NOTES AND CORRESPONDENCE

Using 3DF GPS Heading for Improving Underway ADCP Data*

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ABSTRACT

Systematic error in the cross-track velocity measured under way from shipboard acoustic Doppler current profilers (ADCPs) can be attributed to error in measuring the ship's heading with a gyrocompass. Drift- and direction-dependent errors in marine gyrocompasses may amount to 2°–3°, yet they can be difficult to observe. A new system for obtaining attitude information using differential carrier phase measurements on signals from Global Positioning System (GPS) navigation satellites can provide a heading accuracy of 0.05°. This paper proposes a method of using these GPS heading measurements as a reference, with the gyrocompass as an interpolation device, to reduce the cross-track velocity error from a shipboard ADCP. The practical application of the method is illustrated by a long north–south section dominated by latitude-induced gyrocompass error, and a small-scale survey where heading-dependent errors in the gyrocompass dominated.

1. Introduction

Shipboard acoustic Doppler current profilers (ADCPs) rely on obtaining the ship's heading from a gyrocompass to rotate the velocity measurements from a ship-based frame of reference to earth coordinates. This note examines the systematic errors induced into the earth coordinate velocity components by errors in the ship's heading obtained from the gyrocompass. The RD Instruments ADCP fitted to RRS *Discovery* operates at 150 kHz, with a beam angle of 30° to the vertical, and data were gathered in 8-m bins, averaged over 15 min. RRS *Discovery* was fitted with two SG Brown Mk1000 gyrocompasses, and a new Ashtech 3DF GPS attitude-measuring system.

Gyrocompass errors are significant, as they can be 2°–3° or more (Bowditch 1977; King and Cooper 1993). The critical effect of gyrocompass error on ADCP absolute current measurements is to induce a spurious cross-track velocity component proportional to the ship's forward speed times the sine of the error angle. As a systematic error, it cannot be reduced by averaging, only by obtaining a more precise heading. A method is proposed for correcting the heading by referring the gyrocompass to the more accurate and stable measurement obtained from the 3DF GPS.

Most users calibrate their ADCPs for a misalignment angle; although this is a necessary procedure it is insufficient. The ADCP on RRS *Discovery* was calibrated against accurate navigation to obtain a heading misalignment angle following exactly the procedure in Pollard and Read (1989). The heading misalignment angle obtained includes gyro error as well as static errors; however, drift with time and latitude and heading-dependent errors in the gyrocompass reduce the usefulness of the misalignment calibration.

While gyrocompasses have been identified as a source of systematic error in determining cross-track velocities from ADCPs (Kosro 1985; Pollard and Read 1989), obtaining an accurate description of their error behavior has been difficult. With the advent of systems based on GPS differential carrier phase measurement, the orientation of platforms can now be obtained in real time, in three dimensions, with an accuracy of the order of 1 mrad (0.057°) (Qin et al. 1992). Such a 3DF GPS system, made by Ashtech Inc. of Sunnyvale, California, was installed in August 1992 on RRS *Discovery*. The performance of the system has been discussed in King and Cooper (1993); they conclude that the manufacturer's claim of a 1-mrad noise level in heading was probably met. They also showed that heading-dependent errors in the gyrocompass could exceed 2°. Here, we extend their error description to include gyrocompass drift while stationary and with changes in latitude.

Accurate 3DF GPS data are not yet available 24 h per day, and therefore cannot be used as the sole heading reference for an ADCP. The ship's gyrocompass must therefore be retained as an interpolation device,

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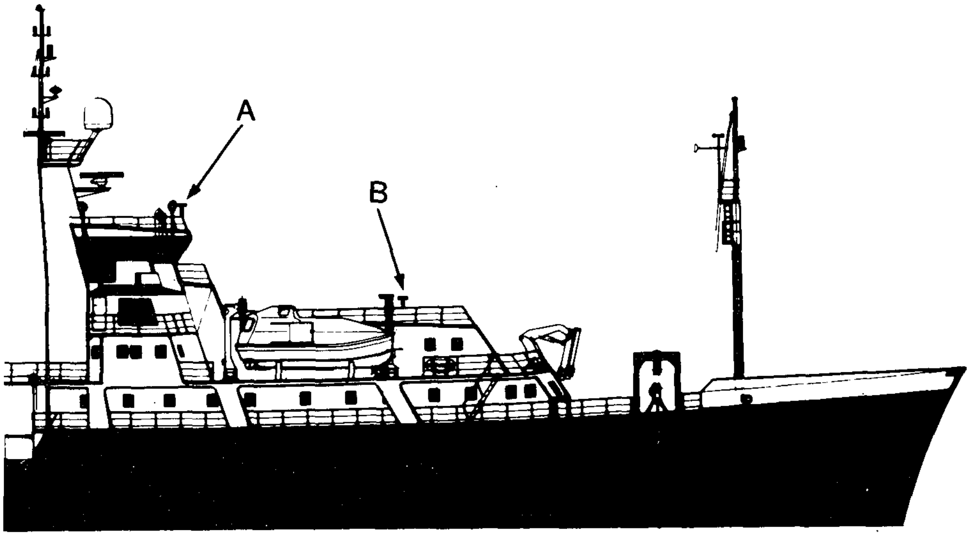

