How To Process LADCP/CTD Data For Vertical Velocity (`LADCP_w` Software V1.0)

A.M. Thurnherr
athurnherr@yahoo.com

October 12, 2015

1 Introduction

1.1 Preliminaries

This manual is intended as a "cookbook," describing how to derive profiles of vertical velocity from data collected with standard LADCP/CTD systems, using processing software available at `http://www.ldeo.columbia.edu/LADCP`. *No special instrument setup is required for acquiring LADCP data suitable for vertical-velocity processing. In particular, vertical velocities can be calculated from archived LADCP data, as long as pressure time series of adequate temporal resolution and quality are available.* The software is a fairly complex implementation of a simple method that consists in subtracting vertical package velocity (w_{CTD}), derived from CTD pressure time series, from the ADCP-derived vertical velocity measurements (w_{ADCP}), before binning the resulting ocean velocities ($w_{\mathrm{ocean}} = w_{\mathrm{ADCP}} - w_{\mathrm{CTD}}$) in depth *(Thurnherr,* 2011). The processing software is implemented in the `perl` programming language and has been tested on UN*X systems, including MacOSX, FreeBSD and Linux. All source files use tab stops every 4 columns; for correct formatting use, e.g. `less -x8` or an editor where the tab separation can be set.

Processing LADCP data for vertical ocean velocity is conceptually much simpler than horizontal-velocity processing *(Firing and Gordon,* 1990; *Fischer and Visbeck,* 1993a; *Visbeck,* 2002). While the unknown horizontal CTD-package velocity required to obtain ocean velocity from the relative measurements must be inferred from external constraints in case of horizontal velocity, the vertical package velocity w_{CTD} is known at all times. As a result, there is no accumulation of random-walk errors *(Firing and Gordon,* 1990) affecting w_{ocean}. This has two important consequences:

1. Profiles with gaps, e.g. due to insufficient acoustic scattering at depth, can be processed without any particular difficulties. Care has to be taken to remove artifacts due to insufficient sampling at the edges of the gaps during post-processing (Section 4.4).

2. Because of the random-walk error accumulation, instrument range is the most important parameter affecting the quality of horizontal LADCP velocities *(Firing and Gordon,* 1990; *Visbeck,* 2002; *Thurnherr,* 2010). For vertical velocities, random error (but not bias) can be reduced by decreasing the vertical resolution of the binned profiles. This allows calculation of w_{ocean} in some regions where the acoustic backscatter is too weak (instrument range too short) for horizontal-velocity processing.

There are additional differences between processing LADCP data for horizontal and vertical velocities:

1. Horizontal ocean velocities are mostly dominated by processes with timescales that are long compared to typical LADCP acquisition times. As a result, down- and upcast data are usually combined to yield cast-time averaged profiles. In contrast, vertical velocities are mostly dominated by internal waves near the buoyancy frequency (e.g. *Thurnherr et al.,* 2014), i.e. with time scales that are not long compared to typical CTD/LADCP sampling time scales. As a result, down- and upcast w_{ocean} data must be processed separately, potentially[1] yielding two profiles from each cast.

2. Good heading (compass) data are required for horizontal-velocity LADCP processing. LADCP data collected near the magnetic poles, in particular, cannot be processed for horizontal velocity. In contrast, heading data are not used at all for w_{ocean} LADCP processing, i.e. data from the magnetic poles or from instruments with bad compasses can be processed for vertical velocity.

1.2 Software Requirements and Installation

The processing software for vertical LADCP velocities is implemented in the `perl` programming language, which is pre-installed on must UN*X systems. Diagnostic plots are produced with the `Generic Mapping Tools` (GMT), a set of UN*X tools to produce Postscript plots from ASCII input files. The following software is required to process LADCP/CTD data for vertical velocity:

Generic Mapping Tools (GMT) GMT must be installed and the GMT binary directory must be included in the search path of the shell.[2] GMT version 4.5.7 or later should work.

ANTSlib This library, available at `www.ldeo.columbia.edu/LADCP`, provides a general data processing and I/O framework. The installation directory must be added to the shell's search path.

ADCP_tools This tool kit provides additional required libraries, as well as a number of ADCP utilities, e.g. for splitting ADCP files from tow-yos and yo-yos into individual casts. The ADCP Tools are available at `www.ldeo.columbia.edu/LADCP`. The installation directory must be added to the shell's search path.

LADCP_w The vertical-velocity processing software is implemented as several separate command-line utilities. It is available at `www.ldeo.columbia.edu/LADCP`. The installation directory must be added to the shell's search path.

Once all required software has been installed, the installation can be tested by running

```
LADCP_w_ocean -V
```

from any directory. If any of the prerequisites are missing (or if the path is not set correctly) an error message is produced. If the installation is complete, a short version and copyright message is produced instead. Running `LADCP_w_ocean` or any other of the utilities described below without command-line arguments produces a short a usage message describing the command-line options and -arguments.

---

[1] In particular when bottle stops are used, upcast data are often considerably inferior to downcast data.

[2] Familiarity with basic UN*X shell concepts is assumed in this manual.

1.3 Vertical-Velocity Processing Overview

Vertical-velocity processing is carried out in several consecutive steps, which are implemented as separate command-line utilities to allow selective re-processing:

1. *Calculate vertical package velocity w_{CTD} with the `LADCP_w_CTD` utility.* Input: 24 Hz CTD time series. Output: 6 Hz time series of pre-processed CTD data, including low-pass w_{CTD}, as well as diagnostic plots. For details, see Section 2 below.

2. *Calculate vertical ocean velocity w_{ocean} with the `LADCP_w_ocean` utility.* Input: 1) 6 Hz time series of pre-processed CTD data. 2) RDI data file (PD0 format). Output: Edited (quality-controlled) vertical velocities, diagnostic data, as well as diagnostic plots. For details, see Section 3 below.

3. *Post-process w_{ocean} with the `LADCP_w_postproc` utility.* This utility carries out arbitrary data editing (removing bad measurements) and creates vertically gridded profiles from the edited w_{ocean} data. Data from uplooker and downlooker ADCPs from dual-headed LADCP systems can be combined into a single profile. Input: One or two `LADCP_w_ocean` output files, and a file with data-editing parameters. Output: Fully processed w_{ocean} profile. For details, see Section 4.2 below.

For processing, every profile must be assigned a unique *profile id* (usually numerical), which is used to construct file names and to select profile-specific processing parameters. Often, it makes sense to use the CTD station number as the *profile id.* In addition to the *profile id,* every processed profile is additionally associated with a *run label*, which can be pretty much any string. This allows multiple processing runs for a single profile.

1.4 Input/Output Data

ADCP Input Data. Binary data in the Teledyne/RDI PD0 format are accepted as input. Supported instrument types include NB150, BB150, WH150, WH300, WH600, WH1200, and the Explorer DVL.

CTD Input Data. Either binary or ASCII 24 Hz CNV time-series files from SBE911plus systems are accepted as input. The header must include the latitude of the station, and the file must contain pressure (`prDM`), *in situ* temperature (`t090c` and/or `t190c`) and conductivity (`c0S/m` or `c0mS/cm` and/or `c1S/m` or `c1mS/cm`) fields. If the CTD file contains a header field called `station`, the content of this field is taken as the default *profile id.*

Output Data. All output files use a whitespace-delimited ASCII file format called the ANTS format. The "#" character is used for comments and metadata header lines; the string `nan` is used to indicate missing values. ANTS files can easily be read by many software packages, possibly after manually removing the headers. The file layout (association of field names with data columns) is defined by the last header line beginning with `#ANTS#FIELDS#`. Header lines beginning with `#ANTS#PARAMS#` define meta-data parameters. In order to load an ANTS file, including metadata, into `Matlab` the routine `loadANTS.m`, which is available as part of the `Matlab_tools` software (available at `www.ldeo.columbia.edu/LADCP`) can be used.

Diagnostic plots. All plots produced by the processing software are in Encapsulated Postscript (eps) format with loose bounding boxes (standard GMT output).

