of a single instrument. Besides increasing the instrument range, dual-head LADCP systems have the added advantage that they avoid data gaps caused by sidelobe interference from the seabed, which affects the ship-drift velocity constraint (King et al. 2001). The reduced internal consistency of uplooker data apparent in error-velocity statistics (Fig. 5) is most likely related to the presence of the hydrographic wire on which

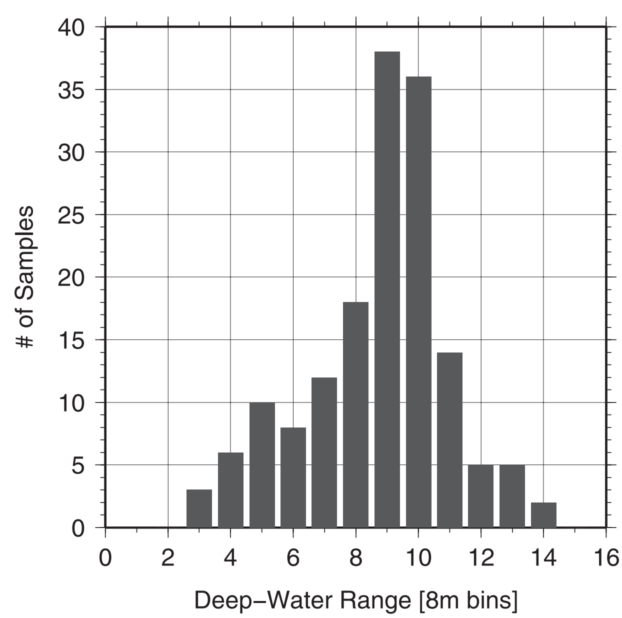

FIG. 8. Single-instrument deep-water range observed during CLIVAR P18 cruise.

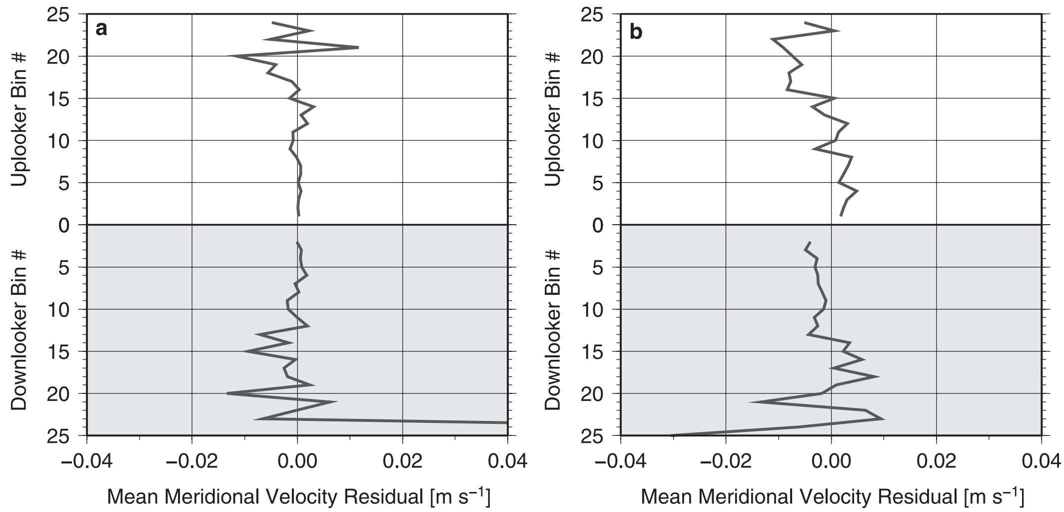

FIG. 9. Mean inversion residuals of the meridional velocity components from two dual-head example casts: (a) example cast from *LADDER-1* and (b) example cast from *LADDER-3*, where inconsistencies between the data from the two ADCPs cause biased residuals in the bins closest to the instruments.

the LADCP system is suspended—both sidelobe interference and wakes are possible. However, these wire effects apparently have no significant effect on the quality of the processed velocity profiles.

In contrast to *LADDER-1* and *LADDER-2*, the LADCP velocity errors for *LADDER-3* are smallest when the down-looker data are processed alone, implying up- versus down-looker data inconsistencies. A likely cause of these inconsistencies are pitch, roll, and/or heading measurement errors, which occur in all dual-head LADCP datasets, not just in those analyzed here. However, the quality of the *LADDER-3* dual-head solutions does not change significantly when the data are reprocessed after disabling the code (identical in the LDEO and IFMG software) that is intended to correct for pitch and roll inconsistencies or when the data are reprocessed without using measurements from either one of the two compasses (not shown). A bad beam is another possible cause for the apparent up- versus down-looker data inconsistencies. The *LADDER-3* up-looker is particularly suspect in this respect because the corresponding single-head solutions are associated with the largest LADCP velocity errors of any single-head profiles derived here (Table 2). However, none of the solutions from eight additional *LADDER-3* reprocessing runs with the LDEO software, each carried out without data from a particular beam, is associated with smaller LADCP velocity errors than the *LADDER-3* down-looker-only profiles (not shown). This observation indicates that the up- versus down-looker data inconsistencies are not caused by a (single) bad beam. Although it has not been possible to determine the exact nature of the problem(s) affecting the *LADDER-3* data, it was found that the bin-averaged inversion residuals (those components of the noise vector **n** in expression (A1) of the appendix corresponding to the LADCP velocities) of the bins closest to the ADCPs are significantly biased, whereas no such biases are found in the *LADDER-1* and *LADDER-2* data (Fig. 9). A corresponding diagnostic figure was therefore added to the output of the LDEO software version IX_6.

