The misalignment angle in vessel-mounted ADCP

OCEANOLOGIA, 42 (3), 2000.
pp. 385–394.

KEYWORDS
Acoustic Doppler current profiler
Misalignment angle
Calibration

Robert Osiński
Institute of Oceanology,
Polish Academy of Sciences,
Powstańców Warszawy 55, PL–81–712 Sopot, Poland;
e-mail: roberto@iopan.gda.pl

Manuscript received 23 February 2000, reviewed 28 July 2000, accepted 4 August 2000.

Abstract

A description of the misalignment angle and the consequences if it occurs is given. It is shown that because of gyrocompass errors, the misalignment angle error α has to be computed for each cruise. A simple method of calibrating the acoustic Doppler current profiler (ADCP) mounted on a vessel has been devised by fitting the cosinusoidal function. This is a post-processing method, suitable for calibrating previously collected data. Nevertheless, because of ADCP's constructional peculiarities, the procedure must be repeated for each cruise.

1. Introduction

The acoustic Doppler current profiler (ADCP) is a device capable of making continuous current measurements at more than one depth from a moving ship. This instrument consists of four transducers set at an angle of 30° in a concave configuration, which transmits acoustic pulses and receives echoes. Acoustic energy is scattered by small particles such as zooplankton, sediments, or other solid particles, which are assumed – a key assumption – to drift with the local current. These particles make random movements, but the errors due to this motion can be reduced by averaging. Using the Doppler frequency shift measured by the transducer, ADCP can compute the component of vector of the water's velocity along the beam direction. ADCP uses four beams pointing in different directions to measure three velocity components (the minimum number of beams is three). In this way the vector of the water's velocity relative to the ship is computed. To obtain the absolute velocity relative to the Earth, the current profiler has to subtract the velocity of the ship from the measured currents. This can be done either by using the bottom-track option or by using navigation data (GPS). With the bottom-track option, ADCP transmits a special acoustic pulse to measure the movement of the bottom; this is obviously a negative vector of the ship's velocity. Although this procedure is effective and convenient because there is no need for an external device (GPS), which could introduce an error, the bottom-track option is applicable, depending on acoustic transmission conditions, only within the 400–600 metre depth range. Now this is sufficient for the Baltic Sea and shallow oceanic areas, but when the depth of the water is greater than the bottom-track range, GPS has to be relied on as a reference. Another external device which ADCP needs in order to obtain the absolute velocity is the gyrocompass, used both in the bottom-track option and in navigation reference. The gyrocompass error affects mainly the navigation reference. Together with this error, the installation procedure error is expressed as the misalignment angle error α.

Joyce (1989) and Pollard & Read (1989) have published a method of estimating the misalignment and the scaling factor β of ADCP. Further research is concentrating on improving heading data. Griffiths (1994) used 3DF GPS – an array of two GPS, but this method requires costly equipment which few research ship owners can afford. Hence, there is a need to search for better ADCP accuracy with the classical gyrocompass. This paper describes how ADCP data can be improved with the use of the classical gyro. The chief concern here is (i) to describe the misalignment angle and the consequences when it occurs, (ii) to describe a simple test if $\alpha \neq 0$, and (iii) to develop a method of eliminating the misalignment angle during the entire cruise.

2. Observations

During the winter of 1998 the hull of r/v 'Oceania' was fitted with an RD Instruments 150 kHz VM Acoustic Doppler Current Profiler. Since then, data have been collected on a number of cruises. Unfortunately, these data were very often unrealistic, especially when navigation was relied on as a reference. This is what forced us to focus on the ADCP and the external devices which ADCP uses: GPS and the gyrocompass.

The ADCP data used in this paper were obtained during two cruises: 'Sty 1' 18–29 January 1999 and 'Wardem' 20–30 November 1998. Pings were collected in five-minutes ensembles (the other main parameters are given in Table 1). All data recorded when the ship was travelling at less than 4 knots and when its motion was not uniform and in a straight line were removed.

The only difference between these two cruises was the information about the mounting angle transmitted to the ADCP: 48° during the 'Sty 1' and 50.9° during the 'Wardem'.

