Estimation of heading gyrocompass error using a GPS 3DF system: Impact on ADCP measurements*

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SUMMARY: Traditionally the horizontal orientation in a ship (heading) has been obtained from a gyrocompass. This instrument is still used on research vessels but has an estimated error of about 2-3 degrees, inducing a systematic error in the cross-track velocity measured by an Acoustic Doppler Current Profiler (ADCP). The three-dimensional positioning system (GPS 3DF) provides an independent heading measurement with accuracy better than 0.1 degree. The Spanish research vessel BIO Hespérides has been operating with this new system since 1996. For the first time on this vessel, the data from this new instrument are used to estimate gyrocompass error. The methodology we use follows the scheme developed by Griffiths (1994), which compares data from the gyrocompass and the GPS system in order to obtain an interpolated error function. In the present work we apply this methodology on mesoscale surveys performed during the observational phase of the OMEGA project, in the Alboran Sea. The heading-dependent gyrocompass error dominated. Errors in gyrocompass heading of 1.4-3.4 degrees have been found, which give a maximum error in measured cross-track ADCP velocity of 24 cm s^{-1}.

Key words: ADCP, heading, horizontal currents, Alboran Sea.

RESUMEN: ESTIMACIÓN DEL ERROR DE LA GIROSCÓPICA DEPENDIENTE DEL RUMBO MEDIANTE EL USO DEL SISTEMA GPS 3DF: IMPACTO EN LAS MEDIDAS DE ADCP. – Tradicionalmente, la orientación horizontal (heading) de los barcos se ha obtenido a partir de una giroscópica. Este instrumento todavía es utilizado en los barcos de investigación, pero tiene un error asociado de entre 2 y 3 grados, provocando un error sistemático en la velocidad medida por el perfilador de corriente por efecto Doppler (ADCP) perpendicular a la trayectoria del barco. El sistema de posicionamiento tridimensional GPS 3DF permite obtener medidas independientes del heading con una precisión mayor de 0.1 grados. El BIO *Hespérides* dispone de este nuevo sistema desde 1996. Por primera vez en este barco, los datos de este nuevo instrumento se han utilizado para estimar el error de la giroscópica. La metodología usada está basada en el método de Griffiths (1994), el cuál compara datos del sistema GPS y de la giroscópica a fin de obtener una función representativa del error. En este trabajo aplicamos dicha metodología a una campaña realizada en el mar de Alborán, durante la fase observacional del proyecto OMEGA. El error de la giroscópica dependiente del rumbo dominó. Se detectaron errores comprendidos entre 1.4 y 3.4 grados, que producen un error máximo de 24 cm s^{-1}, en la componente de la velocidad medida por el ADCP perpendicular a la trayectoria del barco.

Palabras clave: ADCP, orientación horizontal, corrientes, mar de Alborán.

INTRODUCTION

In the last 20 years the use of the Vessel Mounted Acoustic Doppler Current Profiler (VM-ADCP) has been continuously increasing within the oceanographers community. The scientific importance and the quantitative use of the ADCP data can be found in many recent works: Chereskin and Trunnell (1996) combined ADCP records with hydrographic data to obtain absolute geostrophic veloci-

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ties. Pollard and Regier (1992) and Allen and Smeed (1996) also used ADCP to compute the stream function that they use as a reference level for dynamic height derived from CTD data. Recently, Gomis *et al.* (2001) performed a multivariate analysis of hydrographic and velocity data to obtain the optimal estimation of both (dynamic height and current) fields through their mutual influence.

From a general point of view the quantitative use of ADCP data is strongly conditioned by two main aspects: i) the accuracy of the ship's attitude measurements (mainly positioning and heading) and ii) the post-acquisition data analysis (e.g. tidal filter, spatial objective analysis). In this paper we focus on the first issue, in order to evaluate and correct the ADCP velocity error induced by inaccuracy of gyrocompass heading measurements.

