HEADING-DEPENDENT HEADING ERRORS IN MID- AND HIGH-LATITUDE LADCP DATA

JULIA M HUMMON, ERIC FIRING
UNIV. HAWAII; 2002/05/09

Abstract

Lowered Acoustic Doppler Current Profiler (lowered ADCP) velocity data from three hydrographic cruises in the North Atlantic showed marked differences between concurrent shipboard ADCP data. The error in the LADCP data was traced to an error in heading, which is hypothesized to come from a spurious magnetic field associated with the smallest rosette package used. LADCPs use a magnetic flux gate compass to provide heading; the problem was exacerbated when heading data came from a TCM3 (as opposed to a KVH) compass. The heading-dependent heading error was modeling as a sinusoidal function of measured heading and corrections were applied to LADCP data. Comparisons between LADCP and shipboard ADCP data were significantly improved after correction.

1 Introduction

The Lowered Acoustic Doppler Current Profiler (LADCP) is an acoustic device that measures ocean current. The LADCP uses Doppler frequency shifts along two opposing beams to measure velocity past the package as it is lowered on a cable from a ship. The instrument and its battery pack are generally mounted on the same rosette frame as the CTD and Niskin bottles used during a hydrographic station. LADCP velocity profiles form an increasing body of full-depth direct ocean velocity measurements and are an important component of such hydrographic programs as as the World Ocean Circulation Experiment (WOCE).

The LADCP measures water velocity relative to the package, which is free to rotate and tilt as it is lowered to the ocean bottom and raised again. To eliminate package motion in the determination of ocean velocity, the traditional method of processing (Fischer and Visbeck, 1993) uses the vertical derivative of horizontal velocities to generate a shear profile which is then gridded, averaged, and subsequently integrated in the vertical. The constant of integration is determined by adding the net ship velocity during the cast from the time-integrated LADCP measured velocity.

Heading comes from a magnetic flux gate compass; tilt and roll are obtained from tilt sensors. An error in heading will result in an error in measured velocity, since the earth coordinate system will have been erroneously rotated by the amount of the heading error. An error in measured velocity then causes an error in calculated ocean velocity.

One method of determining the veracity of an LADCP profile is to compare the LADCP upper ocean velocity profile (about 20 minutes at each end of the cast) with the velocity profile from the shipboard ADCP where the data overlap. This comparison was performed on data from a cruise in November 1997 in the eastern North Atlantic, in which differences over 50cm s^{-1}were noted. The error in LADCP velocity was found to lie in the heading.

A method for determining a heading correction was developed and applied to three similar North Atlantic hydrographic cruises; all cruises took place from the same ship, had the same suite of instruments, and sampled in a similar geographic region. This document describes the method used to correct the erroneous headings in the LADCP data for these cruises, the effectiveness of the method, and discusses the differences in velocity errors which exist between the cruises.

2 The Data

Three cruises with similar cruise tracks (Figure 1) and instrumentation took place in the North Atlantic in Nov 1996, May 1997, and Nov 1997. During the third cruise, large differences (greater than 50 cm s^{-1}) were observed between the LADCP and shipboard LADCP (Figure 2). The heading used by the LADCP was determined to be in error. The magnitude of the error was roughly correlated with proximity to the magnetic north pole. Figure 1 also shows the inclination of the earth's magnetic field (angle to the vertical).

The cruise tracks were similar, in the sense that they all sampled from the Azores towards Greenland, between Greenland and Ireland, and (for two cruises) between Great Britain and the Azores. In all three cruises, the rosette contained an RDI 150 KHz broadband LADCP, its battery pack, sampling rosette, CTD and associated sensors, altimeter (**???**), Niskin bottles. Three different LADCP instruments were used, each employing one of two magnetic flux gate compasses: a KVH (two-dimensional, fluid-gimbaled) or a TCM2 (three-dimensional). These compasses provide heading, but tilt is removed using data from tilt sensors. Two different instrument frames were used; one was large (about 6' in diameter) and one was small (about 3' in diameter). The details of instrument configurations are shown in the table 1.

All three cruises were conducted on the same ship (*R.V.* Knorr), which had the same shipboard ADCP throughout (an RDI 150KHz narrowband instrument). Our results are based on comparisons between velocity data from the LADCP and from this shipboard ADCP.