All the data used in estimating the calibration curves were divided into 10° heading bins. At least 10 elements needed to be in one bin for them to be included in the least squares fit.

Table 1. Principal parameter settings for ADCP

Parameter	Value
pings per ensemble	1
number of depth bins	30
transmit pulse length [m]	4
blank after transmit [m]	4
transducer depth [m]	4
water track pings to bottom track pings	1:1

3. Description of the misalignment angle

Let us imagine three Cartesian coordinates (Fig. 1): (i) X', Y' is the frame in which ADCP measures currents (the OY' axis of a particular ADCP beam), (ii) X, Y is connected to the ship (the OY axis on the bow-stern line), and (iii) N, E, whose ON axis points north (geographical frame). All the coordinates have the same origin at the centre of ADCP.

ADCP measures the velocity vector of the current relative to the ship as well as the velocity vector of the ship in its coordinate system (X', Y'). With the bottom-track option these two vectors are subtracted in the same coordinate frame. Next, if we know the mounting angle λ, the components of the velocity vector are transformed into the (X, Y) coordinate system. If λ is not correct, a first error occurs. γ, the angle of (X, Y) relative to (N, E) measured by the gyrocompass, is the source of a second error. The result (the current velocity vector) is obtained in the geographical coordinate system (N, E).

The sum of these two errors can be expressed as

$$\alpha = \Delta\gamma + \Delta\lambda. \tag{1}$$

α is the misalignment angle, the difference between the real angle ϕ and the information about angle ϕ received by ADCP. When these errors occur during the bottom-track option, the velocity vector modules will be the same as the real ones, the only difference being the direction of the resulting vector.

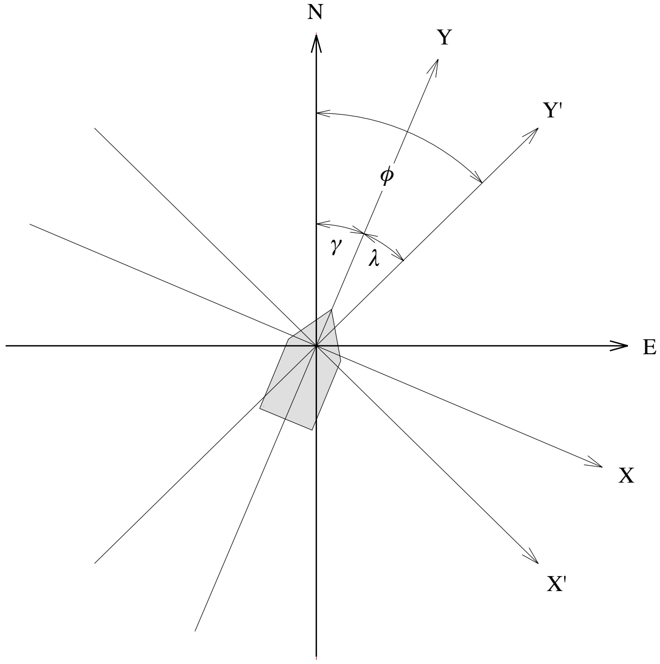

Fig. 1. OX′Y′: ADCP's coordinates. OXY: ship's coordinates, ONE: geographical coordinates

However, a serious error crops up when GPS data is used as reference. The components of the velocity vector of the current relative to the ship transformed from (X′, Y′) coordinates to (N, E) are subtracted from the components of the ship's velocity vector, these latter being obtained on the basis of GPS data measured in a real (N, E) coordinate system. If the angle $\alpha \neq 0$, *i.e.* the ON axis does not point north, and/or $\Delta\lambda \neq 0$ the sum of the current velocity vector relative to the ship and the ship's velocity vector is not equal to the real water velocity. The difference is

$$\varepsilon = |\mathrm{Us}|\sqrt{2(1-\cos\alpha)}, \tag{2}$$

where |Us| – the modulus of the ship's velocity.

Estimating this error is essential, as even a very small error have very serious consequences (Figs. 2, 3). For instance, 0.5° leads to an error of the order of 1% in the ship's velocity (King & Cooper 1993), so when the ship's speed is 4 m s^{-1} the error is 4 cm s^{-1}.