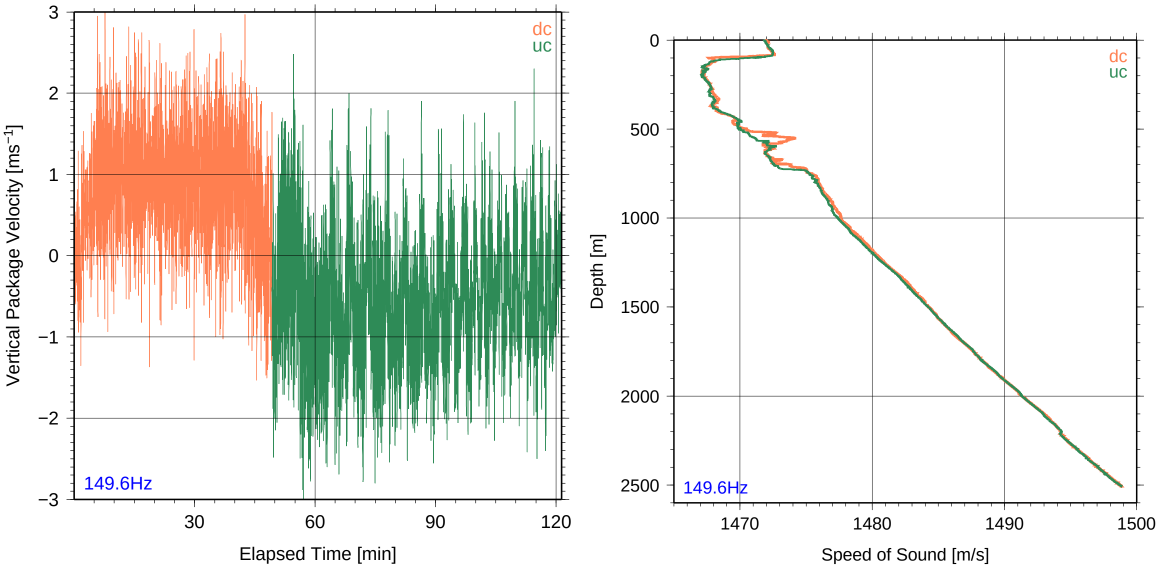

Figure 1: Example plots of output of `LADCP_w_CTD` from DIMES US2 station 149 in Drake Passage. Left panel: Time series of vertical package velocity. Right panel: Soundspeed profile.

2 Calculating Vertical Package Velocity (`LADCP_w_CTD`)

In a first processing step, 24 Hz CTD time-series data are pre-processed with the `LADCP_w_CTD` utility to derive cleaned 6 Hz time series of depth, soundspeed, vertical package velocity, and temperature. The vertical package velocity is low-pass filtered to remove measurement noise; based on tests carried out with an early version of the processing software, a default low-frequency cut-off of 2 s is used.[3] Additionally, the minimum observed pressure is subtracted from all pressure measurements to ensure non-negativity.

`LADCP_w_CTD` takes the name of the CTD file as an argument and, often,[4] a profile id supplied with the `-i` command-line option. By default, `LADCP_w_CTD` only displays error messages. In order to see progress, use `-v 1`; for diagnostic output use `-v 2`. For example, the command

```
LADCP_w_CTD -i 8 -v 2 oc46802008.cnv
```

processes the data in the file `oc46802008.cnv` with diagnostic output on screen, and produces the following three output files:

`008.6Hz` Time-series of CTD measurements (pressure, temperature, conductivity), and derived quantities (depth, salinity, sound speed, vertical package velocity).

`008_wpkg.ps` Diagnostic plot of of vertical package velocity time series (e.g. Figure 1, left panel).

`008_sspd.ps` Diagnostic plot of soundspeed profile (e.g. Figure 1, right panel).

The user must ensure that the CTD time series used for vertical-velocity processing are free from significant glitches. Therefore, all diagnostic plots produced by `LADCP_w_CTD` should be inspected.

---

[3] The low-pass cutoff can be modified with a command-line option to `LADCP_w_CTD`.

[4] For CTD files with the correct profile id in the `station` header field, `-i` is not required.

(Figure 1 shows examples from a station occupied in Drake Passage on a fairly rough day for reference.) Pressure spikes, in particular, introduce package-velocity anomalies that typically cause the time-lagging algorithm used to merge the CTD with the ADCP data (Section 3) to fail. Other errors in the CTD data often do not cause processing to fail, but they increase the vertical-velocity errors and the erroneous data should, therefore, be removed. Profiles for which the automatic data editing implemented in `LADCP_w_CTD` is insufficient must be pre-cleaned by replacing bad values in the input file with `nan` strings. *No scans must be removed from the CNV files that serve as input to `LADCP_w_CTD`.*

Data transmission errors between the SBE 911plus underwater unit and the deck box cause CTD scans to be dropped, resulting in fewer than 24 CTD scans per second. As the SBE deck-box ignores this issue when time-stamping the data — it simply increases the elapsed time by 1/24 s for each received scan — the SBE timestamps are not used for w_{ocean} processing. While the modulo-count field in the SBE data can be used to determine where there are missing scans, I have not found a way to re-construct how many scans have been dropped from the recorded data. Therefore, profiles affected by significant transmission problems, e.g. due to dirty slip rings on a winch, can usually not be processed for vertical velocity. Profiles where the CTD data acquisition is restarted during the cast can usually also not be processed, either.

3 Calculating Vertical Ocean Velocity (`LADCP_w_ocean`)

3.1 Synopsis

In a second processing step the `LADCP_w_ocean` utility is used to calculate w_{ocean} from combined LADCP and CTD data. As input, `LADCP_w_ocean` requires a pre-processed CTD time series (Section 2) as well as a binary ADCP file. (The up- and downlooker data from dual-head LADCP systems are processed separately, but the data can easily be combined during post-processing; Section 4.2.) `LADCP_w_ocean` requires one or two command-line arguments:

`profile-id` This argument is mandatory and usually numeric. It is used to select the CTD and ADCP input files, set profile-specific processing parameters, and to create output file names.

`run-label` This argument is optional and can be any string. It is used to distinguish different processing runs for the same profile. For example, for dual-head LADCP systems the run labels `DL` and `UL` can be used for processing downlooker and uplooker data, respectively. If no run label is specified the label `default` is assumed. Each run label has its own associated output subdirectory, using the label as its name. The output directory must be created before processing.

It is not possible to specify input or output files for `LADCP_w_ocean` on the command line. Rather, `profile-id` and `run-label` are used to define the input and output filenames in the processing-configuration file (Section 3.2), which is also used to set the many configurable parameters controlling different aspects of processing. Some of the processing parameters can alternatively be set with command-line options, including the following:

Screen verbosity (`-v`). `LADCP_w_ocean` produces log output both on screen and in a log file. The `-v` option is used to set the verbosity level (0–3) for the screen output only, with `-v 0` producing only error messages, `-v 1` also including warnings (L0-2, with L2 being the most severe), `-v 2` producing a substantial amount of diagnostic output, and `-v 3` listing everything, including debugging messages. Default screen verbosity level is 1, and the log files always contain level 2 output.

Time lagging (`-i, -n, -w`). Accurate time lagging is crucially important for obtaining good vertical ocean velocities. The time-lagging algorithm involves three steps: i) An initial estimate is made based on the time when each profile reaches 10% of its maximum depth; this algorithm can be overridden by using the `-i` option. ii) A coarse-resolution time lag is calculated from 1 Hz CTD data. iii) A fine-resolution time lag is calculated using the full-resolution (6 Hz) CTD data. For steps ii and iii, the data are split into windows, controlled with the `-n` and `-w` options.

Setting water depth (`-h`). Knowledge of the water depth is important for editing measurements affected by previous-ping interference (PPI) and sidelobe contamination from the seabed. While the water depth is usually detected correctly by downlooking ADCPs, it has to be supplied manually for processing uplooker[5] data. The easiest way to do this is to specify the water depth with the `-h` command-line option to `LADCP_w_ocean`. Either a numerical value (water depth in meters) or the name of the corresponding downlooker w_{ocean} profile, which contains the water depth as meta data, can be provided as an option argument.

3.2 Processing Configuration File (`ProcessingParams`)

There are numerous parameters controlling many processing details. A complete list, including documentation, can be found in the file `defaults.pl` in the installation directory. The default parameter values are suitable for data sets collected with 300 kHz Workhorse instruments (WH300) with 8 m bin size; for different bin sizes and/or instruments some of the parameters likely need to be changed. The file `defaults.pl` should never be modified, however. Rather, non-default processing-parameter values should be set in a processing configuration file. The configuration file is read *after* processing the command-line options, i.e. definitions in the configuration file take precedence over command-line options.[6] There are several possible filenames for the configuration file. Given the run label `DL`, the following filenames are tried in order: `ProcessingParams.DL`, `ProcessingParams.default`, `ProcessingParams`. The first file that is found, is used. When `LADCP_w_ocean` is executed without a run label, only the latter two names are tried.

