Acoustic Current Measurements in the Ocean

Course: Measurement Techniques (Environmental Physics)/ F-Praktikum (Physik)

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Last change: May 2023

1 Background of experiment

1.1 Direct velocity measurements in the ocean

The global oceans form the long-term memory of Earth's climate system, and despite the large timescales (thousands of years) and low velocities (few centimeters per second) of abyssal currents, significant amounts of mass and heat are transported by the ocean circulation (e.g. Vallis, 2012).

To determine mass and heat transports directly, the ocean velocity has to be measured. For distances large compared to the Rossby Radius, classical hydrographic data can be used to determine oceanic velocities from the pressure field using the geostrophic balance. However, to study variability, both in time and space, direct current measurements are invaluable. A widespread method for direct current measurements is based on the acoustic Doppler effect. Doppler current meters are used in moorings, mounted into ships, and may be lowered with a winch from a ship (lowered acoustic Doppler current profiler, LADCP).

During the lab you will work with data from such a lowered ADCP. You will calculate transports in a specified oceanic region starting from the raw data of LADCP measurements from a cruise of a research vessel. This gives you an opportunity to work with 'real world' oceanographic data; it may serve as a preparation for future cruises as you will encounter typical problems and pitfalls associated with this type of data processing. Moreover, you get to practise your programming skills.

1.2 The lowered ADCP system

The lowered ADCP system consists of two 300-kHz devices built by Teledyne RD Instruments. They have pressure cases for exposure to pressures at up to 6000 m depth. Together with a CTD (conductivity temperature depth probe) the instruments and are mounted to a rosette water sampler. One instrument at the top having its transducers facing upwards, and the second at the bottom with downward looking transducers.

Principles of operation

An acoustic Doppler current profiler (ADCP) uses the Doppler effect by transmitting acoustic waves and receiving the signal backscattered by small particles in the water. A frequency of $f = 300\,\text{kHz}$ corresponds to a wavelength of $\lambda = c/f \approx 5\,\text{mm}$, where a sound velocity in water of $c \approx 1500\,\text{m/s}$ has been used. Particles of the same size as λ, such as zooplankton, are exited by the acoustic radiation and re-emit sound waves, which are received by the transducers of the ADCP. A crucial assumption is that the plankton cloud on average moves with the same velocity as the water, i.e. it is transported by the water and the individual animals do not swim all into the same direction. Because the scatterers are usually moved by ocean currents, and also the instrument is not fixed in space, the backscattered acoustic wave is Doppler shifted. Since oceanic velocities v are very slow compared to the velocity of sound ($v/c \ll 1$), the Doppler frequency shift Δf is always given by (RDI, 1996):

$$\Delta f = f\frac{v}{c}. \tag{1}$$

Equation (1) is true for a stationary emitter and moving receiver as well as for a moving emitter and a stationary receiver. The velocity v is positive when emitter and receiver approach each other. Then the frequency shift is positive and the received frequency is larger than f. When emitter and receiver depart from each other, velocity v is negative. Then the frequency shift is negative and the received frequency is lower than f. In any measurement with the ADCP the Doppler effect occurs twice: Firstly the sound pulse is emitted by the transducers of the ADCP and received by the scatterers, and secondly the excited scatterers emit the backscattered sound pulse, which is received back by the transducers of the ADCP. Furthermore, Equation (1) is only true for radial motion, i.e. velocity vectors along the direction defined by transducer and scatterer. Angular motion does not change the distance between emitter and receiver and experiences therefore no Doppler shift. For the geometry shown in Figure 1 and including the doubling, the complete Doppler shift received at the transducers is

$$\Delta f = 2f\frac{v}{c}\cos(A), \tag{2}$$

where A is the angle between the scatterer velocity and the backscattered acoustic beam.