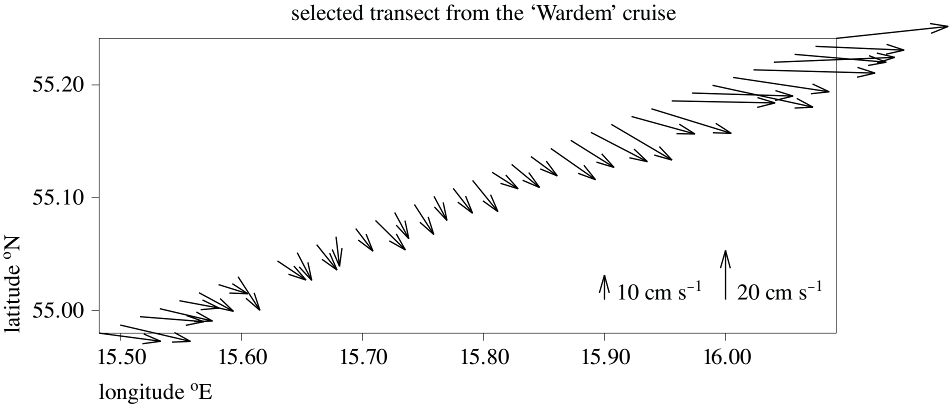

Fig. 2. Vectors of currents at 20 m depth with navigation as a reference

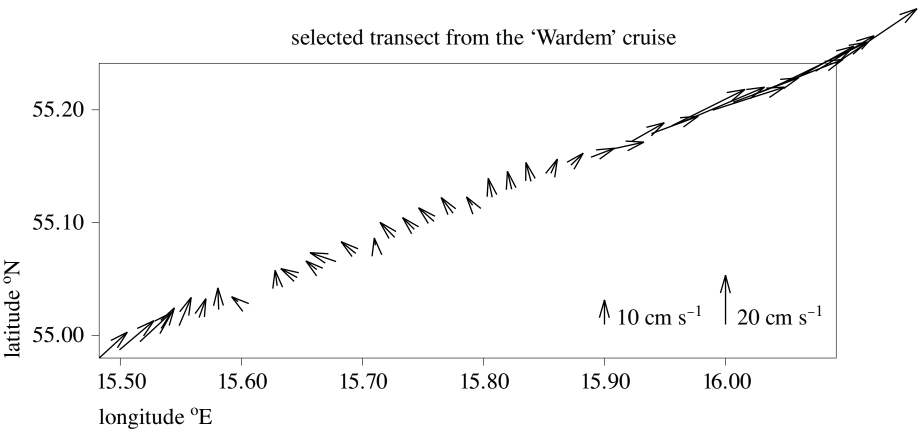

Fig. 3. Vectors of currents at 20 m depth with the bottom as a reference

4. Test for the misalignment angle

The ADCP user may well wonder whether spurious data are indeed due to the misalignment angle problem. A good and quick test for misalignment angle error is to subtract the water velocity vector with GPS as reference (Fig. 2) from the same vector with the bottom as reference when (Fig. 3) the ship is travelling at a uniform speed and in rectilinear motion. If there is misalignment, the solution is the same vector for all measurements (Fig. 4). If we assume the GPS velocity vector of the ship to be the real one, then there can be only one difference between the vectors with the bottom and navigation as references: ADCP does not have correct information about the angle $\phi(\alpha \neq 0)$. There may be two reasons for this: we do not know the actual mounting angle,