FIG. 1. A schematic of part of RRS *Discovery* showing the positions of the Ashtech 3DF GPS antennas on the starboard side of the ship: *A* on top of the bridge deck, and *B* on the boat deck. The distance from *A* to *B* was 10.80 m. The portside antennas had the same fore–aft positions, and were separated athwartships by some 6.53 m.

referenced to the more precise and stable 3DF GPS. A practical approach to providing a suitable reference from sparse 3DF GPS data that is designed to cope with long gaps during which course changes could occur (hence varying heading-dependent errors) is discussed. A method that combines recent error history with a model of the gyrocompass heading-dependent error, tuned using two parameters on a daily basis, is presented as an interim solution to providing a continuous heading reference source.

We also consider the consequences of gyrocompass error on ADCP velocities. First, we use data from a crossing of the Drake Passage in the South Atlantic Ocean where latitude-induced gyrocompass error dominated. Second, a small-scale ADCP box survey shows the severe effects of heading-dependent errors.

TABLE 1. Vector lengths for the Ashtech 3DF GPS attitude system; calibration at Stanley.

Vector	Meters	Change from Brest calibration
7 November 1992		
1 > 2	6.530	−0.010
1 > 3	10.807	−0.006
1 > 4	12.624	−0.001
8 November 1992		
1 > 2	6.532	−0.008
1 > 3	10.813	0.000
1 > 4	12.628	0.003

2. 3DF GPS—A new method for obtaining ship's heading

The Ashtech 3DF GPS system uses differential carrier phase measurements across an array of four GPS antennas to provide real-time attitude measurement (Qin et al. 1992; Van Grass and Braasch 1992). The basis of the system is a 24-channel GPS receiver, configured in four 6-channel banks, with processing firmware to determine the phase relationship between three of the antennas (2, 3, and 4) and the master antenna (1). Given a knowledge of the vector baseline lengths between the antennas in 3D space, determined when the vessel was stationary, the attitude, that is, pitch, roll, and heading, can be determined while under way. On RRS *Discovery,* two antennas (3 and 4) are mounted on the boat deck, forward of the bridge, and two on top of the bridge (1 and 2), Fig. 1. Two surveys of the baseline vector lengths were carried out while tied up to a large pontoon at Stanley, Falkland Islands, on 7 and 8 November 1992. The results are shown in Table 1, together with the differences from a calibration in August 1992 at Brest, France.

A major problem with the 3DF GPS measurement is intermittent data. A minimum of four satellites need to be locked on to each of the four antennas to determine the ambiguities in the phases at each antenna *before* the system can begin to provide attitude information. When the ambiguities have been determined, the system can cope with each antenna locked to three satellites. The receiver outputs a status flag (attf) to indicate lock; this was used to select valid attitude data, and was followed by a screening procedure based on the pitch and roll data being within acceptable limits. The overall effect was that only 43% of 15-min intervals during a typical day at latitude 68°S had acceptable GPS attitude data.[1]

3. Gyrocompass errors

To appreciate the sources of error in a gyrocompass, it is necessary to describe briefly the basic principle of the instrument. A free gimballed gyroscope will, due to gyroscopic inertia, maintain its orientation in space if no external forces are applied to it, if we neglect friction and other mechanical imperfections. This gyroscope may be converted to a gyrocompass by ensuring that the orientation in space is always toward north. To do this, a feedback control loop is employed. In purely mechanical gyrocompasses this feedback is obtained through the force of gravity on weights added to the gyroscope and through the action of precession and a system of reservoirs and tubes filled with mercury known as a mercury ballistic. A detailed description of the operation of mechanical gyrocompasses can be found in Bowditch (1977). The SG Brown Mk1000 gyrocompass does not use purely mechanical feedback; instead it directly measures the tilt of the gyro element, typically a few minutes of arc. The tilt arises from components of the earth's rotation imposed on the gyro spinner when it is not aligned with the north–south meridian, and is used to precess the gyro back to the true meridian. Instrumental errors occur in the gyroscope mode (also known as the directional or open-loop mode) due to friction and other mechanical imperfections, and are minimized by the manufacturer through fine adjustment of the suspension wires inside the gyro element (J. Warren 1993, chief engineer, SG Brown, personal communication).

Errors in the gyrocompass mode (also known as the north-seeking or closed-loop mode) are inherent in a gyro moving over the surface of the earth, and are in addition to the instrumental errors described above. Only the inherent errors are compensated by two user controls on a gyrocompass, one for speed and one for latitude. The errors that relate to the gyroscope mode are not compensated. In a correctly set up gyrocompass, the inherent error is

$$\Delta = 0.0635 S \cos C \sec L, \qquad (1)$$

where Δ is the gyro speed error in degrees at a speed of S knots, and a course of C degrees, at a latitude L degrees (Bowditch 1977).