The processing configuration files are `perl` scripts. When they are executed, the current profile id and run label are stored in the variables `$PROF` and `$RUN`, respectively, allowing profile- and run-specific parameters to be selected with `if`-statements. While all processing parameters have suitable defaults, at the very least the LADCP and CTD input file names must be defined in the variables `$LADCP_file` and `$CTD_file`. The following example code assumes that the LADCP and CTD data for profile 13 can be found in the files `./LADCP/013DL000.000` and `./CTD/013.5Hz`, respectively:

```
$LADCP_file = sprintf("LADCP/%03dDL000.000",$PROF);
$CTD_file = sprintf("CTD/%03d.5Hz",$PROF);
```

If the CTD and/or LADCP input files use inconsistent numbering, a simple lookup table can be implemented, for example, as follows:

```
if (($PROF == 1) && ($RUN eq "DL")) {
    $LADCP_file = "LADCP/003DL000.000";
    $CTD_file   = "CTD/002.5Hz";
} elsif (($PROF == 2) && ($RUN eq "DL")) {
    $LADCP_file = "LADCP/002DL000.000";
```

---

[5] Even LADCP data from upward-looking instruments can be severely degraded by sidelobe contamination from the seabed!

[6] The only exception to this rule is that any expression supplied with the `-x` command-line option is executed after the configuration file has been processed.

```
        $CTD_file   = "CTD/003.5Hz";
    } else {
        die("cannot determine input files for profile $PROF run $RUN");
    }
```

noting that the perl operators `=` and `eq` check for numerical and lexical (string) equality, respectively. Of course, it is also possible to add profile-specific processing parameters to the same `if`-statement.

3.3 Processing Output

`LADCP_w_ocean` creates several output files, all in a subdirectory that uses the run label as its name. (If no run label is specified on the command line, the label `default` is used in the `ProcessingParams` file, but the output directory is called `profiles`.) If the output directory does not exist, the program terminates with an error. Assuming that the downlooker data from profile 13 have been processed successfully with the command

```
LADCP_w_ocean 13 DL
```

the following data files are created:

`DL/013.log` Processing log output at verbosity level 2.

`DL/013.wprof` Gridded vertical velocity profiles from downcast (fields prefixed with `dc_`), upcast (`uc_`), as well as from bottom tracking (`BT_`). For each depth bin, the following quantities are recorded: average depth and elapsed time of all contributing samples (`_depth` and `_elapsed`, respectively); medians of 2-beam vertical velocities (`_w12` and `_w34`); median of 3- or 4-beam vertical velocity (`_w`), mean-absolute-deviation from the 3-/4-beam median (`_w.mad`), as well as the number of samples per bin (`_w.nsamp`). (The 2-beam vertical velocities are primarily useful for diagnosing package-wake effects and bad beams.)

`DL/013.wsamp` Individual vertical velocity measurements (one record per bin for each ensemble). For each sample, the following information is recorded: ADCP ensemble number (`ensemble`), ADCP bin number (`bin`), elapsed time in seconds (`elapsed`), depth of measurement (`depth`), CTD depth (`CTD_depth`), downcast flag (`downcast`), 3-/4-beam vertical velocity (`w`), two separate 2-beam vertical velocities (`w12` and `w34`), gridding residual of the 3-/4-beam solutions (`residual`), vertical package velocity (`CTD_w`), time derivative of vertical package acceleration (`CTD_w_tt`), measured vertical velocity (`LADCP_w`), error velocity (`errvel`), correlation (`correlation`), echo amplitude (`echo_amplitude`), volume scattering coefficient (`Sv`) calculated with the method of *Deines* (1999) with an additional empirical correction for remaining bin-dependent biases, package attitude (`pitch`, `roll`, `tilt` and `heading`), 3-beam flag (`3_beam`), and soundspeed (`svel`).

`DL/013.tis` Time series of ADCP records (one record per ensemble) with merged CTD information: ensemble number (`ensemble`), elapsed time in seconds (`elapsed`), downcast flag (`downcast`), CTD depth (`depth`), soundspeed at the transducer (`xducer_sound_speed`), package attitude (`pitch`, `gimbal_pitch`, `roll`, `tilt` and `heading`), vertical package velocity (`CTD_w`), time derivative of vertical package acceleration (`CTD_w_tt`), LADCP reference-layer vertical velocity (`LADCP_reflr_w` and `LADCP_reflr_w.sig`), and reference-layer ocean w (`reflr_ocean_w`).

In addition to those data files, a number of diagnostic plots are created. Figs. 2–7 show representative examples from high-quality profiles with both weak (left panels) and strong (right panels) vertical-velocity signals.

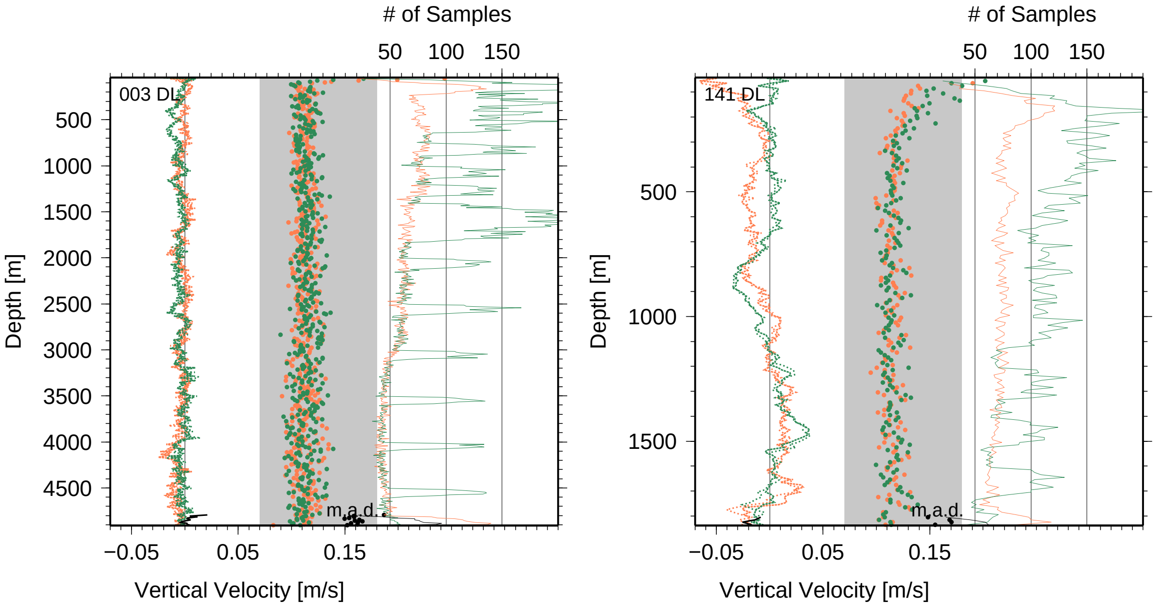

Figure 2: Example `_wprof.ps` diagnostic plots from DIMES US2 cruise with weak (left panel) and strong (right panel) vertical velocities. Orange/green/black indicate downcast/upcast/bottom-tracking data. Each panel contains three types of data: i) Vertical ocean velocity (median in each depth bin); dotted and dashed lines on the left; lower axis. ii) Corresponding mean-absolute-deviations (m.a.d.); bullets in middle of plot, lower axis. iii) Corresponding number of samples; solid lines on the right, upper axis.

`DL/013_wprof.ps` Downcast-, upcast- and bottom-tracked vertical velocity profiles, as well as gridding statistics (Figure 2). The two 2-beam vertical velocities from both the up- and downcast are plotted separately with dotted and dashed lines, respectively. In addition to providing a summary of the data, this plot is useful for diagnosing package-wake effects and bad beams.

`DL/013_wsamp.ps` Time-depth plot of vertical ocean velocity (Figure 3). This plot is useful for diagnosing measurement artifacts, especially in comparatively shallow profiles.

`DL/013_residuals.ps` Time-depth plot of vertical velocity gridding residuals (Figure 4). This plot, too, is primarily useful for diagnosing measurement artifacts.

`DL/013_mean_residuals.ps` Profiles of mean residuals vs. distance from the ADCP transducer (bin number; Figure 5). This plot is useful for determining the range of valid bins.

`DL/013_backscatter.ps` Time-depth plot of acoustic volume-scattering coefficients (Figure 6). This plot is primarily useful for determining whether particular w signals could be biological artifacts (e.g. due to vertical plankton migration) or related to strong turbulence. After applying the correction of *Deines* (1999), the S_v values in each ADCP bin are corrected for remaining depth- and bin-dependent biases using *in situ* data. While this correction ensures horizontal banding in the `_Sv` plots, there remain apparently instrument-dependent biases of up to 5 dB, which must be removed manually before combining the acoustic backscatter data from upward- and downward-looking ADCPs. At present, calculation of S_v only works correctly for 300 kHz Workhorse ADCPs.