In a very brief description, the ADCP gives water velocity measurements with respect to the ship (Fore/Aft Port/Standboard) axis. After that, making use of the ship's heading (horizontal orientation), the velocities measurements are rotated to the actual North reference. Normally, the research vessels obtain the heading measurements from a conventional gyrocompass, which is the auxiliar instrument required by the ADCP to reference the collected velocities. It is well known that the conventional gyrocompass has an estimated error of 2-3 degrees, and introduces a systematic error in the measured ADCP cross-track velocities (Kosro, 1985; Pollard and Read, 1989). This systematic error is proportional to the ship's forward speed times the sine of heading error (Griffiths, 1994).

The handicap of inaccuracy of the conventional gyrocompass can be solved with the 'new' system based on Global Positioning System (GPS) differential carrier phase. This auxiliar instrument can be used to measure the orientation of a platform with an error of 1 mrd (Qin *et al*., 1992). A GPS 3DF model manufactured by Ashtech was fitted to the Spanish research vessel BIO *Hespérides* in 1996.

The main goal of this work is to make use (for the first time on this vessel) of the measurements of heading from the new system in order to: i) estimate the gyrocompass heading-dependent error, and ii) quantify its impact on ADCP velocity data recorded during a cruise performed in October 1996. The paper is structured as follows: (a) First a detailed description of logged data (gyrocompass, Ashtech heading, DGPS and ADCP data) is given; (b) the results section includes the quantification of gyrocompass error and its impact on velocity data measured by the ADCP; and (c) we finally we present our conclusions.

DATA SET

The OMEGA project (1996-1999, EU MAST program) was an interdisciplinary study focusing on the three-dimensional ageostrophic motion in mesosescale features (fronts and eddies) and its implication in biological processes. During its observational phase, ADCP velocities and hydrographic data were collected using a VM-ADCP 153.5 KHz and a Seasoar (undulating CTD) respectively. The cruise OMEGA-1 on board BIO *Hespérides* took place in the western Alboran sea from 1 to 15 October 1996. Three successive surveys were performed, each one consisting in parallel North/South legs, 10 km apart, covering a total area of 100 x 80 km^2 (Fig. 1).

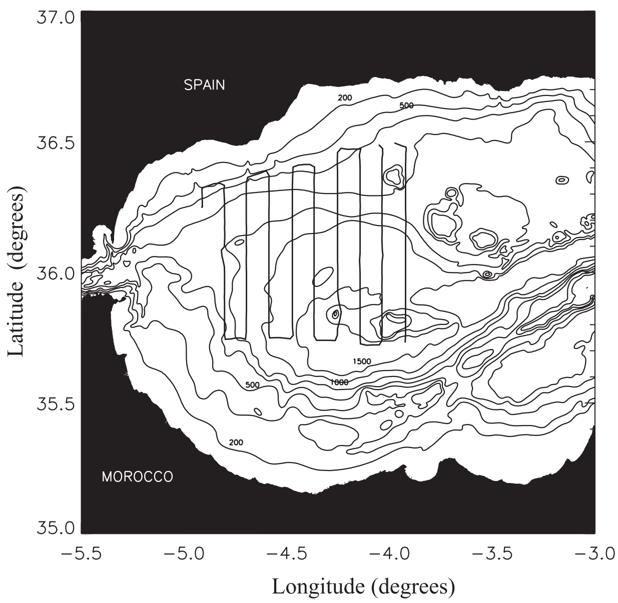

FIG. 1. – The Alboran Sea, with the bathymetry (thin solid lines, in metres) and the ship track of ADCP/SeaSoar during the OMEGA-1 cruise (thick solid line).

Heading data

Heading measurements were logged from two independent systems: conventional gyrocompass and GPS 3DF Ashtech, at a nominal 1Hz frequency. Additionally, DGPS data were recorded in real time with a Trimble GPS system. To illustrate the problem reported in this paper we use data from one of the surveys performed during the OMEGA-1 cruise. The same methodology and analysis were of course applied to the other two surveys.