3 Heading Errors

The LADCP measures flow of water past the package. With any heading error, the error in measured velocity (for a given heading) will be proportional to the flow past the package. Therefore, in the presence of a heading error, measured LADCP velocities will contain an error which is dependent on the package speed through the water. Steaming slightly while on station is common in regions of high currents or strong winds, and can increase the error in measured velocity, because of the increased flow past the package.

Heading errors can be heading-independent or heading-dependent. A common source of heading-independent error comes from a misalignment between the transducer assembly and the chassis. The instruments data acquisition software assumes that the compass has a particular orientation relative to one particular transducer; an error in reassembly of the instrument can result in a constant error in heading. In this situation, the measured velocity will always have the same angle relative to the true velocity (Figure 3).

A heading-dependent error can be caused by a spurious magnetic field located on the package. As the package rotates and wobbles during deployment, the direction of the earth's magnetic field vector will change relative to the package (Figure 4). The presence of an additional magnetic field on the package would result in incorrect readings by the 3-dimensional flux gate compass because it measures attitude relative to the total magnetic field. This creates an orientation-dependent and hence heading-dependent heading error. The nature of such a heading-dependent error would also vary geographically, as the relative strengths of the earth's magnetic field and the spurious magnetic field change with geographic position. Hence, a heading-dependent error can be expected to be strongest near the magnetic poles, to vary with position, and to vary with heading.

During a cast, the rosette package may rotate significantly (up to 70 seconds per rotation for 40 minutes' duration has been observed) or it may stay at approximately one heading for an entire cast. Rotations are common near the surface and also throughout the water column if the wire is new. Steaming on station will often cause the package to take on one heading relative to the ship, much like a weather vane. Therefore it is difficult to know *a priori* how a heading-dependent error will be manifested in the final calculated ocean velocity.

A heading-dependent error caused by a spurious magnetic field on the package can be modeled as a sinusoidal function of measured heading. This is shown graphically in Figures 3 and 4, and is shown mathematically in Appendix A. The difference between the actual heading error and the modeled heading error is shown in Figure 5. With a heading-dependent error, the direction of the measured velocity relative to the the true velocity will change with the sine of the measured package heading.

Because of the variation of the earth's magnetic field over the surface of the earth, the effect of a spurious magnetic field will vary with geographic position. In particular, the amplitude and phase of the sinusoidal heading error may vary over the cruise as the measurement position within the earth's magnetic field changes.

4 Methods

4.1 Correcting Heading Errors in the Data

The error in heading was modeled as a sinusoidal function of measured heading, $H_{err} = A\, sin(H_{meas}) + B\, cos(H_{meas})$, where the correct heading is the sum of the measured heading and the error. The coefficients A and B were assumed to be constant for each cast, but were allowed to vary over the course of the cruise.

For each cast, a grid of possible values A and B (representing phases varying from 0 to 2π, and amplitudes up to 70) was used to generate heading corrections. Each correction was applied to the whole cast and the cast was reprocessed. For each correction, the resulting ocean velocity was compared to the shipboard ADCP at the beginning and end of the cast. The average magnitude of the velocity vector difference between shipboard ADCP and corrected LADCP cast for each A, B combination was used to generate a 2-dimensional field of velocity error magnitudes for that cast.

These (A, B) coefficients represent the effect of the hypothesized spurious magnetic field on the heading measurements made by the compass, and as such, may be expected to vary smoothly with position. Due to sampling conditions, there may not be a clear minimum in the velocity error magnitude for a given cast. Therefore, the final A and B used for a given cast were the coordinates with the minimum velocity error magnitude from a running mean of 5 casts.

4.2 Limitations of the technique

The method used for determining the best heading-dependent correction for a given cast assumes that the shipboard ADCP velocity at the beginning and end of a cast matches the LADCP velocity where they overlap. Although the two instruments are very similar, their different deployments result in different sampling characteristics and different processing issues; they do not measure exactly the same water exactly the same way. Nevertheless, the comparison is reasonable.