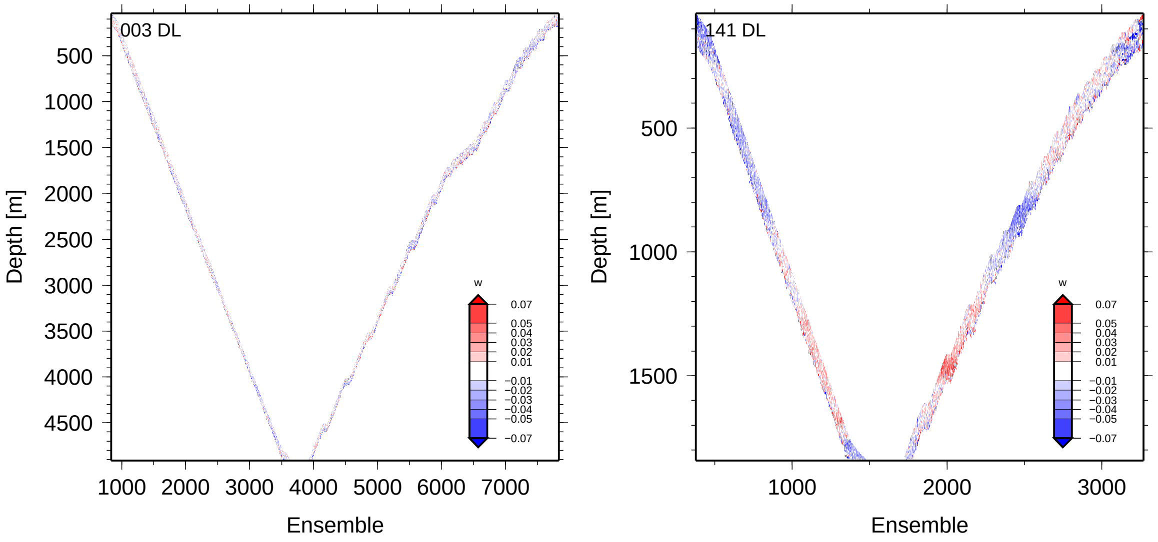

Figure 3: Example `_wsamp.ps` diagnostic plots for the two profiles of Figure 2. Each panel shows all ocean-velocity samples in time-depth space.

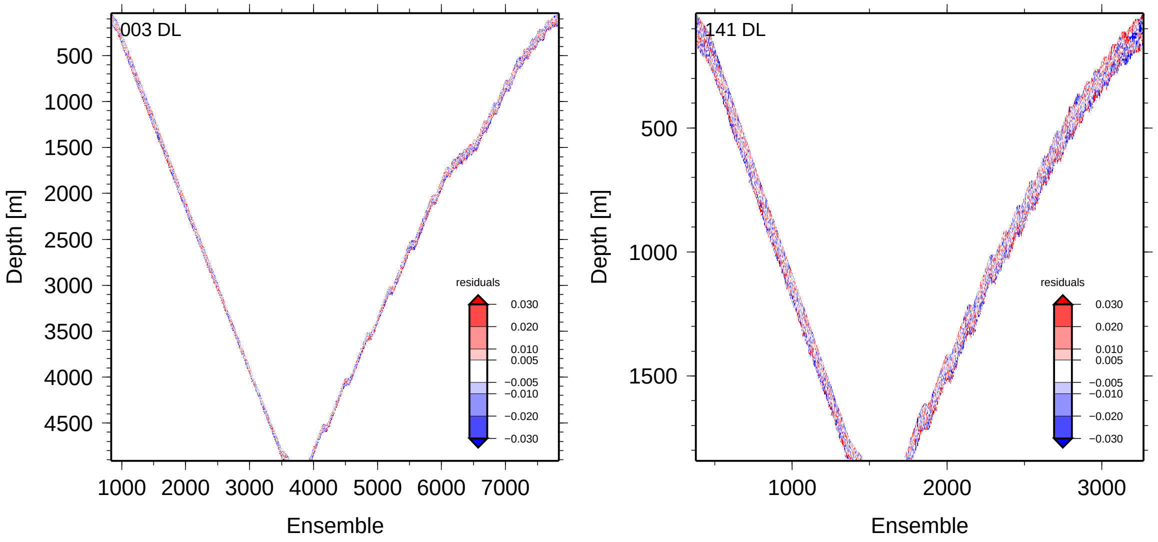

Figure 4: Example `_residuals.ps` diagnostic plots for the two profiles of Figure 2. Each panel shows all ocean-velocity residuals (differences between the individual measurements and the binned medians in the corresponding depth bins) in time-depth space.

`DL/013_time_lags.ps` Time series of lag-correlation offsets used to merge the LADCP to the CTD data (Figure 7). This plot is useful to verify that time-lagging was performing as intended and to diagnose dropped CTD scans (Section 4.3).

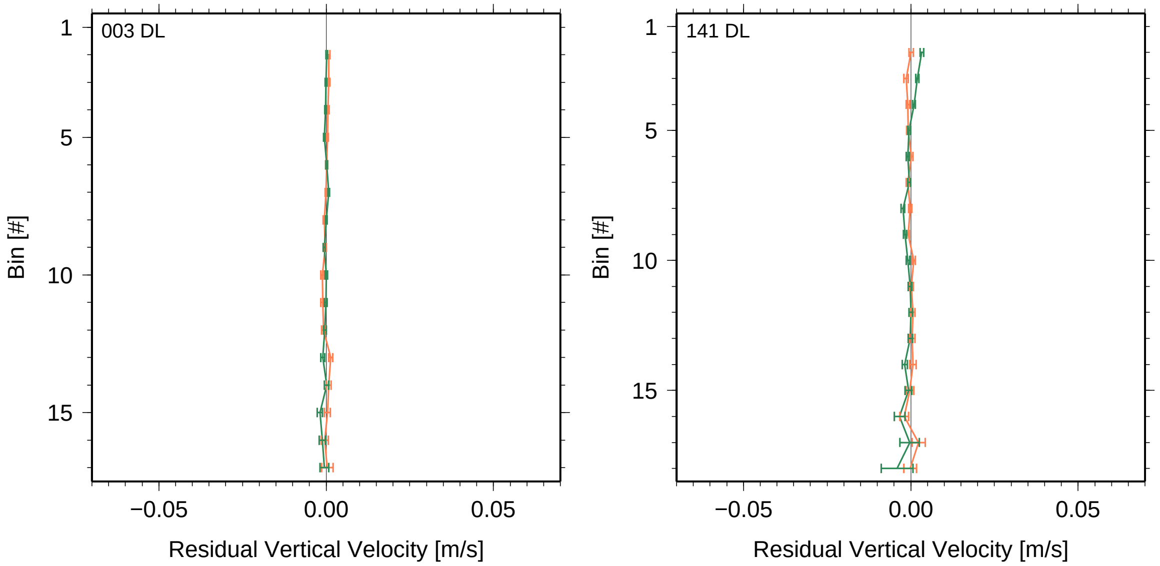

Figure 5: Example `_mean_residuals.ps` diagnostic plots for the two profiles of Figure 2. Each panel shows the mean residuals plotted against bin number (distance from ADCP transducer). Orange/green indicate downcast/upcast data.

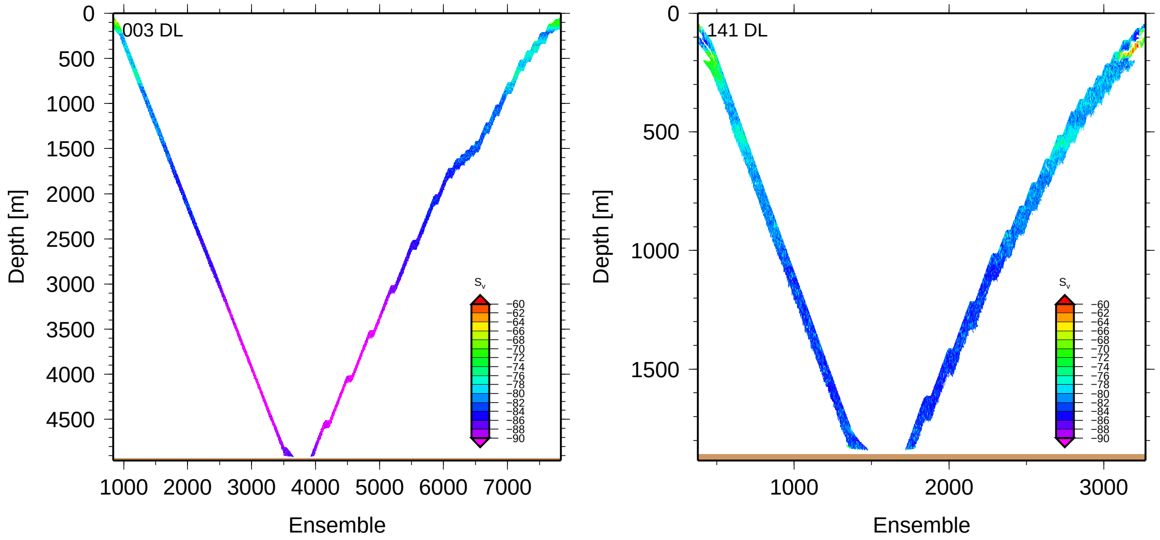

Figure 6: Example `_backscatter.ps` diagnostic plots for the two profiles of Figure 2. Each panel shows all acoustic volume scattering coefficients (S_v) in time-depth space.