Gyrocompass

Normally, the oceanographic vessels use a conventional gyrocompass to measure their horizontal orientation. In fact, this instrument is a gyroscope whose orientation is always forced to the north. A technical description of the operating principles of this instrument can be found in Griffiths (1994). A general description is also given in García-Górriz (1995). A Sperry MK37, model E gyrocompass is fitted on BIO *Hespérides*. As in any conventional gyrocompass, two types of errors affect this device: the instrumental error that should be minimised by the manufacturer through internal adjustment, and the inherent error of the gyrocompass moving over the surface of the earth. The latter can be estimated as a function of the ship's velocity, latitude and course (Bowditch, 1977):

$$\Delta = 0.0635S \cos C \sec L,$$

where S is the ship's velocity, C is the course, and L is the latitude. Working in a limited area (as in this case, between latitudes 35.7 and 36.5 N) and with an almost constant ship's velocity (8 knots, imposed by velocity SeaSoar limitation) the heading dependent error is dominant. This error can be minimised using an independent and more accurate heading measurement. For further technical details about the errors affecting convectional gyrocompasses see Griffiths (1994).

GPS 3DF

The GPS 3DF system measures heading, pitch and roll, as well as the position (latitude, longitude) using an array of four antennas (one master and three secondary). In addition, the system gives different parameters related to quality of data logged that help in the GPS data processing. Using the GPS signal from different satellites (at least four for each antenna), the system computes the signal differential carrier phase between the antennas, giving the three dimensional orientation of the platform. The heading measurement has an accuracy better than 0.01 degrees (Qin *et al*, 1992; King and Cooper, 1993).

Figure 2 shows a partial and schematic view of the BIO *Hespérides* platform with the antenna locations. Antennas 1 and 2 have fore-aft orientation and the installation distance between them is 4 metres. For antennas 3 and 4 there is the same distance, with port-stand orientation. The system must be calibrated in order to know the precise distance between the antennas. Table 1 gives the results of the calibration performed previously to the OMEGA cruise. The second column of this table corresponds to the exact horizontal distance between the diferent antennas; the third column reports the vertical distance.

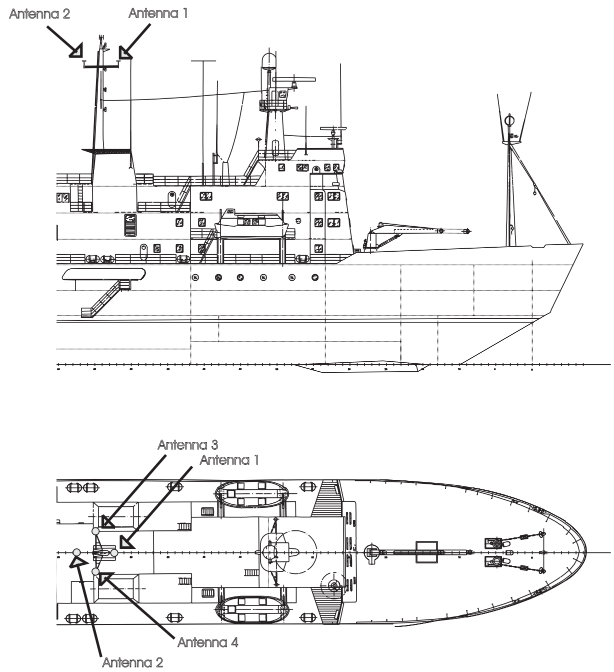

FIG. 2. – Schematic view of part of BIO *Hespérides*: the location of GPS 3DF antennas is indicated.

Until 1996, the only available source to obtain the heading on BIO *Hespérides* was the gyrocompass described in the previous section. Garcia-Gorriz *et al.* (1997) developed a data quality checking protocol for VM-ADCPs installed on platforms that only have a gyrocompass as a source of heading measurement. With the advent of new systems based on GPS differential phase carrier, a considerably more precise source can be used for ship's attitude measurement and consequently there is a potential

Table 1. Calibration results (distance in metres) of the GPS 3DF system perfomed while BIO *Hespérides* was in Cartagena harbour.