The parameters A and B in the sinusoidal heading correction, $H_{err} = A\ sin(H_{meas}) + B\ cos(H_{meas})$, are the values at which the magnitude of the velocity vector difference between shipboard and lowered ADCP is at a minimum. This minimum may not be well-defined. As the package rotates and wobbles on its way down and up, it may not measure every heading. Hence the shape of the velocity error magnitudes as a function of A and B could look like a plane or a valley, but may not look like a bowl. In addition, any heading for which there is little flow past the package will have a weak velocity error (section 2). Because the comparison between shipboard and lowered ADCP was only made in the upper 400 m (or less), strong flow past the package and sampling of all headings must take place in the first and last 20 minutes of the cast, or a minimum in the velocity error magnitude may not exist.

A five-cast running mean was used for all casts in determining A and B, to help strengthen the minimum in casts where the velocity error magnitudes did not show a clear minimum. This is only reasonable in cases where the casts are in geographic proximity and the instrument configuration on the package remains static.

4.3 Other limitations

Reprocessing every cast many times (once for each A, B combination) to get a grid of velocity error magnitudes is very time-consuming. One can speed up the process by increasing the granularity of A and B tested, but the cost is to lower the accuracy of the heading correction.

Assuming a spurious magnetic field is the cause of the heading-dependent error, a sinusoidal function of measured heading does not completely characterize the error. For small corrections, there will be a small error due to the model. As the magnitude of the correction increases, the error in the model becomes larger (Figure 5). In most cases, these model errors will pale in comparison with the errors due to ambiguity in the velocity error magnitude minimum, and the error induced by the granularity of the A, B grid. The effect of the heading-dependent heading error on the final ocean velocity calculated will depend strongly on the sampling conditions during the cast (for example, did the rosette sample particularly bad headings? was the ship steaming on the wire?)

5 Results

Heading-dependent heading corrections were applied to LADCP data from three cruises with three similar cruise tracks and instrumentation, modeling the heading error as a sinusoidal function of measured heading. Corrections to the LADCP headings varied between cruises and ranged from negligible to 65°. The velocity corrections and the magnitude of the heading correction are shown by cast for each of the cruises and instrument configurations: November 1996 (Figure 6), May 1997 (Figure 7), November 1997 (Figures 8, 9, and 10). A summary of mean and RMS for the magnitude of the velocity difference between shipboard ADCP and LADCP is shown in table 2).

A small segment of the cruise track was occupied in both May and November, 1997. Figure 11 shows the original and corrected data from November are shown along with the original data from May 1997 (plotted for reference). The major difference in instrument configuration between occupations was the use of the large ODF package in May, and the small WHOI package in November. The heading-dependent correction brought the magnitude of the shipboard ADCP – LADCP velocity difference to levels comparable with the

May cruise (right panel).

6 Discussion

The magnitude of the heading correction changed with geographical position, getting stronger near the magnetic pole (Figure 12). It also varied between sections. In the Nov, 1996 cruise and in both sections of the Nov, 1997 cruise which used a TCM2 compass, the magnitude of the heading error is clearly correlated with proximity to the magnetic pole, although it is about twice as high in the Nov, 1997 cruise. The strength of this correlation leads us to postulate the presence of a magnetic field on the rosette package which is strong in the two November cruises but weak or absent in the May cruise.

As shown in Figure 11, data collected near 64°Nusing the same LADCP (table 1) required very different corrections in spite of their nearly identical locations. A high degree of correction was required for the November 1997 cruise to bring the LADCP data difference from the shipboard ADCP down to the levels of the uncorrected LADCP data from the May cruise.

The rosette frame and CTD instrument suites used in the two November cruises were the same (WHOI); a different rosette frame and CTD instrument suite was used in May (ODF). Therefore, we postulate a spurious magnetic field associated with the WHOI rosette and instrument suite. This could simply be due to rosette frame size: the WHOI rosette used was very small, about 3' in diameter, as opposed to the ODF rosette frame which was closer to 6' in diameter.

If there had been a spurious magnetic field associated with the WHOI rosette frame and instrumentation, why would the correction be so different between them the two November cruises? The answer may lie in the compass. The LADCP used during the Nov, 1996 cruise employed a KVH compass. The LADCP used during the Nov, 1997 cruise started out with a TMC2 compass which was swapped for another TCM2 compass about one third through the cruise. For casts closest to the earth's magnetic pole (2000 km - 4000 km), the magnitude of the correction for the TCM2 data was about twice the correction required for the KVH data. Farther away (5000km), the correction required for each November cruises is similar to that of the May cruise.