This error, inherent to all gyrocompasses, should be compensated by the speed and latitude user controls but only if the gyrocompass had been correctly adjusted mechanically. The gyrocompasses on RRS *Discovery* were adjusted in the open-loop mode by the manufacturer in the Northern Hemisphere (54°N). However, they should have been readjusted for operation in mid to high southerly latitudes (52°–69°S). The correct adjustment procedure for gyrocompasses requires the open-loop errors to be minimized mechanically *before* the control loop is closed and the gyrocompass used in its north-seeking mode. These errors cannot be minimized by the untrained user. However, the adjustments can be made by gyro service engineers during port calls, taking less than half a day (J. Warren 1993, personal communication).

4. Gyro error—Identification using 3DF GPS

a. Gyro drift while stationary

Observations of the ship's heading from the gyrocompass and from 3DF GPS were made while stationary at Stanley, Falkland Islands, at a latitude of 52°S. The heading was approximately 270°. Taking the long-term drift of the 3DF GPS system to be negligible (confirmed by the repeatability of the baseline vector calibration discussed earlier), the difference between the 3DF GPS heading and the gyrocompass can be considered purely as drift of the gyrocompass. The slow drift, Fig. 2, over periods of several hours to days reached a maximum of 0.84°. There is some evidence for a diurnal variation. This may be due to ambient temperature variations caused by daytime warming of the wheelhouse affecting the gyrocompass (J. Warren 1993, personal communication). The maximum error was at about 1200 UTC, or 0800 local solar time (LST), with the minimum at 2300 UTC, 1900 LST, which is consistent with solar heating. Superimposed on the longer-term drift is a smaller high-frequency variation of less than 0.1°, some of which is due to the quantization noise (0.1° resolution) of the gyrocompass.

b. Gyro drift with latitude—Drake Passage section

On a section southward across Drake Passage the course was steady (about 165°), as was the speed, about 8 kt. Yet a change in the difference between the 3DF GPS and gyrocompass heading took place over the 3 days of the passage from 52° to 61°S. The manual gyro latitude compensation control was kept set to the correct latitude, and the speed compensation was kept at 8 kt. The time series of the drift is shown in Fig. 3, the heading difference having been linearly interpolated across absent data and a low-pass filter with a cutoff of 75 min then applied to the difference.

For an ideal gyrocompass, (1) predicts a gyro error of −1.00° for 165°/8 kt at 61°S, and −0.77° at 52°S. The change seen in Fig. 3 is much larger than the predicted 0.23° and is believed to be due to suboptimal

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[1] A firmware upgrade to the 3DF GPS receiver in March 1993 raised the data coverage to 95% of 10-min time slots at a latitude of 45°S. We conclude that our poor data coverage was due to bugs in the firmware, and not to poor antenna siting.

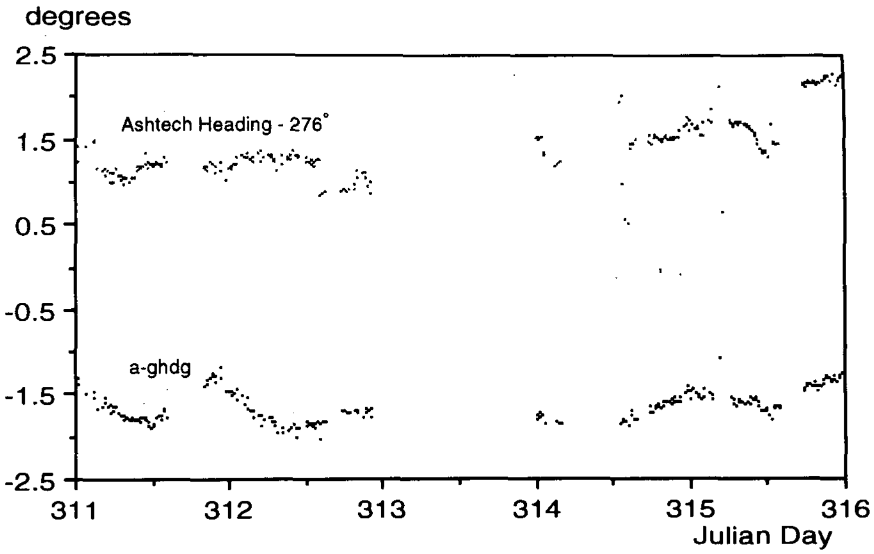

FIG. 2. A 5-day time series of the heading from an Ashtech 3DF GPS receiver and the difference between the Ashtech and the Gyro heading, a-ghdg. The data were obtained while moored to a large pontoon at Stanley, Falkland Islands. The effect of a short test of the bow thruster on day 314 can be seen as a rapid change of heading in the Ashtech heading, but the difference remains unaffected. The short-period fluctuations are of the order of 0.05°, while the fluctuations at longer periods approach 0.8°.

speed compensation, due to an inadequate nulling of the mechanical errors in the open-loop mode (J. Warren 1993, personal communication).

c. Gyro heading-dependent error

A heading-dependent error curve was compiled from data gathered from day 321 to 334 (November 1992), and is shown in Fig. 4a. The form of this curve is similar to that in King and Cooper (1993), but with an offset of about 2.5°. This change was either due to time (ca. 2 months), or more likely due to latitude (61°S vs 37°N).