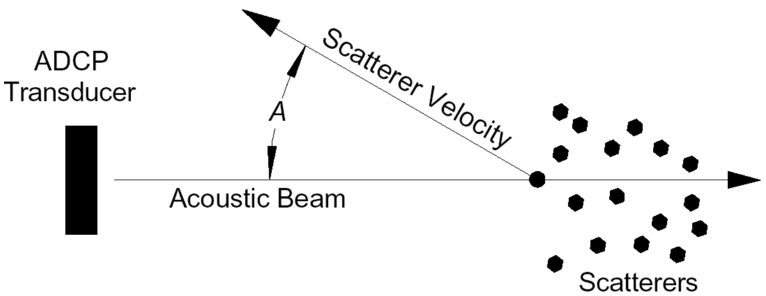

Figure 1: Geometry of the scattering event (RDI, 1996).

After the ADCP has transmitted a pulse, it waits for a short period of time until ringing has disappeared. Ringing means that the energy of the transmit pulse lingers in the transducer for a certain time after the transmission has finished. After this blank, the ADCP is listening for echos to be processed. The received echos are range-gated by breaking the echo into several successive time gates. The first gates contain the echo received in the beginning, i.e. from scatteres near to the ADCP, while later gates contain the echo from more distant scatterers. The length of each time gate corresponds to a certain distance range, a depth cell, over which the velocity is averaged. Several depth cells with average velocities form a continuous, regular sampled velocity profile. It should be emphasized that this profile is obtained from a single ping. Then the next pulse is transmitted and the cycle continues. The size of the depth cells and the number of depth cells, i.e. the range, depend on the frequency of the ADCP, the mode it is operated in, and further customizable settings.

Since the water sampler is connected to a cable only and may thus carry out motions that are not under direct control of the user, some correction has to be applied. The ADCP contains a flux-gate compass to determine the heading and inclinometers to determine pitch and roll of the device. They allow to transform the velocity data from beam coordinates, which follow the direction of the acoustic beam, into earth coordinates, i.e. north-, east- and upward velocity components. Since three independent velocity components shall be obtained, at least three beams are required. Each of the ADCPs has four beams for better quality control.

Data processing

The post processing is done semi-automatically using a purpose-build toolbox. The first step is to remove low quality data. Velocity with a low signal to noise ratio ("percent good" parameter) or large pitch and roll angles are rejected as well as velocity outliers are removed. Then the actual processing can be done: As described above, every ping yields a short velocity profile. Thus, a large number of individual profiles are collected during the downcast and upcast of the instrument. Visbeck (2002) shows how a complete profile of absolute velocities can be calculated from the short velocity profiles that are relative to the ADCP: Each individual measured velocity U_{meas} can be expressed as the sum of the oceanic velocity U_{ocean}, the speed of the instrument through the water U_{inst}, and some noise U_{noise} due to measurement noise and non-homogeneous flow in a depth cell.

$$U_{\text{meas}} = U_{\text{ocean}} + U_{\text{inst}} + U_{\text{noise}} \tag{3}$$

Since the instrument is put into the water at the beginning of each station and returns onboard the ship at the end, the time integral over its motion is known. It must equal the distance that the ship drifted during the station

$$DX_{\text{ship}} = X^T_{\text{ship}} - X^0_{\text{ship}} = \overline{U_{\text{ship}}}T = \int_0^T U_{\text{inst}}\,\mathrm{d}t, \tag{4}$$

where T is the total time of the deployment. The position of the ship is determined with high accuracy by GPS and yields together with T the ship's mean velocity $\overline{U_{\text{ship}}}$. For the calculations each velocity estimate in a depth cell of the small profiles must be assigned to the corresponding depth. While the relative distance of the depth cell to the ADCP can be determined by the ADCP itself, the depth of the ADCP is calculated from pressure measurements of the CTD. To get a solution for the oceanic velocities U_{ocean} using measured ADCP velocities U_{ADCP}, Equation (3) shall be considered as a set of linear equations of the form