4 Data Editing and Postprocessing

4.1 Measurement Errors

Every processed w_{ocean} profile is associated with measurement errors that can include random noise, down-/upcast biases, winch-acceleration anomalies, as well as “glitches” caused by bad measurements

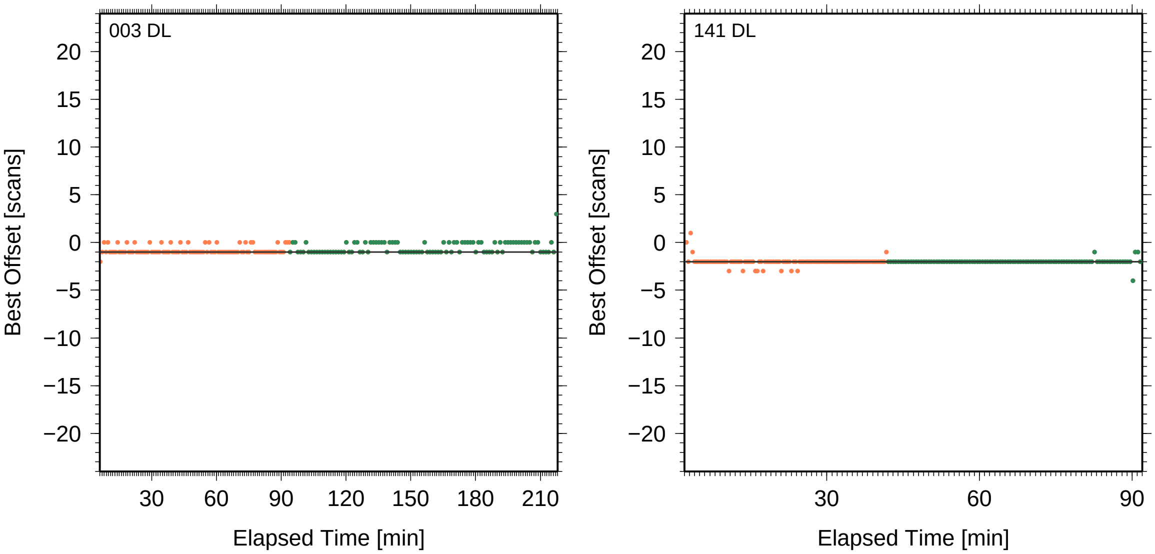

Figure 7: Example `_time_lags.ps` diagnostic plots for the two profiles of Figure 2. Each panel shows a time series of the lags required for optimal matching of the CTD to the ADCP data. Orange/green indicate downcast/upcast data.

that are not removed by the automatic data editing implemented in `LADCP_w_CTD` and `LADCP_w_ocean`. While isolated bad measurements can be removed with the `LADCP_w_postproc` utility (Section 4.2) other errors, such as down-/upcast biases, are more difficult to deal with.

Apart from discrepancies between the two individual 2-beam solutions (which is is equivalent to large error velocities) the most common indicator for problems with the vertical-velocity data are consistent differences (biases) between downcast and upcast profiles (Figure 8). Often, the upcast velocities are more biased than the downcast velocities. While, sometimes, the biases are approximately uniform throughout the water column (right figure panel), more often the biases are reduced during bottle stops (left panel), i.e. there can be significant vertical structure in the vertical-velocity errors of upcasts in particular. Depth-dependent errors are difficult to deal with in general. In case of the data set from the East Pacific Rise (example profile in left panel) vertical-wavenumber spectra of w_{ocean} indicate that vertical wavelengths shorter than ≈150 m in that data set are significantly degraded by measurement errors, whereas noise effects in several other data sets collected with the same instrument type and setup are more typically "clean" down to wavelengths of ≈80 m *(Thurnherr et al.,* 2015).

4.2 Postprocessing (`LADCP_w_postproc`)

There is often a need for post-processing the w_{ocean} data calculated with `LADCP_w_ocean`, e.g. to edit bad measurements, to combine the data from dual-headed LADCP systems, to set the water depth for partial-depth profiles, etc. All this is accomplished with the `LADCP_w_postproc` utility, which takes one or two `.wsamp` files as input and creates a single profile and a diagnostic plot. For example, the command

```
LADCP_w_postproc DL/004.wsamp UL/004.wsamp
```

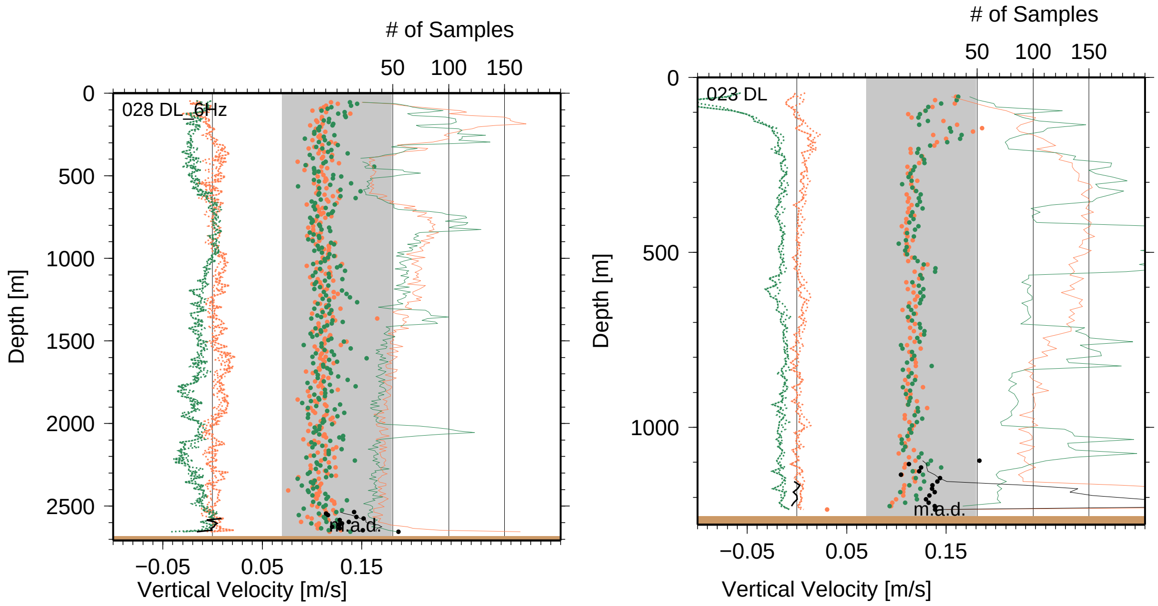

Figure 8: Example `_wprof` plots from two data sets associated with apparent downcast-/upcast vertical velocity biases. Left panel: East Pacific Rise crest. Right panel: Gulf of Mexico.

combines the measurements from `DL/004.wsamp` and `UL/004.wsamp` to create a combined w_{ocean} profile (`001.wprof`), as well as a diagnostic plot (`001_wprof.ps`; Figure 9). The profile output from `LADCP_w_postproc` is similar to the the `.wprof` output from `LADCP_w_ocean`, except that there are no bottom-track and 2-beam solutions, but with an added height-above-bottom (`hab`) field. The figure is similar to one of the diagnostic plots produced by `LADCP_w_ocean` (Figure 2); when two input files are used, the individual profiles are plotted with thin dashed and dotted lines, and the combined profile is plotted with heavy solid lines (right figure panel). In order to plot the BT solution as well, a downlooker profile can be supplied with the `-b` command-line option.

Since most data sets contain at least a few automatically processed profiles with glitches that require additional editing, `LADCP_w_postproc` also implements manual data editing. The file `./EditParams` is a `perl` script that is executed for each of the `.wsamp` files. There is a small library of data-editing functions:

`output_resolution(40);` Set vertical output resolution to 40 m, as appropriate for data collected in a region with weak acoustic backscatter. By default, the output resolution is taken from the input files (i.e. it is set by `LADCP_w_ocean`). Alternatively, it can be set with the `-o` command-line option to `LADCP_w_postproc`. It is good practice, however, to define the output resolution explicitly in the `EditParams` file.

`bad_range_uc("depth",3700,"*");` Exclude the upcast vertical velocity data between 3700 m and the seabed from the gridded output profiles. The first argument can be any field name from the `.wprof` input file(s). Any number of “bad ranges” can be defined.

`good_bins(2,3);` Include only bins 2 and 3 from the profiles from the gridded output profiles. If required for specific profiles, the call can be made conditional with an `if`-statement, of course.

