Acoustic Current Measurements in the Ocean

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

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1 Background of the experiment

The global oceans form the long-term memory of Earth's climate system, and despite the long timescales (thousands of years) and slow velocities (a few centimeters per second) of abyssal currents, significant amounts of mass and heat are transported by the ocean circulation (e.g. Vallis, 2012). For distances much larger than the Rossby Radius, which is a measure of the influence of Earth's rotation on ocean currents, the pressure field and oceanic velocities can be determined from measured hydrographic data (temperature and salinity) using the geostrophic balance, a principle that assumes a balance between the pressure gradient force and the Coriolis force. However, this provides only the vertical shear of horizontal velocity, and therefore requires a reference velocity, i.e., a level-of-no-motion or level-of-known motion, for which direct current measurements are invaluable.

Many available instruments that measure water velocity directly are based on Doppler technology. They transmit acoustic signals and measure the frequency shift of the signals reflected by particles in the water. These current meters measure either the velocity in a single volume element near the device or a velocity profile composed of multiple adjacent volume elements at varying distances. Such devices are commonly known as acoustic Doppler current profilers (ADCPs). First introduced in the early 1980s, they have since been continuously developed for a wide range of applications.

Today, ADCPs are deployed on various platforms, including ships, moorings, and autonomous underwater vehicles. The range of an ADCP, determined by the frequency of its transmitted sound pulses, varies from a few meters to over 1000 meters. In most parts of the world's oceans, this range is insufficient to cover the entire water column with a single instrument mounted on a ship or on the seafloor. To obtain a continuous vertical profile of horizontal current velocity, measurements at multiple depths are often required. One method is to *lower* the ADCP on a long wire from the sea surface to the seafloor. The first lowered ADCP (LADCP) cast was conducted near Hawaii in 1989 by Firing and Gordon (1990). Fischer and Visbeck (1993) used measurements from a more accurate free-falling instrument to evaluate LADCP performance and found that LADCPs successfully reproduced most observed signals. Visbeck (2002) developed an inverse method to improve data processing by adding external constraints, such as bottom-track velocities.

During the lab, you will work with a lowered ADCP dataset obtained during a research cruise in the northwestern North Atlantic. You will process the raw data using a provided software tool, visualize the results graphically, and determine the transports of ocean currents. This will give you the opportunity to work with real-world oceanographic data while also allowing you to practice your programming skills.

2 Experimental setup

2.1 The lowered ADCP

The system as used in the Physical Oceanography group at the University of Bremen consists of two 300-kHz ADCPs built by Teledyne RD Instruments. Their pressure housings allow for deployments at depths of up to 6000 m. Together with a CTD (conductivity-temperature-depth probe) the instruments are mounted on a rosette water sampler (Fig. 1), one instrument at the top with the transducers facing upwards, the second at the bottom, with down-looking transducers.



Figure 1: a) Rosette water sampler with Niskin bottles and two 300 kHz ADCPs. b) Close-up of the ADCP transducer head. c) CTD sensors installed beneath the Niskin bottles.

Before each deployment, the ADCPs are connected to a computer and configured. The system is then lowered from the ship to the seafloor using a winch, and then hoisted back onto the deck. For deep-sea deployments, this process usually takes a few hours, as lowering and hoisting occur at a speed of around 1 m s^{-1} . The ADCPs process and record the measured data internally. The CTD data are transmitted to the lab in real-time via the cable and can be viewed online. After the cast, the ADCPs are reconnected to the computer, and the data are retrieved.

2.2 Principles of operation

The ADCP uses the Doppler effect by transmitting acoustic waves and receiving the signal backscattered by small particles, such as zooplankton, in the water. A crucial assumption is that the plankton cloud moves with the same velocity as the water, i.e. it is transported by the water and the individual animals do not swim all in 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 much smaller compared to the speed of sound in seawarter (c), with $v/c \ll 1$, the Doppler frequency shift Δf is appromixmated by