6.1 Identifying and Correcting Heading Errors

A heading-dependent error is most likely to be caused by a misalignment between the transducer assembly and the electronics holding the compass. Consistent, proper alignment of these components will alleviate this problem. Nevertheless, one can either calibrate the instrument in the lab (record actual headings and measured headings, and look for a consistent offset) or test the data in the manner described in section (4), instead using a collection of heading-independent corrections. If there is a simple alignment problem, the heading correction should be constant throughout the cruise.

There is no easy formula for determining whether a cruise has LADCP data containing a heading-dependent error. Figure 3 illustrates the geometry of a heading-independent and a heading-dependent error and the resulting effect on velocity. In both examples, the LADCP is being towed east through quiescent water, which results in flow past the package to the west. A heading error with amplitude of 30°is added to show the effect of package rotation on the measured velocity in this example. At any time during a real cast, the water past the package could come from any direction and the package could be heading in any direction so the effect on calculated ocean velocity is unknown *a priori*. In the case of the heading-dependent heading error, the heading error varies with the heading of the package and adds to the complexity.

Figures 7 through 10 show the zonal and meridional components of the difference between shipboard ADCP and original and corrected LADCP velocities. In general, there is a higher bias in u or v when there is a greater heading-dependent error. Because of the variability of sampling conditions and their effect on the final calculated ocean velocity, there is a high degree of station-to-station variability in the u and v velocity differences; hence, a higher RMS difference between shipboard and lowered ADCP may also indicate a heading error.

There is no practical way to calibrate the instrument or otherwise enable it to automatically account for a heading-dependent error caused by a spurious magnetic field. During a cruise, the presence of a spurious magnetic field associated with the package suggests attempting to isolate it and remove it or switch to a different rosette package. Post-cruise processing may be the only realistic way of dealing with LADCP data with heading-dependent heading errors.

7 Summary and Conclusions

Velocity differences between shipboard ADCP and LADCP velocities during three similar cruises in the North Atlantic revealed an error in LADCP heading which was due to a magnetic field on the smaller of the rosette packages used. The heading error was greatest when the LADCP on the small rosette used TCM2 compass (as opposed to a KVH compass, used for the rest of the data).

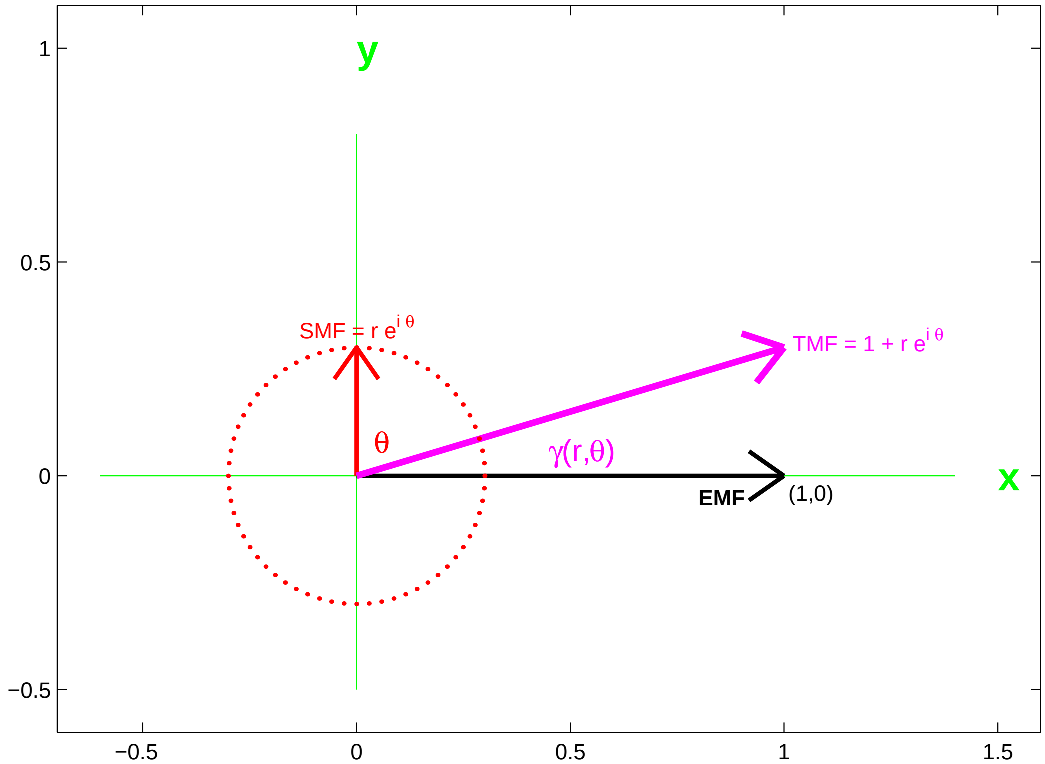
The error in heading due to a spurious magnetic field on the package can be modeled as a sinusoidal function of magnetic heading. This model was used to correct each cast with a representative grid of coefficients. For each cast, the optimal correction was determined by minimizing the magnitude of the velocity difference between shipboard and lowered ADCP where the data overlapped.