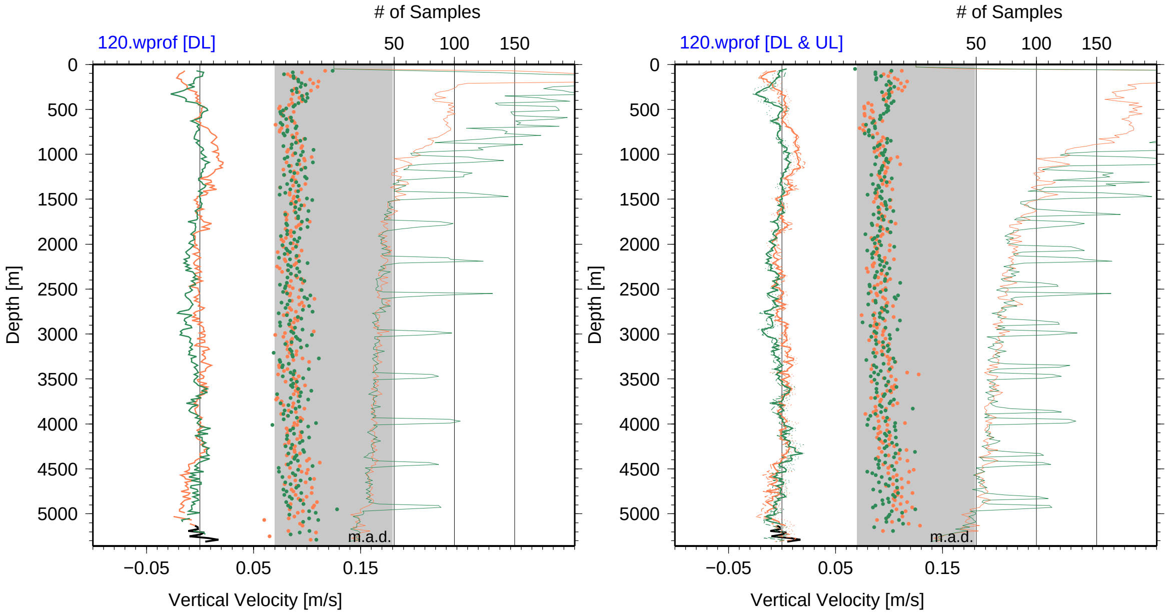

Figure 9: Example `_wprof.ps` diagnostic plots produced by `LADCP_w_postproc` showing a profile from the western tropical Pacific (GO-SHIP P16N profile 120). Left panel: Using only the downlooker `.wsamp` input file. Right panel: Using both `.wsamp` input files (dual-head LADCP system). Bottom-tracking information for both plots was supplied with the `-b` command-line option to `LADCP_w_postproc`.

In order to apply data editing only to specific profiles and/or run labels (e.g. to set separate bin ranges for uplooker and downlooker data) the editing functions must be made conditional with `if`-statements as shown in the `ProcessingParams` example in Section 3.2.

In many cases the bad data to be removed can be found quite easily by inspecting the diagnostic plots produced during data processing (Section 3.3). The following Sections 4.3–4.8 describe problems commonly encountered with automatically processed vertical velocity profiles produced by `LADCP_w_ocean`.

4.3 Dropped CTD Scans

As described in Section 2 data transmission problems in the CTD system cause dropped scans. As long as only one or two “scan-drop events” occur during a profile this problem is usually easily detectable in the `_time_lags` plots (Figure 10). Profiles with more than two “scan-drop events,” on the other hand, usually cannot be processed with `LADCP_w_ocean` at all. In the example shown in the upper two figure panels three CTD scans (1/8 s worth of data) were dropped approximately 15 min after the beginning of the cast. As the pre-drop time lag is used for the downcast (solid line) the downcast data after the dropped scans are bad and must be removed before gridding the profiles. [Alternatively, the `-p` option of `LADCP_w_ocean` can be used to carry out the piece-wise time lagging. By default, `LADCP_w_ocean` lags the downcast and upcast data separately.] In the example shown in the bottom two panels of the figure, the number of scans dropped was too great for the time-lagging algorithm to work correctly at the beginning of the cast. For the downcast data of this profile, the

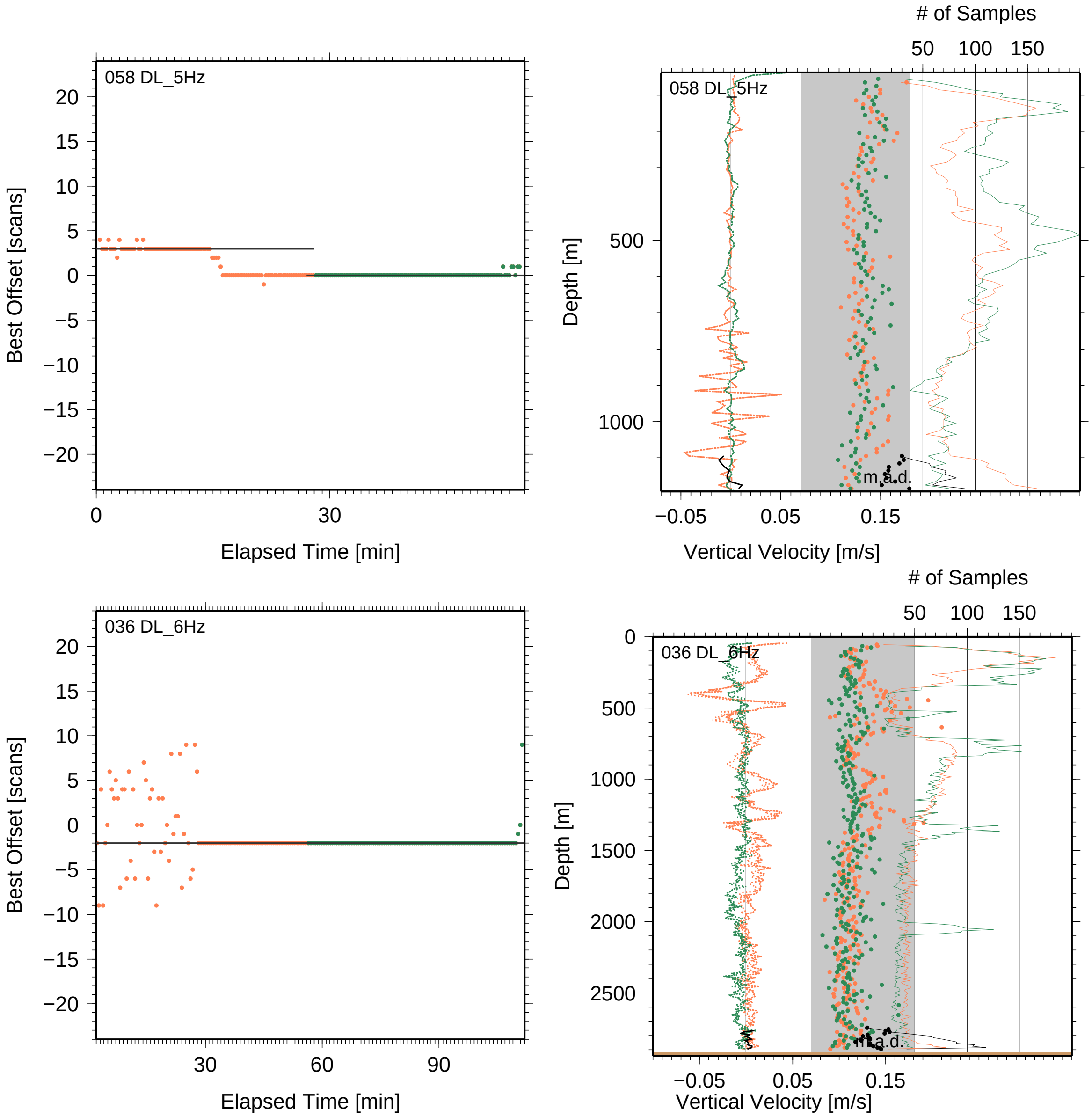

Figure 10: Diagnostic plots from two example profiles (upper and lower panels, respectively) with dropped CTD scans. Left panels: `_time_lags` plots. Right panels: `_wprof` plots.

post-drop time lag is used, implying that the data before the dropped scans are bad and must be removed.