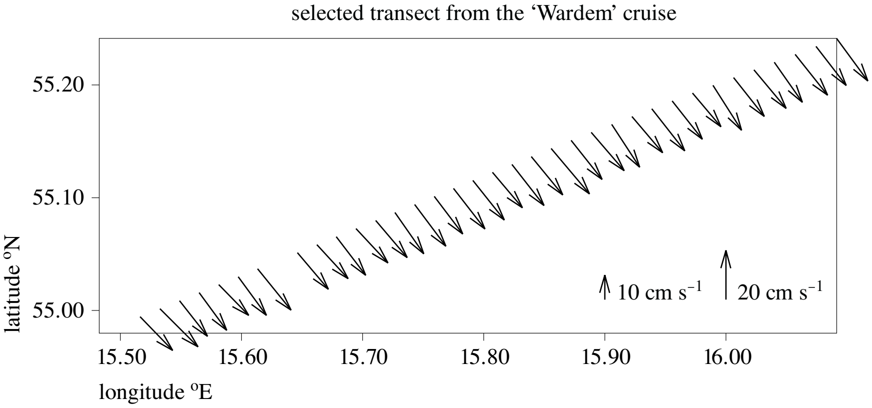

Fig. 4. Difference of vectors with navigation and bottom as references

and/or the information provided by the gyrocompass is incorrect (in the case of the 'Oceania' the first problem occurred because of an error in the installation procedure). Then, we can subtract this constant vector from the data to obtain the real (Fig. 5) absolute velocity with navigation as reference. Although this method is quick, it is inconvenient because each transect has to be treated separately. Moreover, it cannot be used in Arctic seas, where transects are more often like zigzags than straight lines, so it is impossible to find such a constant vector. A better way is to find the misalignment angle.

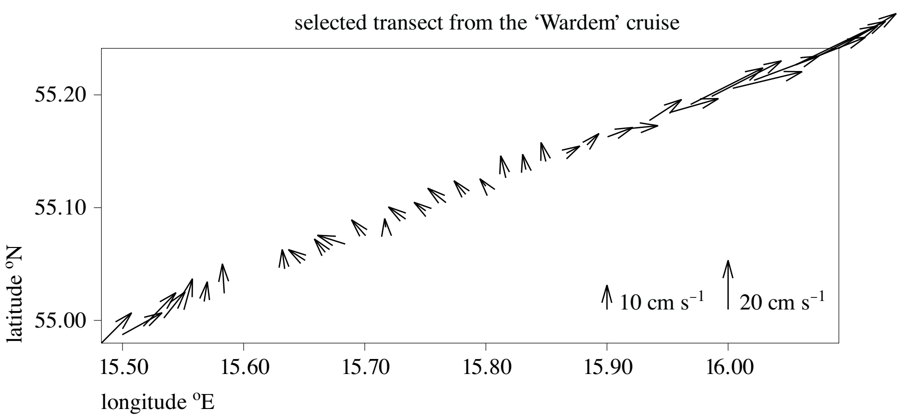

Fig. 5. Vectors of currents at 20 m depth with navigation as a reference after subtracting constant vector

5. Estimating the misalignment angle

The misalignment angle occurs if two coordinate frames assumed to be the same are not: one of the frames has rotated relative to the other by some unknown angle δ.

The vector components transformed from one coordinate frame to the other are expressed by

$$\begin{aligned} U_{\mathrm{OEN}} &= U_{\mathrm{OX'Y'}} \cos\delta - V_{\mathrm{OX'Y'}} \sin\delta, \\ V_{\mathrm{OEN}} &= U_{\mathrm{OX'Y'}} \sin\delta + V_{\mathrm{OX'Y'}} \cos\delta. \end{aligned} \tag{3}$$

So in ADCP we have (Joyce 1989, Pollard & Read 1989):

$$\begin{aligned} U_{\mathrm{w-nav}} &= U_{\mathrm{s-nav}} + \beta(U_{\mathrm{w-doppler}} \cos\alpha - V_{\mathrm{w-doppler}} \sin\alpha), \\ V_{\mathrm{w-nav}} &= V_{\mathrm{s-nav}} + \beta(U_{\mathrm{w-doppler}} \sin\alpha + V_{\mathrm{w-doppler}} \cos\alpha), \end{aligned} \tag{4}$$

where

β – an adjustment factor related to errors in transducer geometry,
$U_{\mathrm{w-nav}}$, $V_{\mathrm{w-nav}}$ – components of currents with navigation as reference,
$U_{\mathrm{s-nav}}$, $V_{\mathrm{s-nav}}$ – components of the ship's velocity,
$U_{\mathrm{w-doppler}}$, $V_{\mathrm{w-doppler}}$ – components of currents relative to ADCP.