Vector	Calibration (distance XY)	Calibration (distance Z)
1-2	3.987	0.017
1-3	2.814	0.055
1-4	2.847	-0.021

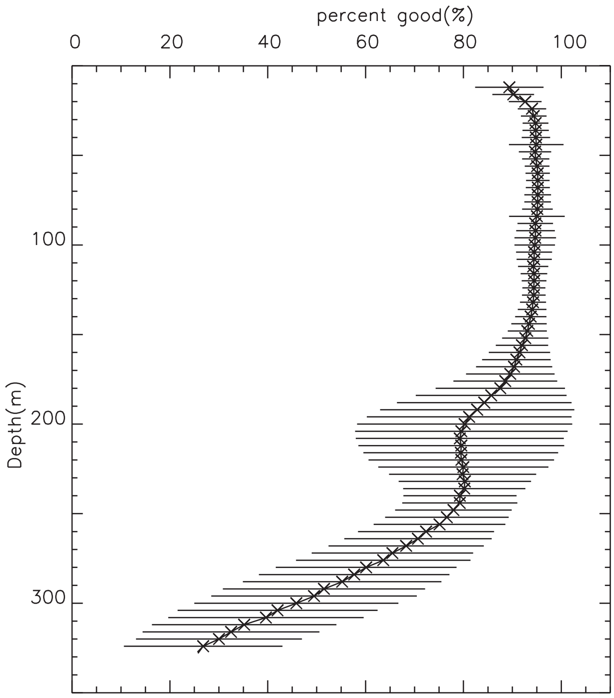

FIG. 3. – Mean (x) and standard deviation (__) of the ADCP percent good index for the survey 1.

benefit in quality for the velocity measurements collected with the ADCP.

The main problem of this new system is the intermittent availability of data caused by temporal satellite 'missing' situation. It produces gaps in data series that can be from a few seconds to a few hours. For this reason the system cannot be used as a permanent reference for ADCP (it should be taken into account that every ping launched by the ADCP needs a heading reference and normally a frequency of 1Hz is used). This problem can be solved using the scheme proposed by Griffiths (1994) that will be described later.

ADCP data and DGPS

Raw ADCP ensemble profiles were averaged along-track every 2.5 km (~10 minutes). A raw ADCP ensemble is defined as the averaged interval of return signals performed by the deck unit; in this particular case the interval was set to 2 minutes. The basic ADCP configuration was set to 80 with 4 m-thick bins each one, giving a maximum profile depth of 328 metres (the first cell was set to 8 metres). The percent good is a key parameter indicating the quality of recorded pings. It was set to 25%, which means that the unit deck requires a minimum of 25% of 'good pings' to interpret and ensemble them into velocity current (only a ping with a noise-to-signal ratio higher than an imposed threshold is considered a 'good ping'). The percent good averaged for survey one is represented in Figure 3. The high percentage (more than 80%) of good pings in the upper layer (up to 175-200 m) guarantees a priori a reliable acquisition step (in other cruises, a deficient acquisition caused by harsh meteorological conditions is reflected in a very low percentage at every depth, even in the upper layer). Below 200 m, the percentage decreases rapidly to values lower than 50%, alerting of the poor quality of data at these levels. Independently of the estimated gyrocompass heading error, this index should be taken into account when the ADCP data collected below 200 m are discussed.

Before the start of regular velocity data collection, the ADCP was calibrated following the methodology proposed by Pollard and Read (1989). This calibration consists in 6 zig-zag legs of 30 minutes duration with changes of 90 degrees between them in order to evaluate the misalignment angle (ϕ) and scaling factor (A). The resulting values were 0.75 and 1.02 respectively, but the usefulness of the misalignment calibration is reduced by the heading dependent gyrocompass error and consequently this calibration is insufficient to assess the final quality of ADCP data.