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

Equation (1) applies to a stationary transmitter and a moving receiver or for a moving transmitter and a stationary receiver. The velocity v is positive when transmitter and receiver approach each other. Then the frequency shift is positive, meaning the received frequency is higher than f. When transmitter 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 every ADCP measurement, the Doppler effect occurs twice: The sound pulse is first emitted by the ADCP's transducers and received by the scatterers. The scatterers then re-emit the signal, which is received again by the ADCP transducers. Furthermore, Equation (1) only applies to radial motion, i.e. velocity vectors along the direction defined by transducer and scatterer. Angular motion does not change the distance between transmitter and receiver and therefore experiences no Doppler shift. Thus, with α being the angle between the scatterer velocity and the backscattered acoustic beam, the complete Doppler shift received at the transducers is

$$\Delta f = 2f \frac{v}{c} \cos \alpha. \tag{2}$$

After the ADCP has transmitted a sound pulse, it waits for a short time until ringing has disappeared. Ringing refers to residual energy from the transmitted pulse lingering in the transducer for a short period after transmission, which can interfere with the echoes. After this blank, the ADCP listens for echoes to be processed. The received echoes are range-gated, meaning they are divided into time intervals (or gates) corresponding to specific distances from the ADCP. The first gates contain the echo received at the beginning, i.e. from scatterers close to the ADCP, while later gates contain the echo from scatterers further away. The length of each time gate corresponds to a specific distance range, a depth cell, over which the velocity is averaged. Multiple depth cells form a continuous, uniformly spaced velocity profile. This profile is obtained from a single ping. Then the next pulse is transmitted and the cycle repeats. 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 other instrument settings.

Since the water sampler is connected to the ship solely by a wire, it makes uncontrolled movements, so attitude data must be recorded with each ping. The ADCP has a flux-gate compass to determine the heading and inclinometers to determine pitch and roll of the device. These data allow the velocity measurements, originally in the coordinate system aligned with the acoustic beams, to be transformed into Earth coordinates (north, east, and upward velocity components). Since three independent velocity components are to be determined, at least three beams are required. Each ADCP has four beams, providing redundancy and enabling quality control.

3 Data analysis

3.1 Post processing

A large number of individual velocity profiles are collected during the down- and upcast of the instrument. Visbeck (2002) shows how a complete profile of absolute velocities can be calculated from the short profiles that are relative to the ADCP: Each individual velocity measurement U_{adcp} can be expressed as the sum of the velocity of the ocean currents U_{ocean} , the velocity of the instruments through the water U_{ctd} , and some noise U_{noise} due to measurement errors and non-homogeneous flow in a depth cell:

$$U_{\rm adcp} = U_{\rm ocean} + U_{\rm ctd} + U_{\rm noise}.$$
 (3)

As the instrument is lowered into the water at the beginning of each cast and returns on board at the end, the time integral over its motion is known. It must equal the distance that the ship drifted through the water during the station

$$DX_{\rm ship} = X_{\rm ship}^T - X_{\rm ship}^0 = \overline{U_{\rm ship}}T = \int_0^T U_{\rm ctd} \,\mathrm{d}t,\tag{4}$$

where T is the total time of the deployment. The position of the ship is determined 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 short 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

$$d = Gm + n, \tag{5}$$

where d is the data vector with all measured U_{adcp} velocities, G is a coefficient matrix corresponding to Equation (3) and n is the noise due to imperfect measurements in d and imperfect predictions by Gm. The vector m contains the unknown velocities U_{ctd} and U_{ocean} :

$$\boldsymbol{m} = \begin{bmatrix} U_{\text{ctd}} \\ U_{\text{ocean}} \end{bmatrix}$$
(6)

The dimension of matrix G is determined by the number of velocity measurements n_d and the number of unknowns n_u . The number of velocity measurements is given by the number of pings n_{ping} times the number of depth cells n_{cell} times the number of ADCPs used n_{adcp} , i.e. $n_d = n_{ping}n_{cell}n_{adcp}$. The number of unknowns is the sum of the number of instrument velocities n_{ctd} , which equals the number of pings n_{ping} , and the number of ocean velocities sought $n_{ocean} = H/\Delta z$, where H is the length of the full profile (e.g. water depth) and Δz is the vertical resolution. Typically Δz is chosen equal to the depth cell size of the ADCP. An important assumption here is that the ocean velocities only vary with depth, but do not change significantly during the time between down- and upcast. The number of unknowns is $n_u = n_{ping} + n_{ocean}$. Since usually $n_d > n_u$ holds true, the system is overdetermined and can be solved using the least squares method, i.e. by minimizing the objective function