$$\boldsymbol{d} = \boldsymbol{G}\boldsymbol{u} + \boldsymbol{n}, \tag{5}$$

where $\boldsymbol{d}$ is the data vector containing all U_{meas} velocities, $\boldsymbol{G}$ is a coefficient matrix expressing the dynamics of Equation (3) and $\boldsymbol{n}$ represents noise due to imperfect measurements in $\boldsymbol{d}$ and imperfect predictions by $\boldsymbol{Gu}$. The vector $\boldsymbol{u}$ contains the unknown velocities U_{inst} and U_{ocean}:

$$\boldsymbol{u} = \begin{bmatrix} U_{\text{inst}} \\ U_{\text{ocean}} \end{bmatrix} \tag{6}$$

The dimension of the problem, i.e. the dimension of $\boldsymbol{G}$, is determined by the number of velocity observations $n_{\boldsymbol{d}}$ and the number of unknowns $n_{\boldsymbol{u}}$. The number of velocity observations is given by the number of pings n_{ping} times the number of depth cells per ping n_{cell} times the number of ADCPs used $n_{\text{ADCP}} = 2$, i.e. $n_{\boldsymbol{d}} = n_{\text{ping}} n_{\text{cell}} n_{\text{meas}}$. The number of unknowns is a sum of the number of instrument velocities n_{inst} which equals the number of pings n_{ping}, and the number of desired ocean velocities $n_{\text{ocean}} = H/\Delta z$, where H is the length of the total profile (e.g. water depth) and Δz is the resolution. Typically Δz is chosen equal to the depth cell size of the ADCP. The number of unknowns is $n_{\boldsymbol{u}} = n_{\text{ping}} + n_{\text{ocean}}$. Since usually $n_{\boldsymbol{d}} > n_{\boldsymbol{u}}$ holds true, the system is overdetermined and can be solved using the least squares method, i.e. by minimizing the objective function

$$J = (\boldsymbol{Gu} - \boldsymbol{d})^T (\boldsymbol{Gu} - \boldsymbol{d}), \tag{7}$$

which is the sum over the squared differences between the data $\boldsymbol{d}$ and their prediction $\boldsymbol{Gu}$. The solution to this problem is well known:

$$\boldsymbol{u} = [\boldsymbol{G}^T \boldsymbol{G}]^{-1} \boldsymbol{G}^T \boldsymbol{d}, \tag{8}$$

A strong advantage of the least squares system is the possibility to add additional constraints[1]. The most important one is the barotropic constraint, which prescribes the time average of unknown instrument motion using Equation (4). This adds an extra line to the system of Equation (5) according to:

$$\begin{aligned} \hat{\boldsymbol{d}} &= \begin{bmatrix} \boldsymbol{d} \\ \nu U_{\text{ship}} \end{bmatrix}, \\ \hat{\boldsymbol{G}} &= \left[\begin{array}{ccccc|c} & & \boldsymbol{G} & & & \\ \nu \frac{\mathrm{d}t_1}{T} & \nu \frac{\mathrm{d}t_2}{T} & \nu \frac{\mathrm{d}t_3}{T} & \ldots & \nu \frac{\mathrm{d}t_n}{T} & 0\,0\,0\,\ldots\,0 \end{array} \right] \end{aligned} \tag{9}$$

Here, the $\mathrm{d}t_i$ with i running up to $n = n_{\text{ctd}}$ represent the times between subsequent instrument velocities U_{ctd} and ν is a weighting factor which controls how strong the solution is forced to follow this constraint. For the barotropic constraint ν is typically a larger number, since it is for sure that the instruments returned to the ship. Furthermore, a constraint for the bottom track, which forces the instrument to a certain velocity using the echos from the (non-moving) bottom, and a smoothness constraint are applied (for both cf. Visbeck, 2002). The result is an optimized estimate of a velocity profile from the surface to the bottom.