At 1600 UTC on day 334 an interruption to the ship's ac power supply caused all instruments to lose their supply. Upon restarting, it soon became clear that the heading-dependent error had changed, it did not follow the error curve of Fig. 4a. The new error curve is shown in Fig. 4b. The gyrocompass had been

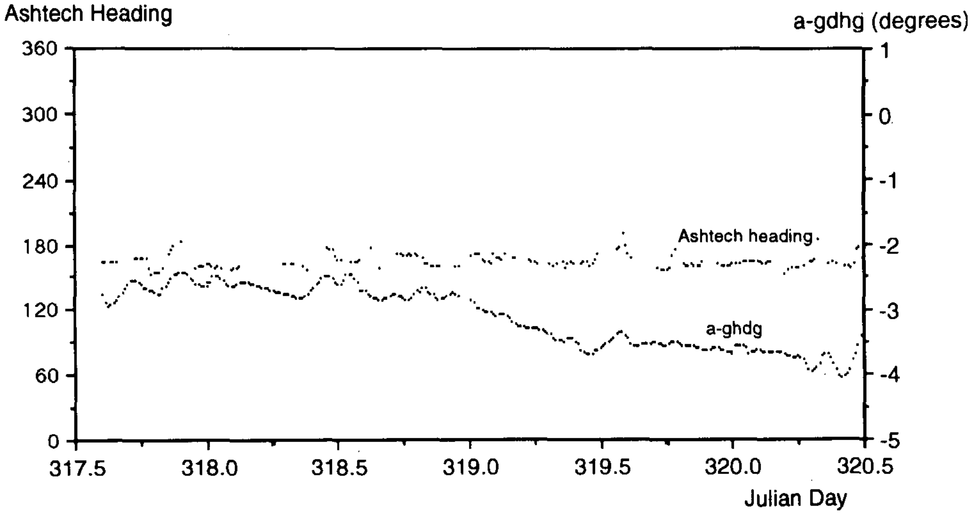

FIG. 3. Ashtech 3DF GPS heading and the difference (a-ghdg) for the 3 days crossing Drake Passage. The slow drift amounts to 1.5°.

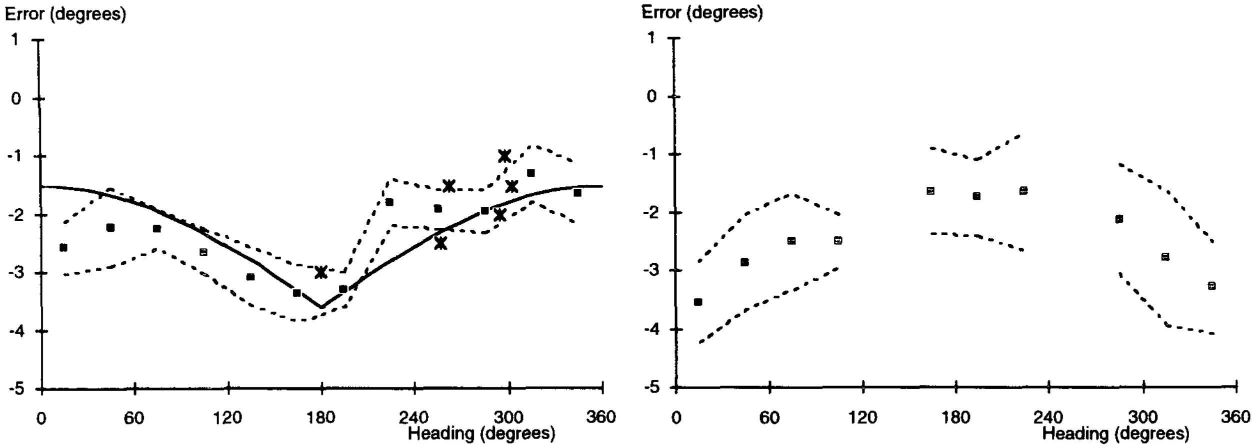

FIG. 4. (a) The error of the number 1 gyrocompass on RRS *Discovery* from data gathered from days 321 to 334 in azimuth bins of 30° (squares). The dashed lines indicate one standard deviation either side of the mean. Astronomical azimuth observations are shown as asterisks. The error model fitted to these data is shown as a solid line. (b) Heading-dependent error of the number 1 gyrocompass on RRS *Discovery* after a power failure and a restart of the gyro on day 334. The heading with maximum error has shifted from 180° to 0°.

switched on in the United Kingdom on 19 August 1992, and had been powered-up continuously between the measurements of King and Cooper (1993) and those reported here. The reasons for this change are not yet entirely clear.