The right figure panels show the effects of the time-lagging errors on the vertical velocity profiles. Note, in particular, how even a small error in time lagging (0.125 s offset between CTD and LADCP data case of the example in the upper two panels) causes the resulting vertical velocities to be garbage. In regions with small w_{ocean} the errors are readily apparent in the final profiles. In regions with larger

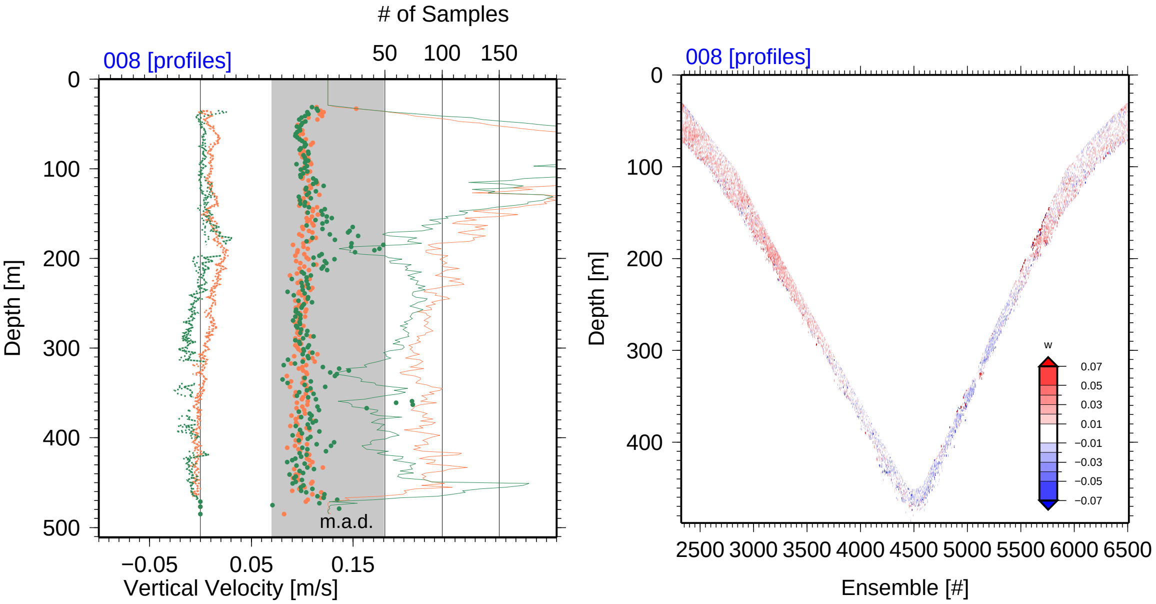

Figure 11: Diagnostic plots from a profile from the equatorial Pacific with insufficient sampling. Left panel: `_wprof` plot. Right panel: `_wsamp` plot.

w_{ocean}, the time-lagging anomalies can sometimes be difficult to spot in the processed profiles.

4.4 Insufficient Sampling & Profile Gaps

Bad ADCP data, e.g. due to insufficient acoustic scattering or large instrument tilts, can cause insufficient sampling and, in extreme cases, gaps in the vertical-velocity profiles. While such data gaps are not problematic *per se* (Section 1), there are often vertical-velocity artifacts where the number of samples per depth bin is low, including at the edges of profile gaps, as well as near the sea surface and seabed. In the example shown in Figure 11, there are insufficient (<40, in this case) upcast samples in the following depth ranges: 186–196 m, 316–338 m, 356–368 m, 402–414 m, in addition to couple of isolated single-record gaps. At the edges of some of these gaps (e.g. just above 185 m in Figure 11, and also at both edges of the wake-affected upcast data gap shown in the right panel of Figure 12), there are clear artifacts that must be removed during postprocessing. Alternatively, the gaps in this profile can be avoided altogether by processing (or post-processing) at a coarser vertical resolution.

4.5 Package-Wake Effects

It is a fairly common observation in LADCP work that uplooker downcast data and/or downlooker upcast data are affected by package wakes. In the context of vertical-velocity processing, these wakes manifest themselves as vertically coherent layers where the two independent 2-beam solutions for w_{ocean} disagree significantly. In the example shown in Figure 12 package-wake effects affect the upcast data between 50 and 100 m and, more importantly, the wake causes an erroneous apparent upwelling peak centered at 190 m in one of the two 2-beam upcast solutions, which must be removed during postprocessing.

It is important to note that the difference between the two 2-beam solutions is identical (except for

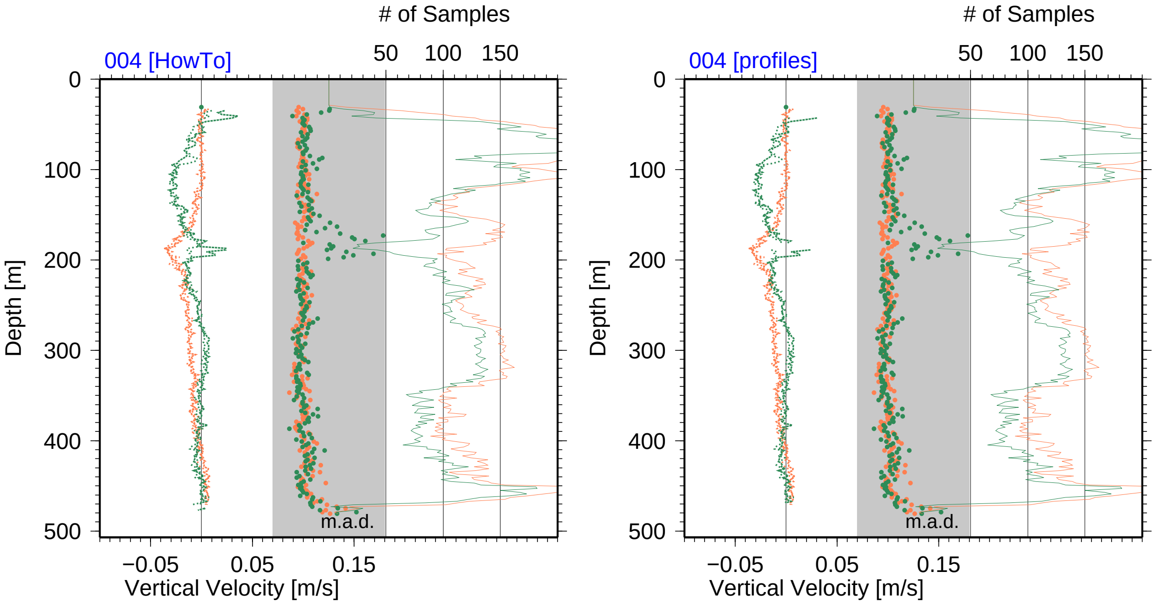

Figure 12: Diagnostic `_wprof` plots from an equatorial Pacific profile affected by package wake. Left panel: Profile processed with the requirement of $\geq$20 samples per depth bin. Right panel: Profile processed with the requirement of $\geq$40 samples per depth bin.

a scaling constant) to the so-called ADCP *error velocity.* Since error velocity is used as a data-editing criterion in `LADCP_w_ocean`, the most severely wake-affected samples are discarded automatically during processing, leading to gaps in the $w_{\rm ocean}$ profiles and gap-edge artifacts (Section 4.4), which can be difficult to attribute to wake effects (right panel in Figure 12).

4.6 Vertically Moving Organisms

Not all vertical motion measured by ADCPs near the sea surface is due to vertically moving water, as at least some of the organisms giving rise to the acoustic backscatter required for ADCP measurements are capable of rapid vertical movement. There are regions where vertical plankton migrations dominate upper-ocean ADCP vertical-velocity measurements at certain times of the day (e.g. *Fischer and Visbeck,* 1993b). In the example shown in Figure 13 there is a likely ≈10 m-thick layer of upward-moving plankton rising from 160 to 60 m during the cast (left panel). While this vertically moving layer does not appear to affect the processed $w_{\rm ocean}$ profiles significantly (right figure panel) there are apparent downcast artifacts associated with another thin acoustic scattering layer near 160 m.

Vertical velocities in the upper ocean should generally be treated with particular caution, especially in regions of high biological productivity. In a data set collected in the northeastern Gulf of Mexico, for example, consistently strong downward motion was observed in the upper 200 m in the profiles taken between sunset and sunrise, but not during daylight hours (Figure 14). While inconsistent with diel vertical plankton migration, the observed downward motion is associated with strong acoustic backscatter anomalies (middle panel), consistent with the hypothesis that the apparent motion is caused by swimming organisms, which are perhaps fleeing into deeper water to avoid the approaching instrument rosette.