[1] In this case it is in fact necessary to define additional constraints, since the matrix $[\boldsymbol{G}^T \boldsymbol{G}]$ is not invertible otherwise. This is due to the fact that the unknowns are not linear independent, since the LADCP measurements alone can give only a baroclinic velocity profile relative to the moving device itself (Visbeck, 2002)

Settings

As already indicated above, two ADCPs with a frequency of 300 kHz have been used as LADCP during the cruise you will work with. They have been run in Narrowband Mode for maximum range, which means roughly 130 m. Thus the range of a profile from one ping in the optimal case is of about 260 m. The true range depends on the abundance of scatterers, which decreases with water depth. Thus, the maximum value of 260 m cannot be reached in the deep water surveyed in this study. The size of the depth cells, also called bin length, has been set to $\Delta z = 10$ m.

2 Experimental setup

The ADCP is a self-contained instrument. In practice (during station work at sea), this means the instruments are programmed before each cast, and the data are downloaded to a computer afterwards. During the cast, certain informations as time and ships position have to be logged carefully to ensure a proper velocity profile. Post processing is done on a computer with MATLAB using a purpose-build toolbox. The logged data are entered into a parameter file, which is then combined with the raw data to calculate a velocity profile. The resulting profiles are the basis for further analysis, here for the calculations of a volume transport.

2.1 Dataset

You will be provided with raw data files and the log sheets for casts obtained during a R/V Meteor or R/V Merian expedition. There are separate raw data files for each of the two instruments.

2.2 Software

For this lab, you will use a MATLAB post processing toolbox that carries out all the steps outlined above. Detailed descriptions of the processing can be found in Fischer and Visbeck (1993) and Visbeck (2002). A short description of the toolbox is given below:

LADCP General

- **About** About LADCP
- **Quit** Quits LADCP

File Data import/export, window options

- **New** Create a new parameter file
- **Open** Opens previously created parameter file and loads raw data
- **Edit** Allows to edit previously created parameter files
- **Load** Loads a previously saved data mat file
- **Save** Saves the current state of post processed data as mat file

Export Exports the data in standard ascii file and creates a log sheet

Print Prints the current window

Process Data processing steps

Depth Calculate depth of instrument

Shear Profiles of velocity shear and number of shear estimates/depth bin

Velocity Profiles of horizontal velocity in the ocean

View View raw data

Attitude Pitch, roll, and heading of instrument

Sensors Internal ADCP sensors (temperature, salinity, and sound velocity)

CTD Data External CTD sensors (temperature, salinity, and sound velocity)

Bottom Track Bottom track velocities and distance to bottom

Raw Data Raw velocities and target strength

Raw Trace Raw velocities, shear, and target strength vs. depth

Ensemble Data Ensemble averages

Ensemble Trace Ensemble averages vs. depth

3 Experimental procedure and tasks

The processing and the analysis of the LADCP data consists of the following tasks. You will find detailed instructions in section 5.

1. Enter the cast-specific parameters in the input mask and save them in a new parameter file. After saving the parameter file the data files will be loaded automatically.
2. Process the raw data and check the quality by doing the following
   (a) Initial quality check (instrument tilt, completeness)
   (b) Computation of instrument depth
   (c) Computation of shear profiles
   (d) Computation of velocity profiles
3. Export the velocity data
4. Produce a suitable visualization of the current data (e.g. contours of velocity); here your MATLAB programming skills are required
5. Calculate the volume transport (horizontal and vertical integral if the stream function) across the transect

6. Estimate the errors in a) the individual velocities and b) the derived transports

Discuss the results of tasks 5, 6, and 7, and the data quality: What is the data quality, and what are the factors affecting it on this transect? Are there possible sources of errors? What is the velocity structure on the transect? How large are the velocities? What is the volume transport? How large are the errors compared to the signal? If you were to calculate volume transports for different horizontal and vertical ranges, which would you choose? And why?

4 Detailed instructions for practical: Acoustic Current Measurements

Tasks 1 – 4 deal with the data processing, tasks 5 – 7 with the analysis/interpretation of the velocity measurements. You will have to repeat the tasks 1 - 4 for each of the profiles.