5. Developing an algorithm to make best use of the 3DF GPS data

Having used the 3DF GPS system to determine gyro drift and the dependence on latitude and course, the next stage was to apply corrections to the gyrocompass data for use with the ADCP. First, a scheme for obtaining quasi-continuous data from the 3DF GPS was needed to cope with gaps that spanned periods of seconds to tens of minutes. Typically, in 24 h at latitude 68°S, there were 29 gaps of over 1 min in the 3DF GPS coverage—*irrespective of quality.* Of these, six were greater than 10 min. While gaps in the 3DF GPS heading can be tolerated on long sections on a steady course, and dealt with by linear interpolation, box survey patterns with several course changes per day require a more complex technique. The approach developed and described here is based on postprocessing the heading data. Whenever available the 3DF GPS heading correction is used; if it is not available a heading-dependent error curve, termed the "error model," is used as a method of interpolation. The scheme is shown in the flowchart of Fig. 5. This algorithm also uses an estimator based on the time history of the heading to weight model and observed corrections when heading changes of less than 90° occur between 15-min time steps. The error model does not handle short-term transient errors following a course change in the absence of 3DF GPS data. They could be dealt with by an addition to the model when further data on the transient behavior of the gyrocompass become available.

a. Error model

The error model is an ad hoc analytical approximation to the observed heading-dependent error of the

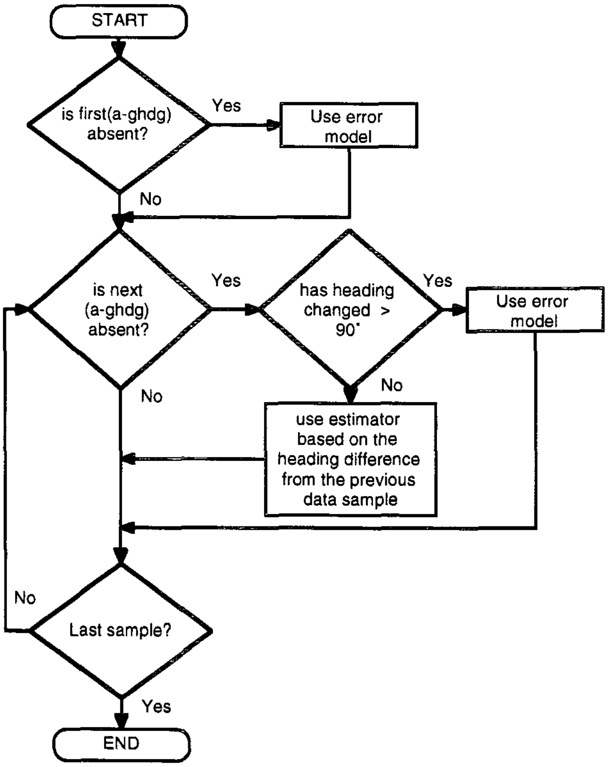

FIG. 5. Flowchart for interpolating across gaps in the 3DF GPS coverage using a heading-dependent error model.

gyrocompass. The analytical form in (1) was not used because the real data indicated a cusplike behavior at a heading of 180° [Fig. 4a and King and Cooper (1993)]. Instead, the heading error was modelled as

$$\text{gyroerr} = \Theta \operatorname{abs}\left[\cos\left(\frac{\text{heading}}{2}\right)\right] + \Theta_i,$$

$$\Theta = \Theta_m - \Theta_i, \quad (2)$$

where Θ_m is the error at a heading of 0°, and Θ_i is the error at 180°. Specifying these two model parameters allows for change in the magnitude of the error and its absolute value, for example, due to changes in operating latitude. A comparison of the error model and actual data is shown in Fig. 4a. Another reason why the analytical form (1) was not used was because our data, Fig. 3, had shown a much larger change than predicted in the latitude-induced gyro error.

Following the power interruption to the gyro on day 334, a change to the error model was required to describe the new heading-dependent error. The change was from a cosine- to a sine-dependent error in (2). A listing of Θ_m and Θ_i is given in Table 2, which illustrates the day-to-day variation in the gyrocompass error and the magnitude of the error difference between headings of 0° and 180°.

TABLE 2. The Θ_m (error at 0°) and Θ_i (error at 180°) model parameters for the heading-dependent error.