The same equations can be written for the bottom reference. By comparing the components of velocity vectors with navigation and bottom references, the value of α can be computed. The results of implementing this method are illustrated in Fig. 6.

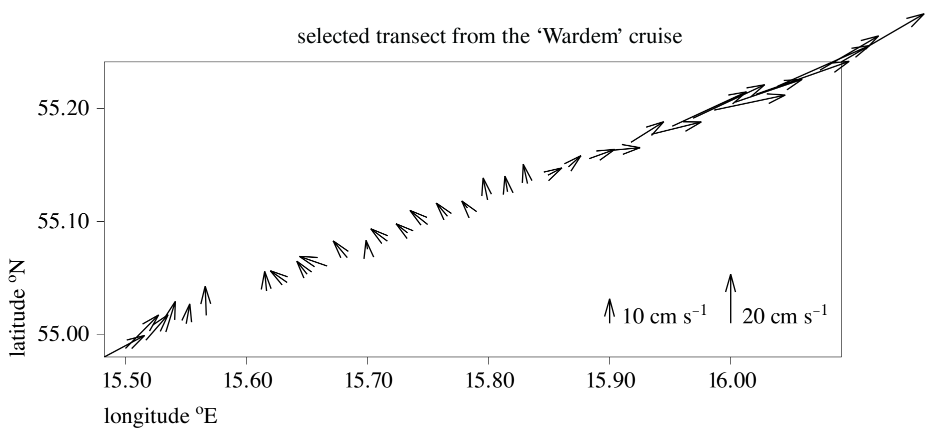

Fig. 6. Vectors of currents with navigation as a reference after calibration $\alpha = -2.64$, $\beta = 1.0004$

This estimation of the misalignment angle α when the classical gyrocompass is used is applicable only to one part of a cruise since $\alpha = \alpha(\gamma, \lambda)$ and $\gamma = \gamma(\omega, \varphi, V)$, where

λ – mounting angle,
ω – head,
φ – latitude,
V – ship's speed.

According to the manufacturer's information, the gyrocompass correction is expressed by the equation

$$\sin\sigma = \frac{V\ [\text{knot}]\ \cos\omega}{904[\text{knot}]\ \cos\varphi}, \tag{5}$$

where

σ – gyrocompass correction,
V – ship's speed.

We noticed that this correction was not equal to the observed value: the difference between σ for heads of 0° and 180° was too small. In order to estimate the misalignment angle, it is preferable to compute the sum of λ and γ as one angle rather than estimate σ. We therefore suggest an empirical method of estimating the correction for the entire cruise. A further reason in support of this concept is that the misalignment angle also depends on the initial resolution at which the ADCP is set, *i.e.* 1°, which leads to rather serious error.

The idea of the method is to fit the curve

$$f(\omega) = a\ \cos(b\ \omega + c) + d, \tag{6}$$

to ADCP data using the least squares procedure. All the data recorded when the ship was travelling at 4–6 knots were averaged into 10° heading bins. (For inclusion in the computation there had to be at least ten elements in a bin). The best result would be obtained if there were 36 such groups, but this is not possible on every cruise. For each 10° heading bin the misalignment angle was computed by comparing the velocity vector components with navigation and the bottom as references (Joyce 1989, Pollard & Read 1989); the least squares method was then applied to the resulting bins.

Comparison of both curves (Figs. 7, 8) shows that they cannot be treated as a universal way of estimating the misalignment angle. We hold the view that such curves must be computed for each cruise. One reason for this is that merely switching the ADCP on and off causes a difference in the d coefficient. None the less, this method does enable the misalignment angle to be computed for the entire cruise and data collected during previous cruises can be calibrated.