For the present study three different publicly available software packages were used to process the LADCP data. Two are based on the velocity inversion method of Visbeck (2002), and the remaining one is an extension of the SOEST implementation of the shear method, which was used extensively during WOCE. No consistent quality difference between the different processing methods was found. Although high-quality LADCP profiles can be obtained with either of the processing systems used here, it is clear that multiple velocity-referencing constraints significantly increase the quality of the solutions. Therefore, the quality of the WOCE-era LADCP data processed with the SOEST software could be improved significantly by reprocessing with an inversion-based method. Processing LADCP data with multiple methods can be valuable for detecting problem profiles (e.g., Thurnherr et al. 2008), which is particularly important in regions of marginally sufficient scattering. Therefore, continued maintenance of at least one implementation of both processing methods is advisable.

Acknowledgments. I learned most of what I know about LADCPs from numerous discussions with Eric

Firing and Martin Visbeck, who pioneered the use of this instrument system. Without their publicly available processing packages, and the additional user support provided by Jules Hummon and Gerd Krahmann, this study would not have been possible. Both Eric and Martin contributed valuable comments on an early draft of this manuscript and additional comments by two anonymous reviewers are gratefully acknowledged. During my first LADCP cruise, John Church motivated me to develop an early version of the shear inversion method. The *LADDER* data were collected under the U.S. National Science Foundation Grant 0425361. The LADDER-2 data were acquired and processed by Jim Ledwell and Ryan Jackson. The *GRAVILUCK* survey was funded by the U.S. National Science Foundation under Grant 0550730, with additional support from the French IDAO/LEFE *GRAVILUCK* project. Phil Mele carried out all processing with the IFMG software.

APPENDIX

Velocity Inversion Error Estimates

The velocity inversion method of Visbeck (2002) consists of solving the system of linear equations

$$\mathbf{d} = \mathbf{G}\mathbf{m} + \mathbf{n}, \qquad \text{(A1)}$$

where $\mathbf{G}$ is the "model matrix" that relates the velocity measurements (vector $\mathbf{d}$, which contains LADCP, SADCP, bottom-tracking, and ship-drift velocities) to the CTD-package and ocean velocities (vector $\mathbf{m}$). The "noise" vector $\mathbf{n}$ represents measurement errors and errors caused by imperfect predictions of the measured velocity field by $\mathbf{Gm}$ (data and model errors). The formal velocity errors estimated by both the LDEO and IFMG implementations of the velocity inversion method are derived from the diagonal elements of the model parameter covariance matrix $\mathbf{C}$ given by expression (37) of Visbeck (2002); that is

$$\mathbf{C} = \sigma_d^2(\mathbf{G}^{\mathrm{T}}\mathbf{G})^{-1}, \qquad \text{(A2)}$$

where σ_d is a measure of the data uncertainty, which is assumed to be constant. As implemented, a velocity error profile is first calculated using

$$\mathbf{e}_1(z) = \frac{\sqrt{\mathrm{diag}_{\mathrm{oc}}(\mathbf{C})}}{\mathrm{median}[\sqrt{\mathrm{diag}_{\mathrm{oc}}(\mathbf{C})}]} \times \mathrm{median}[\sigma(z)], \qquad \text{(A3)}$$

where $\mathrm{diag}_{\mathrm{oc}}(\mathbf{C})$ denotes the diagonal elements of the covariance matrix $\mathbf{C}$ that correspond to the ocean velocity estimates, and $\sigma(z)$ is the profile of the standard deviations of all ocean velocity estimates at each depth. [At each depth, there are generally multiple ocean velocity samples from multiple partially overlapping (super)ensembles.] At the end of each velocity inversion, the baroclinic velocities are additionally estimated using an implementation of the shear method. If the standard deviation of the differences between the two baroclinic velocity profiles s is larger than the mean inversion-derived velocity error estimate $\langle\mathbf{e}_1(z)\rangle$, the velocity error profile is then empirically rescaled using

$$\mathbf{e}_2(z) = \frac{\mathbf{e}_1(z)}{\langle\mathbf{e}_1(z)\rangle} \times \frac{s}{1.5}. \qquad \text{(A4)}$$

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