Julian day	Noon latitude (S)	Θ_m	Θ_i	Comments
330	66°58′	−1.50°	−3.50°	
331	66°57′	−1.68°	−3.47°	
332	66°52′	−1.82°	−3.94°	
333	66°30′	−1.82°	−3.94°	
334	67°05′	−1.11°	−2.89°	
335	67°18′	−2.77°	−1.34°	Change after power failure
336	66°57′	−3.49°	−1.94°	
337	68°04′	−3.76°	−2.00°	
338	67°44′	−3.60°	−1.83°	
339	67°27′	−3.78°	−2.03°	
340	68°33′	−3.70°	−1.89°	
341	68°01′	−4.34°	−1.81°	
342	67°36′	−4.00°	−1.80°	
343	67°48′			
344	67°36′	−3.77°	−1.80°	Θ_i nominal as no courses near 180°
345	64°20′	−3.67°	−1.80°	Θ_i nominal as no courses near 180°
346	61°26′	−3.13°	−1.80°	Θ_i nominal as no courses near 180°
347	57°25′			
348	54°50′	−2.67°	−1.00°	
349	51°19′	−2.00°	1.00°	

b. *Estimator for determining the balance of model and observed error*

Where the difference in heading between an absent data cycle and a previous good (or estimated) data cycle is less than 90° the algorithm uses an estimator based on part previous observation and part error model, the weighting determined by the magnitude of the heading difference between the current and previous observation. This estimator is empirical, and unlikely to be optimal; however, it does meet the criteria of responding quickly to large heading changes yet remaining close to previous 3DF GPS corrections while on steady courses. The effective time constant of this estimator depends on heading change, varying from 15 min (one time step) for a change of 25°, to 120 min for a heading change of 3.8°.

The estimator used is

$$\Delta h = \text{heading}\,(n) - \text{heading}\,(n-1)$$

$$\text{datafrac} = [1 - \sin(\Delta h)]^2$$

$$\text{modelfrac} = 1 - \text{datafrac}$$

$$\text{error} = \text{datafrac} \times [\text{a-ghdg}(n-1)] + \text{modelfrac} \times \text{model error function for heading}\,(n),$$

where datafrac is the weighting used for the previous real (or estimated) data cycle, modelfrac is the weighting used for the error model estimate of the direction-dependent error, and a-ghdg is the difference between the 3DF GPS and gyrocompass heading.

c. *Testing of the algorithm—Response and sensitivity*

The algorithm was tested for its ability to follow changes in ship's heading when no 3DF GPS data were available, and for the reasonableness of the predicted error of the gyrocompass. Figure 6 shows a 12-h section of data on day 334 where there were three changes of course and four periods on reasonably steady heading. The gyrocompass error (a-ghdg) is a composite of the error model (faint line) and the real data (solid line). Note that during periods on a steady course, for example, 120–360 min, the error algorithm approaches a linear interpolation between the real data points. However, simple linear interpolation would not resolve the course change at 390 min, and would give a poor correction (up to 1.5° in error) for 2 h. In contrast, the error model algorithm responds to the course change; before the course change, the real data are propagated forward as the course variations were small. In response to the change of course, the algorithm switches to the error model, producing a more realistic representation of the gyrocompass error. The error model in Fig. 6 was tuned with Θ_m of −1.11° and Θ_i of −2.89°, the parameters being estimated from 3DF GPS data that day.

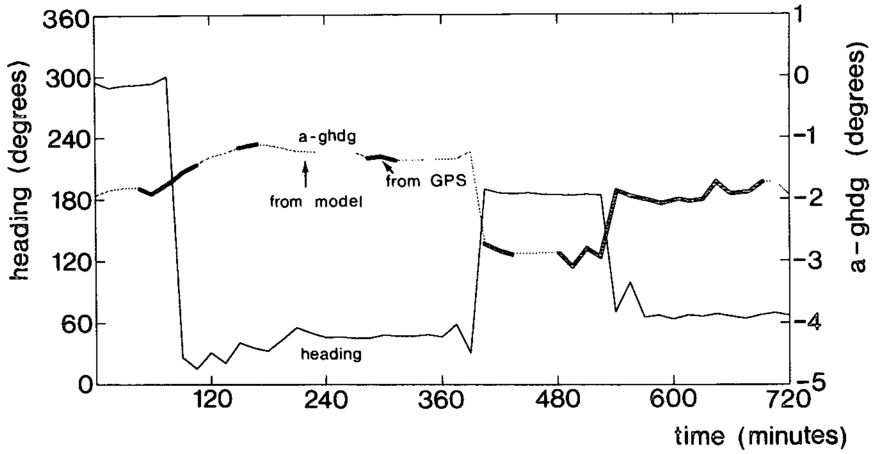

FIG. 6. A 12-h section of ship's heading from the gyrocompass with the gyrocompass error a-ghdg from 3DF GPS measurements (solid) and the estimator model (faint). The figure shows the advantage of such a model over linear interpolation during changes in course.