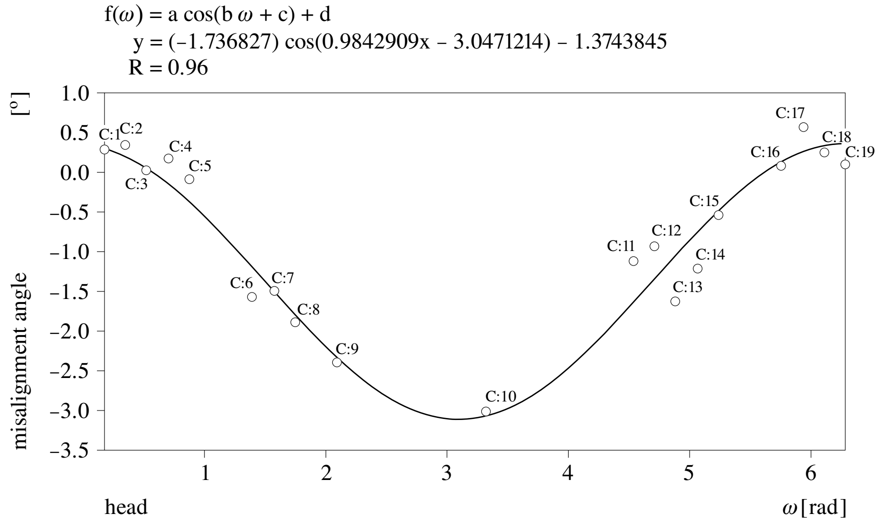

Fig. 7. Data and fitted curve for the 'Sty 1' cruise

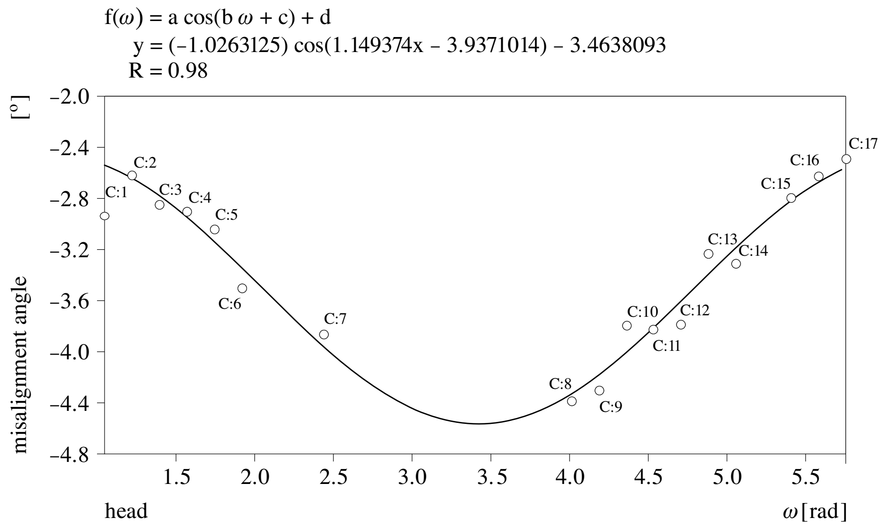

Fig. 8. Data and fitted curve for the 'Wardem' cruise

6. Conclusions

1. Subtracting vectors with GPS and the bottom as references is a good way of checking whether there are problems with misalignment.
2. Computing α in the way described by Joyce (1989) and Pollard & Read (1989) for the entire cruise is not possible because of gyrocompass errors.

3. The least squares fit procedure can be used to compute the cosinusoidal function – the calibration curve – for the entire cruise.
4. Such a curve is suitable for one cruise only.

References

Pollard R., Read J., 1989, *A method for ship-mounted acoustic Doppler profilers and the limitations of gyrocompasses*, J. Atm. Oceanic Technol., 6, 859–865.

Joyce T. M., 1989, *On the in 'situ' calibration' of shipboard ADCP*, J. Atm. Oceanic Technol., 6, 169–172.

King B. A., Cooper E. B., 1993, *Comparison of ship's heading determined from an array of GPS antennas with heading from conventional gyrocompass measurements*, Deep-Sea Res., 40, 2207–2216.

Griffiths G., 1994, *Using 3DF GPS heading for improving underway ADCP data*, J. Atm. Oceanic Technol., 11, 1335–1143.