Another factor afecting the reliability of ADCP data is the accuracy in the ship's velocity that is computed from GPS positioning. It is well known the limitation in the accuracy of GPS positioning because of deliberate degradation by the U.S. Defense Department (producing an error of 10-100 metres in fixing position). This degradation was operating during the 1996 OMEGA-1 cruise, but no longer exists. Using a well-referenced station on land, differential correction for GPS (DGPS) can be obtained and used to significatively reduce this error. Because in 1996 degradation of GPS positioning was present, differential GPS correction broadcast by Raccal Skyfix was collected with a Trimble GPS system. This is important to ensure accurate ship's velocity, which has to be subtracted from raw ADCP velocity data.

RESULTS

Comparison of GPS 3DF and gyrocompass heading

Observations of heading from gyrocompass and GPS 3DF obtained during legs carried out in north

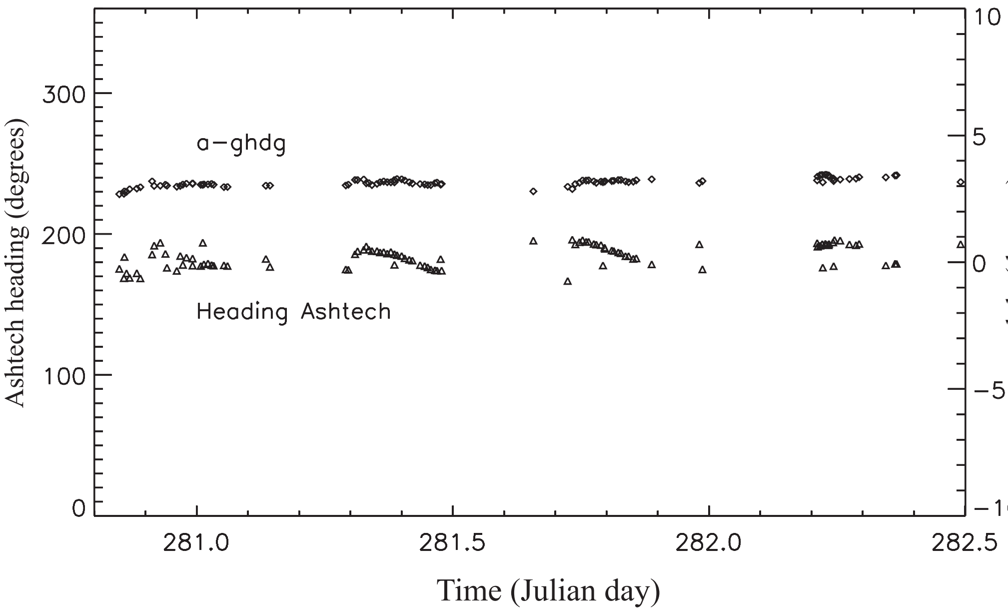

FIG. 4. – Differences between gyrocompass and Ashtech heading (diamonds) for heading in between [180-200] degrees (triangles) corresponding to a near 2 days period.

to south direction were compared. GPS heading data available during at least 10 minute periods were selected and averaged to plot differences with gyrocompass measurements. Figure 4 shows the GPS heading and the difference from gyrocompass for a period of 2 days. Differences of more than 3 degrees can be identified for a heading range of 180-200 degrees. As mentioned above, the GPS heading data were not available 24 h a day, so gaps in data series (where on absent indicator was set) were filled using the method described by Griffiths (1994). The method is based on the estimation of the gyrocompass error by fitting a function to a representative heading error series obtained during the cruise. Figure 5 shows the observed error for different headings (asterisk) and the fitted function (solid line), which can be written as:

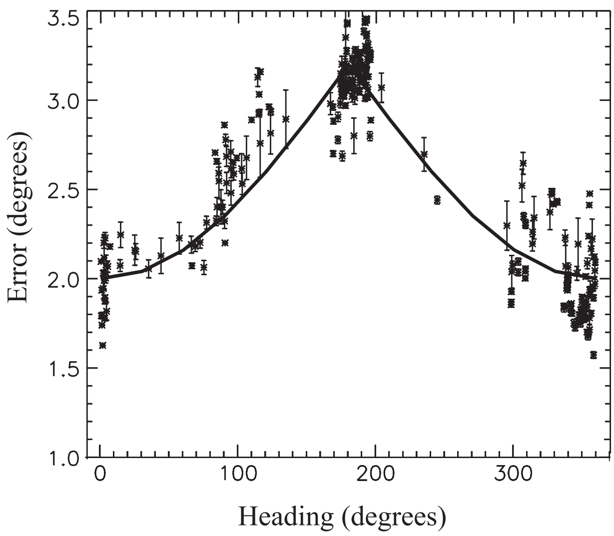

FIG. 5. – Heading dependent gyrocompass error computed (asterisk) plus associated error bars and fitted function (solid line).

$$Err = A * abs(\cos(\alpha)/2) + \Theta_{180}$$

$$A = (\Theta_0 - \Theta_{180})$$

where α is the heading, Θ_{180} is the mean gyrocompass error for 180 degrees heading (3.2 degrees) and Θ_0 is the mean gyrocompass error for 0 degrees heading (2 degrees). Taking into account that we worked in a reduced area (no large variation in latitude) and the ship's velocity was almost constant, the observed error can be associated with the heading alone. 87.6% of gyrocompass errors are between 1.4 and 3.4 degrees (Fig. 6), with a maximum frequency around 3 degrees (25.9%) and 1.7 degrees (21%) as second relative maximum. This is consistent with the bibliography that gives for a conventional gyrocompass an estimated error of between 2 and 3 degrees (Kosro, 1985). Figure 7 reveals the distribution of gyrocompass error over the domain. The clear dependence on heading is confirmed: sections run from north to south give the 3 degrees dominant error plotted in Figure 4, and sections from south to north reveal a range error of 1.5-2.5 degrees.

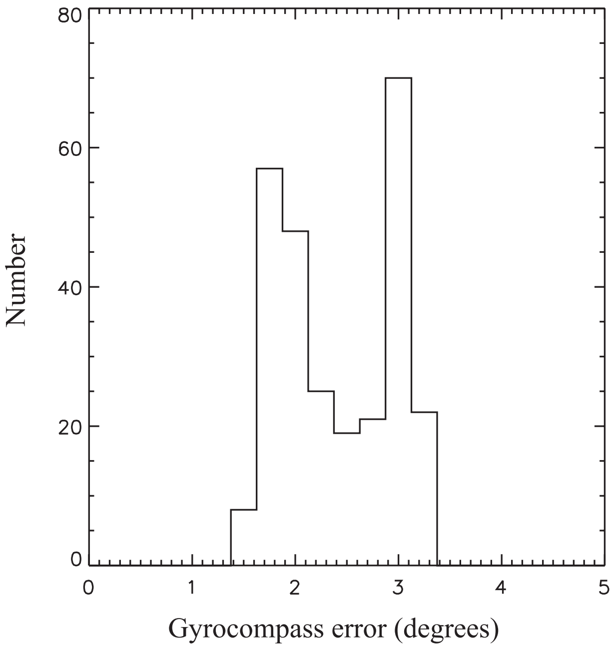

FIG. 6. – Histogram of gyrocompass error for nearly 3 days of data.

Impact on ADCP data

The different steps for processing ADCP data including gyrocompass heading error correction are as follow: the calibration parameters (A and ϕ) are applied in a first step to 2 minute averaged ADCP profiles. After that, gyrocompass error correction is performed over these profiles. Finally, velocity profiles are averaged at 10 minute intervals and the ship's velocity is obtained using DGPS positioning and subtracted to the averaged profiles for each interval (for further details about the ADCP processing methodology, see Allen *et al.,* 1996). Figure 8 presents the absolute current velocity field at 13 meters depth after replication of all the corrections mentioned above. The characteristic jet of Atlantic water coming from the Gibraltar strait can be identified at the northern part of the domain. A maximum velocity of 1.2 m s^{-1} was measured here, while velocity falls to 70 cm s^{-1} at the southern part.