6. Effect of gyro errors on ADCP data, and correction using 3DF GPS

a. Latitude-induced errors—Drake Passage section

The section across Drake Passage cuts across the Antarctic Circumpolar Current (ACC) that flows from west to east, but with a significant northerly component, and several flow reversals. These characteristics make it difficult to show convincingly that applying the heading correction to the ADCP data gives the "correct" values for the current, especially as there was no independent measurement as a comparison. The large easterly flow conceals any bias in the ADCP cross-track velocity due to the heading error for individual measurements. A clockwise heading error, as shown in Fig. 3, gives rise to an error velocity to the left of

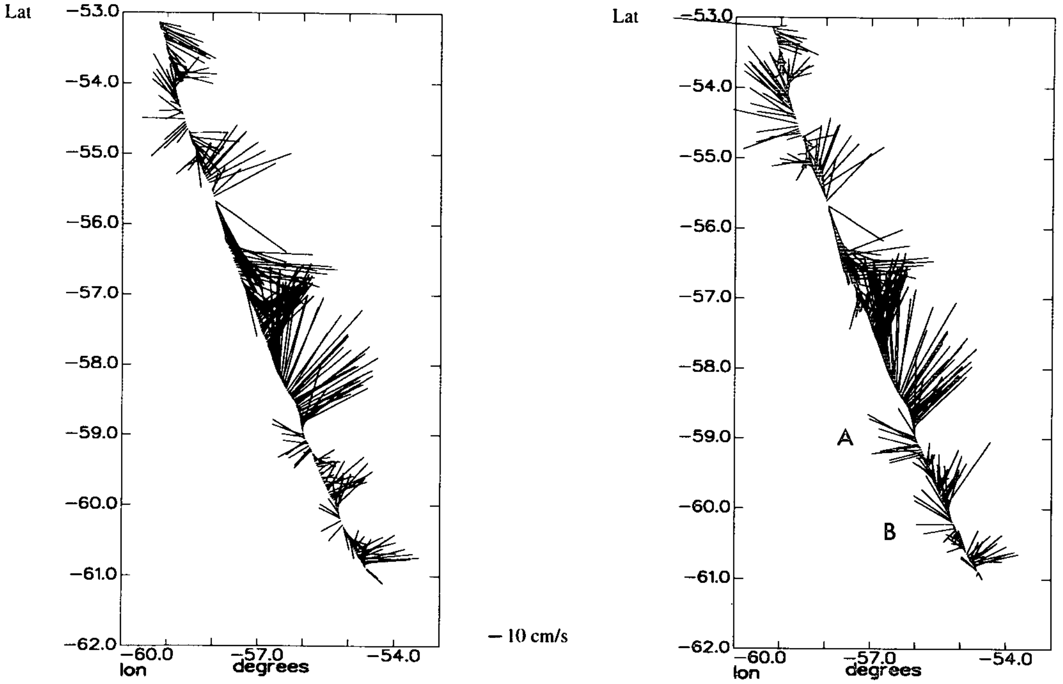

FIG. 7. (a) Currents at 53 m across Drake Passage, ADCP calibrated, but not corrected for gyro error. (b) As (a) but with a correction for the gyro drift shown in Fig. 3. The effect of the error, a bias to the left of the track, is most clearly seen at the southern end of the track in the increased westerly flow at *A* and *B*.

the track (i.e., east). The current vectors at a depth of 53 m, uncorrected for gyrocompass drift, are shown in Fig. 7a. They show the flow to be predominantly to the east and north, with three occasions of significant flow reversal, near 54°–55°S, 59.5°S, and 60.2°S. The mean east component was 10.95 cm s^{-1}.

After correction for the gyrocompass drift, the current vectors in Fig. 7b show a clear increase in the westward component (both in terms of magnitude and along-track extent) at the flow reversals. The mean east component was reduced to 7.10 cm s^{-1}, the difference of 3.85 cm s^{-1} amounting to 35% of the uncorrected mean current. This shows that deriving cross-track volume transport estimates directly from ADCP measurements is very prone to gyrocompass-induced error. The easterly volume transport in the upper 400 m using the corrected mean flow is 25 Sv (10^6 m^3 s^{-1}) against 38 Sv for the uncorrected data.

The difference between the calibrated, but uncorrected for gyrocompass error, and the fully corrected east velocity component is shown in Fig. 8. Near the calibration latitude of 52°S the error of −2.5 cm s^{-1} is due to the heading-dependent gyro error on the course of 165° compared to the calibration courses of 135° and 225°. By 60°S the velocity error due to latitude-induced gyrocompass error reached −9 cm s^{-1}.

b. Heading-induced error

The effect of heading-dependent error upon the ADCP currents during a small-scale grid survey in the Bellingshausen Sea are shown using a fragment of data near two 90° turns. The ship's tracks alternated north and south, spaced 15 km apart, with a joining section running east. As shown in the heading-dependent error curve in Fig. 4, this alternating north–south track gives maximum change in the heading error. This is especially insidious because reciprocal tracks cannot therefore be used to completely average out gyrocompass error. Any heading-independent error will be averaged—for example, a fixed gyro bias, or the ADCP transducer misalignment angle—but heading-dependent gyro error will remain and may only be removed by correcting the gyro data.