4.1 Task 1: Preparation

In MATLAB, change the working directory to where the raw data are stored and enter `ladcp` in the command window. In the 'File' menu, chose 'New' or 'Edit'. Choose the files upward and downward looking instruments and the CTD data file. You can use TAB to switch between the input fields. Positions and times are taken automatically from the CTD data file if specified. The 'Options' parameters are normally not changed by the user.

4.2 Task 2: Load the data

Save the parameter file under a suitable name. When you click on 'Save', the raw data files specified in the parameter file are loaded. When this is finished, a screen displaying the instrument orientation parameter is shown. (You can also look at these parameters under 'View', 'Status'.) At this stage, the first quality check is done - the pitch and the roll (i.e., the inclination of the instruments) should not be higher than a certain threshold (here: 21°), else the data are thrown out (why?). The heading difference between the two instrument should be fairly constant (if not, this is an indication of a compass problem and the direction of the measured velocities might not be useable).

4.3 Task 3: Process the raw data and check the quality

Initial Quality Check

The first step in data processing is to check whether the instruments have both measured without failures, and have a sufficient range. The easiest way to do so is to inspect the vertical velocity ('View', 'Raw Data', 'Vertical Velocity'). The vertical velocity displayed is the raw velocity as measured - the axis shown are the time of the deployment and the distance from the water sampling unit, the velocity is color coded. Positive values on the y-axis refer to the water column above the package (i.e. data from the upward looking instrument), negative values refer to the downward looking instrument. The velocity values reflect mainly the motion of the instrument package, i.e. the lowering and heaving of the water sampling unit, and should therefore be more or less constant for each ping (time) and lie between -1.5 and +1.5 m/s. The range is the distance from the instrument with the last data points. It should not be less than 4-5 bins (=10m increments) of good data - else the overlap between pings during the lowering and heaving is too small to calculate a statistically stable average velocity/shear in this depth range.

If there are time intervals without any data, there has probably been a power failure or the instrument has broken down, in which case the profile is incomplete and no velocity profile can be computed. If several, short data gaps occur, it may be a sign of data flagged 'bad' because of strong instrument inclination (you can double check this under 'View', 'Status'); depending on the duration of the gaps, it may still be possible to produce a velocity profile.

Instrument Depth

The next step is the calculation of the instrument depth from the pressure measurements in the CTD data file. When you click on 'Process', 'Depth', the calculation is done and the result is displayed. On the display, you can see the velocity (upper panel) and the depth of the instruments (lower panel). The deepest point should also be within a reasonable distance to the actual water depth . You can check this by looking at the target strength vs. depth display ('View', 'Depth Trace', 'Target Strength') - here, water column data are displayed in blueish colors - strong reflectors, like the sea surface, or the seafloor, show up in yellow/red. If the seafloor was within the range of the instrument, there are also the bottom track velocities available as a constraint for the inverse solution. You can view them under 'View', 'Bottom Track'.

Shear

The next step is the calculation of the velocity shear in depth bins ('Process', 'Shear Profiles'). On the display, you get the resulting shear vs. depth in the two horizontal direction, and a third panel with the number of shear estimates per depth bin. As a rule of thumb, the profile will be of good quality if the number of estimates/bin is higher than 100. This is normally the case if the two instruments are in good working order and the range is sufficient (what affects the range?). In the shear vs. depth display, you can see up- and down-cast of the instrument as well as the total. If the scatter is high, or if up- and down-cast deviate significantly, this is an indication of too few estimates (=bad statistics) in the affected depth range, and the profile may be flawed.

Velocities

Finally, the velocities are calculated ('Process', 'Velocity'). On display there are the velocities on N-S and E-W direction. Typical deep ocean velocities lie in the range of a few to a few tens of centimeters per second.

4.4 Task 4: Export the data

There are two ways to export the data - as a binary file (MATLAB .mat file) or as a plain text file, which can be loaded into every program which can handle text files. The second option also creates a log sheet (PDF), which summarizes the important information and plots of the post processing.