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

which is the sum over the squared differences between the data d and their prediction Gm. The solution to this problem is well known:

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

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:

$$\hat{\boldsymbol{d}} = \begin{bmatrix} \boldsymbol{d} \\ \boldsymbol{w}\boldsymbol{U}_{\text{ship}} \end{bmatrix},$$

$$\hat{\boldsymbol{G}} = \begin{bmatrix} \boldsymbol{G} \\ \boldsymbol{w}\frac{dt_1}{T} \boldsymbol{w}\frac{dt_2}{T} \boldsymbol{\nu}\frac{dt_3}{T} \dots \boldsymbol{w}\frac{dt_n}{T} \mid 0 \ 0 \ 0 \dots \ 0 \end{bmatrix}$$
(9)

Here, the dt_i with *i* running up to n_{ctd} is the time interval between subsequent instrument velocities U_{ctd} and *w* is a weighting factor which controls how strong the solution is forced to follow this constraint. A larger number is typically used for the barotropic constraint *w*, as it is certain that the instruments returned to the ship. Furthermore, a constraint for the bottom track, which forces the instrument to a certain velocity using the echoes from the (non-moving) seafloor, 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.

3.2 Settings

Two 300 kHz ADCPs were used for the data set you will work with. The data were collected in narrowband mode for maximum range, i.e. approximately 130 m. Thus, the range of a single-ping profile is about 260 m in the optimal case. The actual range depends on the abundance of scatterers, which generally decreases with water depth. The size of the depth cells, also called bins, was set to $\Delta z = 10$ m.

3.3 Dataset

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 afterwards. During the cast, the time and the ship's position are logged by the CTD deck unit. Post processing of the raw data files is done using a purpose-built toolbox for MATLAB that semi-automatically carries out all the steps outlined above to calculate the velocity profile. Detailed descriptions of what's done in the processing can be found in Fischer and Visbeck (1993) and Visbeck (2002). The resulting velocity profiles are used for plotting and for transport calculations. You will be provided with raw data files obtained during a specific R/V *Meteor* or R/V *Maria S. Merian* expedition in the North Atlantic. There are separate raw data files for each of the two ADCPs and the CTD.

¹In this case it is in fact necessary to define additional constraints, since the matrix $[\mathbf{G}^T \mathbf{G}]$ 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)

4 Experimental procedure and tasks

The processing and the analysis of the data set consists of the following tasks:

- 1. Process the raw data for *each cast* by doing the following:
 - (a) Initial quality check,
 - (b) calculating a time series of instrument depth,
 - (c) calculation of vertical profiles of velocity shear,
 - (d) calculation of vertical profiles of absolute velocity.
 - (e) export resulting velocity profile data to text files for further analysis.
- 2. Create an appropriate visualization of the processed velocity data.
- 3. Calculate a stream function and volume transports.
- 4. Estimate the errors/uncertainties in
 - (a) the individual velocity profiles,
 - (b) the derived transports.

Discuss the results of tasks 3 and 4: What is the data quality, and what are the factors affecting it? Are there possible sources of errors? What is the velocity structure in the research area? How large are the velocities at different depth levels? How large is the volume transport? How large are the errors compared to the signal? Calculate volume transports for different horizontal and vertical ranges. Which ranges do you choose, and why?

5 Questions for preparation

- 1. What is the role of the ocean circulation in the Earth's climate system?
- 2. What is the Atlantic Meridional Overturning Circulation (AMOC), and how much heat and water does it transport?
- 3. What are oceanic boundary currents, why are they intensified to the west of ocean basins?
- 4. What are the methods for measuring ocean currents?
- 5. What is the Doppler effect?
- 6. Why are acoustic signals used for remote sensing in the ocean instead of electromagnetic signals, as in the atmosphere?
- 7. What is the speed of sound in seawater and what determines it?
- 8. How does the frequency of an acoustic pulse affect its range in seawarter?k
- 9. What does an ADCP measure, and how does it do it?

- 10. How does the instrument range and bin size affect the quality of the ADCP data?
- 11. What is broadband and what is narrowband processing?
- 12. How are the individual ADCP measurements transformed into a vertical profile of horizontal current velocity?
- 13. What additional data are used in the inverse method?
- 14. What are barotropic and baroclinic velocities?
- 15. What are the errors that occur during the measurement, and what causes them?

References

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