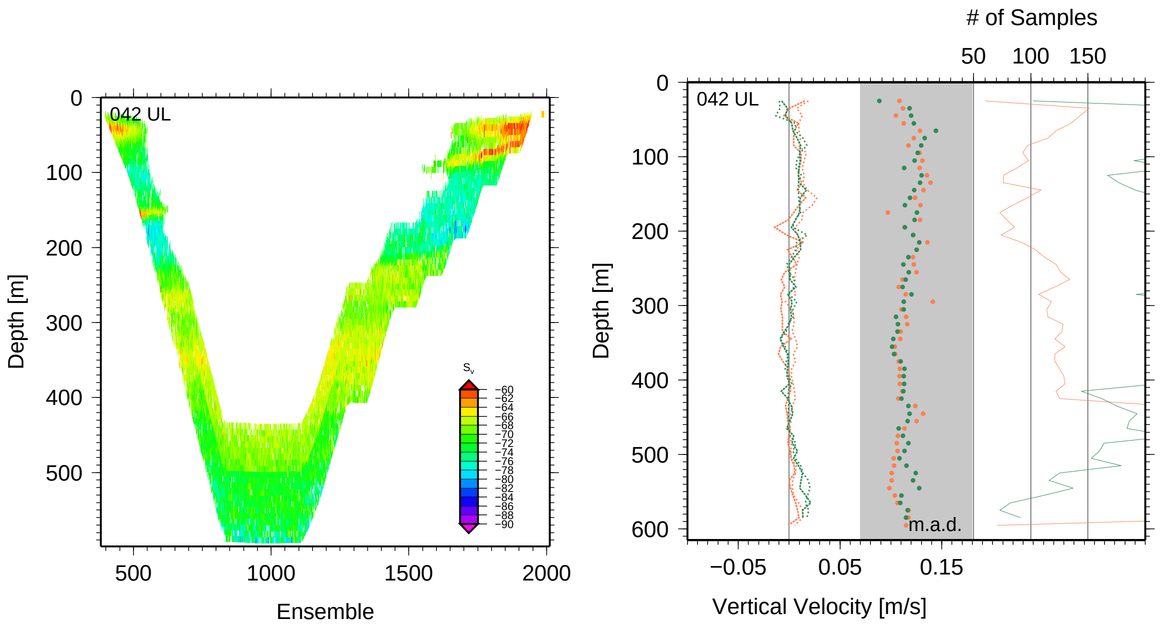

Figure 13: Diagnostic plots from a profile with a likely ≈10 m-thick layer of vertically moving plankton rising from 160 to 60 m during the cast. Left panel: `_Sv` plot; the anomalous vertical structure of acoustic backscatter below 400 m is due to imperfections in the backscatter calculation algorithm. Right panel: `_wprof` plot.

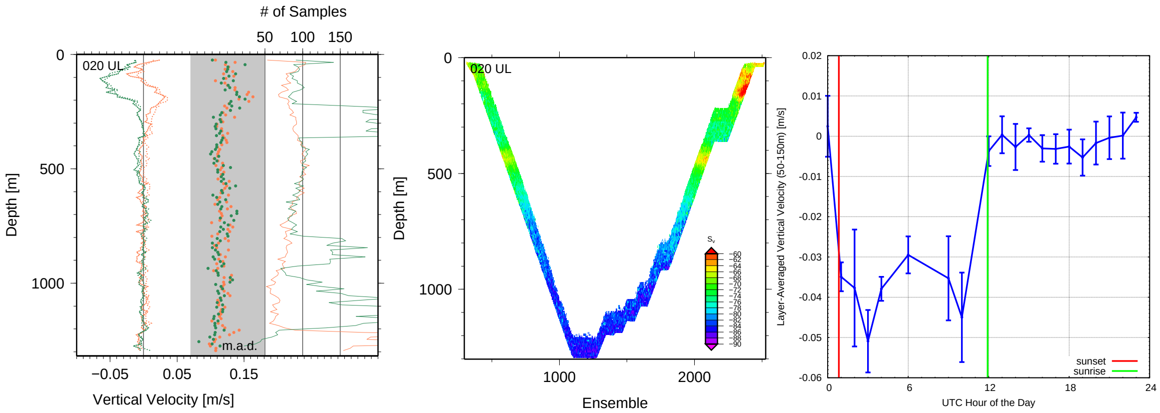

Figure 14: Upper-ocean vertical velocity signals in the northeastern Gulf of Mexico likely caused by biology. Left and middle panels: Diagnostic `_wprof` and `_backscatter` plots from an example profile with strong apparent downwelling observed during the upcast in the upper 200 m of the water column. Right panel: Average w_{ocean} between 50 and 150 m vs. hour of the day for all profiles from this site.

4.7 Boundary Effects

In addition to biology, there are other causes for potential contamination near the sea surface, including reduced sampling, interference from acoustic instruments mounted on the surface vessel, sidelobe

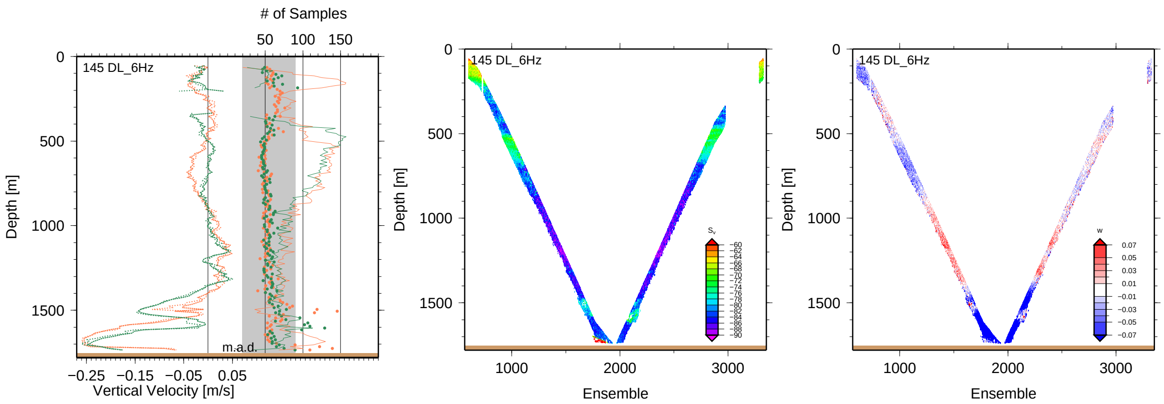

Figure 15: Diagnostic plots from a profile in a region with extreme turbulence. From left to right: `_wprof`, `_Sv` and `_w` plots, respectively.

reflections from its hull and the sea surface, as well as high-frequency vertical motion associated with (long) surface-gravity waves. Near the seabed, reduced sampling and sidelobe reflections from steep topography can adversely affect the data. (Sidelobe contamination from the seabed affects uplooker data just as much as downlooker data, which makes it important that the water depth is set correctly when processing uplooker profiles; Section 3.1.) Vertical-velocity spikes near the surface or seabed must be removed from the data during postprocessing.

4.8 Strong Turbulence

High levels of turbulence in regions such as Drake Passage and Luzon Strait can affect LADCP-derived vertical-velocity profiles. The example profile shown in Figure 15 was collected slightly east of the crest of a meridionally trending ridge blocking deep flow through Luzon Strait. At the time of observation, there was strong eastward bottom-intensified flow at the location. Following the sloping topography, the eastward flow is associated with strong downwelling (left figure panel). Both the elevated acoustic backscatter between 1500 and 1600 m (center panel) and the bursts of upward motion embedded within the strongly downwelling background (right panel) are consistent with the signatures of large turbulent eddies in this layer of extreme vertical shear of the zonal flow ($\approx 0.5\,\mathrm{m\cdot s^{-1}}$ over 100 m). The vertical velocities associated with the turbulent eddies contaminate both downcast and upcast profiles of w_{ocean} (left panel).

References

Deines, K. L., 1999: *Proceeding, CWTMC'99 (IEEE)*.

Firing, E. and R. Gordon, 1990: Deep ocean acoustic Doppler current profiling. *IEEE Fourth Working Conf. on Current Measurements*, 192–201.

Fischer, J. and M. Visbeck, 1993a: Deep velocity profiling with self-contained ADCPs. *J. Atm. Oc. Tech.* **10**, 764–773.

Fischer, J. and M. Visbeck, 1993b: Seasonal variation of the daily zooplankton migration in the Greenland Sea. *Deep Sea Res. I* **40**, 1547–1557.

Thurnherr, A. M., 2010: A practical assessment of uncertainties in full-depth velocity profiles obtained with Teledyne/RDI Workhorse Acoustic Doppler Current Profilers. *J. Atm. Oc. Tech.* **27**, 1215–1227.

Thurnherr, A. M., 2011, March): Vertical velocity from LADCP data. *Proceeding, CWTMC'11 (IEEE).*

Thurnherr, A. M., S. S. Jacobs, P. Dutrieux, and C. F. Giulivi, 2014: Export and circulation of ice cavity water in Pine Island Bay, West Antarctica. *J. Geophys. Res.* **119**, 1754–1764.

Thurnherr, A. M., L. St. Laurent, K. J. Richards, J. M. Toole, E. Kunze, and A. Ruíz Angulo, 2015: Vertical kinetic energy and turbulent dissipation in the ocean. *Geophys. Res. Lett. (in review).*

Visbeck, M., 2002: Deep velocity profiling using Lowered Acoustic Doppler Current Profilers: Bottom track and inverse solutions. *J. Atm. Oc. Tech.* **19**, 794–807.