When the data are stored as a mat file, two variables (structured arrays) are created: p and l. p stores the information of the parameter file, and the processed data, l stores the raw data. You should export the data as text file ('File', 'Export'). Choose a sensible file name (e.g., something matching the parameter file name). The text file consists of a header detailing the cast information, and three columns with depth (z, in m), velocity (u (E-W) and v (N-S) in cm/s). When the export is finished, keep the log sheet for the appendix of your report!

4.5 Task 5: Produce a suitable visualization of the current velocity data (e.g. transect of velocity)

Here is described how to load the text files into MATLAB. If you want to use another software for plotting, e.g. Python, you have to find your own way to import the data. The text files can be loaded into MATLAB with rodbload.m (part of the toolbox), that requires a certain syntax: To load the data into MATLAB, type

[lat,lon,prf,u,v,z] = rodbload(data,'Latitude:Longitude:Profile:u:v:z');

where *lat, lon, u, v, z* are the names of the variables where the parameters *Latitude, Longitude, Profile, u, v*, and *z* are stored. Valid parameters are all header variables and the 'Field' identifier in the header (*z,u,v*). *data* is a matrix with all filenames (as strings) you wish to load. If your data are stored in a.dat, and b.dat type

data= str2mat('a.dat','b.dat')

to produce such a matrix. Useful commands for plotting are *contour* & *contourf*.

4.6 Task 6: Calculate the transport stream function along the ship track

The transport stream function change between two stations is given by $\Delta\psi = H(\overline{u}\Delta y - \overline{v}\Delta x)$, were H is the mean water depth and $\overline{u}$ and $\overline{v}$ are the mean top-to-bottom velocities between the stations in east and north directions respectively. In physical oceanography the volume transport is commonly expressed in units of Sverdrup (1 Sv = 10^6 m^3 s^{-1}). Calculate $\Delta\psi$ for adjacent stations, plot the horizontally integrated stream function along the ship track, and discuss the result.

4.7 Task 7: Estimate the errors in a) the velocities and b) the stream function

Give a rough error estimate for the individual 10 m velocities, based on the accuracy given in RDI (1996), and on your judgment of the quality of the results. The random error of the top-to-bottom mean velocities $\overline{u}$ and $\overline{v}$ for a single cast is approximately 2 cm/s. Do you think the data quality in all the profiles is good? If not, which are good, which are not so good? What is the (relative and absolute) uncertainty of the volume transports calculated in Task 6?

5 Questions for preparation

1. Instrument
   (a) What does an ADCP measure? And how?
   (b) What is meant by broadband, what by narrowband ADCP?
   (c) How are the measurements converted into an actual current profile?
   (d) What information is necessary to generate a current profile in addition to the actual measurements (in other words: what do you need to generate a parameter file)?
   (e) What is meant by the term inverse solution, what by shear solution?
   (f) Which informations are used in the inverse solution, which in the shear solution?
   (g) What are the errors occurring in the measurement, and what causes them?
   (h) What effects do the following aspects have on the data, esp. on the quality: Range of the instrument; orientation(tilt, heading) of the instrument; bin size?
   (i) What affects the range? What affects instrument orientation?

2. Physics
   (a) What is the Doppler effect?
   (b) What is the speed of sound in seawater and what determines it?
   (c) Why do we use acoustic means to do remote sensing in the ocean, and not electromagnetic signals as in the atmosphere?
   (d) What is the relation between the frequency of an acoustic pulse and its range in water?

3. Oceanography
   (a) What methods are there to measure currents in the ocean?
   (b) What is a barotropic, what a baroclinic velocity?
   (c) What is the ocean conveyor belt?
   (d) What are boundary currents?
   (e) Why are volume and heat transports in the ocean important for the worlds climate?
   (f) When and where was your data recorded? What are the prevailing currents at that place, i.e. what do you expect to find out with your measurements?

References

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