The expression for cross-track velocity error induced on ADCP velocity by gyrocompass heading error is given in Griffiths (1994):

$$Verr=V_t *\sin(\Theta)$$

where V_t is the underway ship's velocity and Θ is the gyrocompass error. Using data from Figure 5 (only observed error data, not estimated from fitted function) we made an estimation of the velocity error induced on ADCP cross-track measurements (Fig. 9). A maximum value of 24 cm s^{-1} is obtained, alerting of the high magnitude of this kind of error. It should be remembered that in this particular case this error represents about 20% of the total velocity, but in areas where currents are weaker, the error could be of the same order of magnitude as the actual current. For instance, during a cruise performed

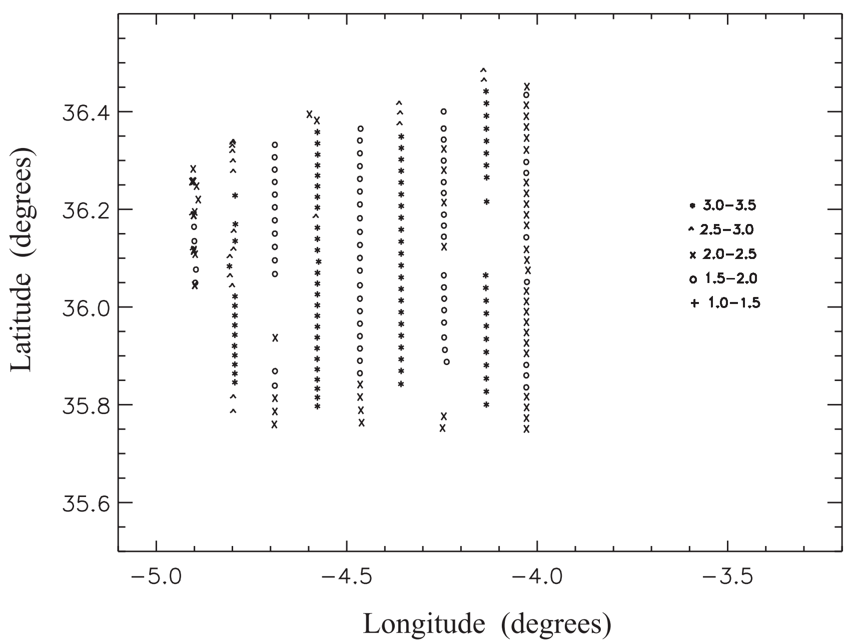

FIG. 7. – Horizontal distribution of gyrocompass error (degrees) along tracks.