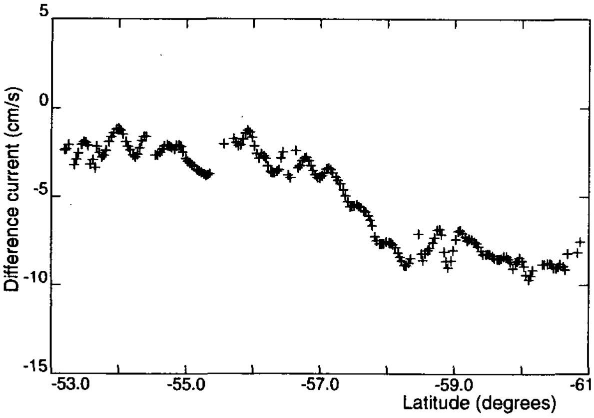

FIG. 8. Difference between the calibrated ADCP east velocity component with and without correction for the gyro error during the crossing of Drake Passage.

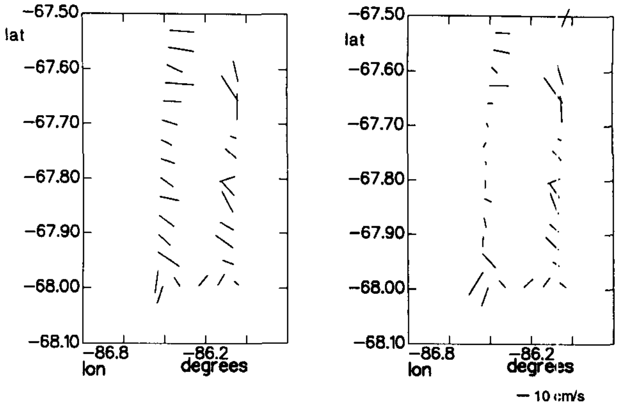

FIG. 9. Vector plots of absolute currents along part of the track of a small-scale survey on RRS *Discovery* in November 1992, with the left leg running in a southerly direction, and the right leg running north. Currents computed without compensating for the gyro error are shown on the left (a), and the currents after compensation as determined from 3DF GPS are shown on the right (b). The effect of a heading error producing spurious currents to one side of the track can be seen clearly in (a) where there is a tendency for the currents to be to the left of the ship's track. This effect is reduced in (b) after compensation for gyro error.

Figure 9a shows the current vectors at a depth of 101 m along part of the track prior to correction for the heading error. A strong convergence is evident; on each of the three legs, there is a consistent current to the *left* of the ship's track. On the south-going leg, the mean indicated current was 11.9 cm s^{-1} to the *east,* while on the north-going leg the mean indicated current was 7.7 cm s^{-1} to the *west.* When corrected for the heading error (Fig. 9b), the mean current on the south-going leg was reduced to 2.6 cm s^{-1} to the *east* and the mean current on the north-going leg to 5.9 cm s^{-1} to the *west.*

7. Conclusions

We have confirmed that significant errors of 2°–3° in the measurement of ship's heading can occur in a marine gyrocompass based on comparisons with heading measurements by GPS differential carrier phase techniques. Drift with time and latitude and heading-dependent errors in the gyrocompass were identified and corrected by referring the gyrocompass to the GPS system using an error model and a data-dependent filter designed to overcome gaps in the GPS heading data. The comparisons have shown the importance of carefully setting the latitude and speed compensation settings, and of making internal mechanical adjustments when gyrocompasses are used in latitudes removed from those at which they were last adjusted.

The effects on absolute ADCP underway velocities of correcting the heading were investigated using data from a long section and a small-scale box survey. Following correction, the mean cross-track current from the Drake Passage section was reduced by 35%, from 10.95 to 7.10 cm s^{-1}. Converging currents along three sections of a box survey, due to a velocity bias to the left of the ship's track, were significantly reduced when the gyrocompass heading was corrected for a direction-dependent error.

GPS-based heading measurements cannot yet take over from the gyrocompass for real-time use; however, by integrating the measurements in a way that combines the availability of the gyrocompass with the stability and precision of the GPS system a significant improvement in heading data quality can be obtained. In turn, the improved heading data has led to less biased ADCP absolute cross-track velocities.

Acknowledgments. The 3DF GPS system on RRS *Discovery* was financed through the UK WOCE Capital Fund and its installation owes much to the energy of Edward Cooper of NERC's Research Vessel Services. Brian King of IOSDL "broke trail" with processing the attitude data and provided valuable comment, as did Richard Babb. John Warren, chief engineer at the SG Brown Division of HSDE Ltd., provided information on the error behavior of the Mk 1000 gyrocompass. Mike Harding, master of RRS *Discovery* answered, with good humor, many questions on gyrocompasses during cruise 198.

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