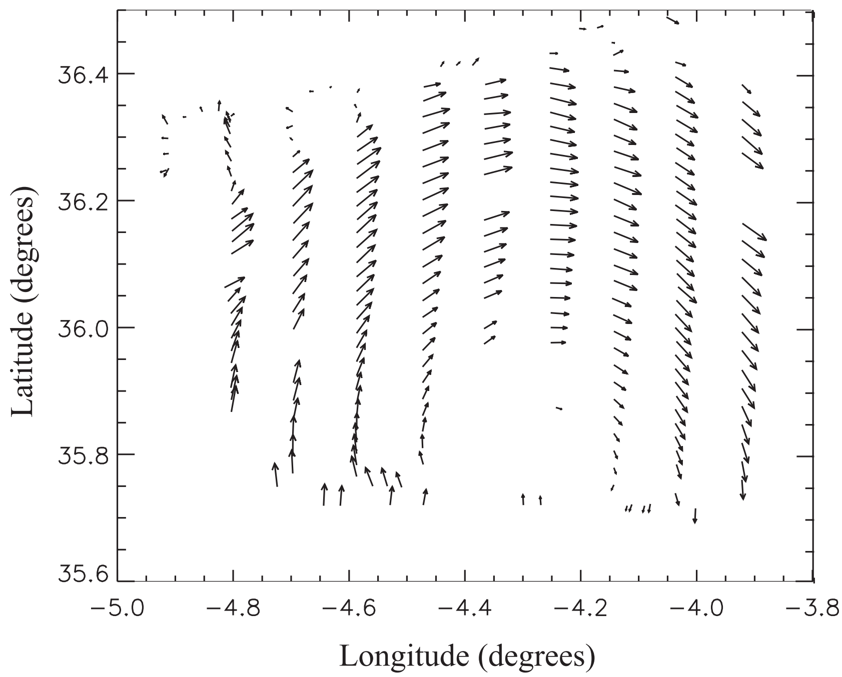

FIG. 8. – Absolute ADCP velocity at 13 metres depth.

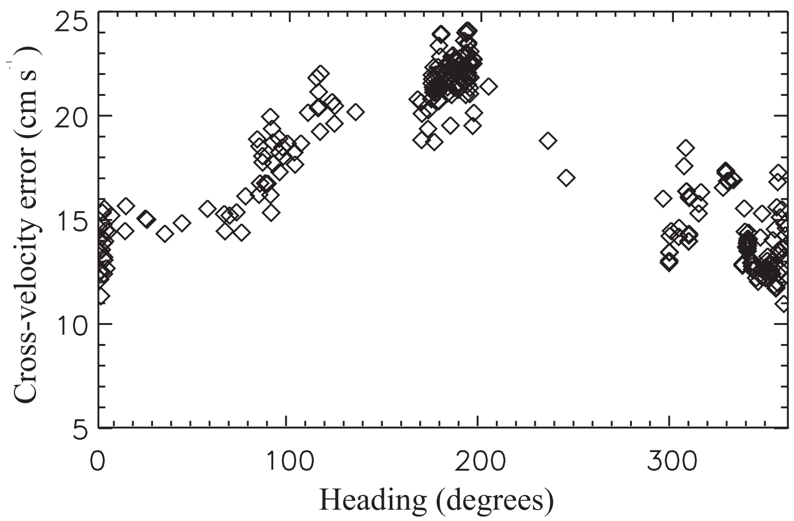

FIG. 9. – Induced errors in cross-track velocity measured by ADCP using computed error from Figure 5.

on board R/V *García del Cid* in the northwestern Mediterranean Sea in May 2000, ADCP velocities of about 30-50 cm s^{-1} were registered (Gomis, 2001). With this weaker current, the velocity error induced by inaccuracy of heading gyrocompass is more critical and has to be corrected; otherwise, the quantitative analysis derived from these ADCP data will not be reliable. As R/V *García del Cid* is also equipped with the GPS 3DF system, the heading correction was applied following the same methodology described in this work.

CONCLUSIONS

The heading dependent error in gyrocompass was evaluated for the first time on BIO *Hespérides* using precise measurements of attitude from a GPS 3DF system. A maximum error of 3.4 degrees was found on the gyrocompass, inducing a significant error (24 cm s^{-1}) in the cross-track ADCP measured velocity. Using a GPS 3DF system as a reference and fitting a simple function to the computed gyrocompass heading error, we obtain an estimation of this gyrocompass error at any time (mainly at a time when GPS heading is not available). Then, the corrected heading is used to process the ADCP data and improve their final quality. Thanks to this improvement pioneer quantitive studies have been carried out with the ADCP data set from this OMEGA-1 cruise (see Gomis *et al* (2001); Ruiz *et al* (2001)).

In general, errors in ADCP velocity of the order of 10-20 cm s^{-1} are critical for a quantitative use, so correction of the gyrocompass error has to be systematically performed. It should be noted that in areas where maximum velocities are not as large as in the Alboran Sea, the error velocity due to the heading gyrocompass error could be of the same order of magnitude as the measured current.

A complete analysis of ADCP data is much more complicated than has been described in this work (we should recall the problem of tidal and inertial filtering, the interpolation scheme, and so on). Nevertheless, it is important to emphasise that the quality of ADCP velocity can be improved considerably during the first stage of data collection and processing by making use of the GPS 3DF technology.

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