A bias in the difference between shipboard ADCP and LADCP may be indicative of a heading error, but the presence of a bias in the velocity is not sufficient to deduce whether the heading error is independent or dependent on heading, nor how bad it is. RMS difference between shipboard and lowered ADCP data is highest in sections of data needing the highest heading-dependent correction.

The sinusoidal model of heading error was effective at correcting the LADCP velocities. Because a spurious magnetic field is hard to detect *in situ*, routine comparison between shipboard and lowered ADCP should be part of standard LADCP processing, especially in mid- and high-latitude regions.

Appendix: LADCP heading error

MODELING LADCP HEADING ERROR AS SIN(MEASURED HEADING)



Notes:

- Math is in standard complex notation (counterclockwise is positive radians).
- The Earth's Magnetic Field (EMF) is $(1, 0)$.
- The magnitude of the Spurious Magnetic Field (SMF) is r.
- The SMF rotates with the package (i.e. is fixed in package coordinates). For this development, the "heading" of the package is arbitrarily defined as the direction of the SMF, θ.
- The Total Magnetic Field (EMF + SMF) is $1 + re^{i\theta}$. Its angle with the horizontal is γ, which is a function of r and θ (because of its dependence on the effect of the SMF).
- The ERROR in heading, i.e. the difference between the correct heading and the measured heading, is (-γ).
- The measured heading will be denoted $\hat{\theta}$.

Strategy: rewrite the magnitude and the angle of the total magnetic field as series expansions about r and match terms of order r^n.

First, the measured heading is the angle of the SMF relative to the TMF:

$$\hat{\theta} = \theta - \gamma$$

or

$$\theta = \hat{\theta} + \gamma \tag{1}$$

Now, rewrite the Total Magnetic Field (TMF) as

$$\text{TMF} = 1 + re^{i\theta} = \hat{r}e^{i\gamma}$$

Substituting for θ from eqn (1) we have

$$\begin{aligned} \hat{r}e^{i\gamma} &= 1 + re^{i\theta} \\ &= 1 + re^{i(\hat{\theta}+\gamma)} \\ &= 1 + re^{i\hat{\theta}}e^{i\gamma} \end{aligned}$$

So,

$$\hat{r} = e^{-i\gamma} + re^{i\hat{\theta}}$$

and

$$e^{-i\gamma} = \hat{r} - re^{i\hat{\theta}}. \tag{2}$$

Now expand $\hat{r}$ (the magnitude of the TMF) and γ, (the angle of the TMF), about r, for small r, where the coefficients a_n and b_n are functions of $\hat{\theta}$. Since $\hat{r}$ and γ are real values, the coefficients a_n and b_n are real.

$$\hat{r} = 1 + ra_0(\hat{\theta}) + r^2a_1(\hat{\theta})r^3a_2(\hat{\theta}) + ... \tag{3}$$

or

$$\gamma = rb_0(\hat{\theta}) + r^2b_1(\hat{\theta}) + r^3b_2(\hat{\theta}) + ... \tag{4}$$

Expanding the left hand side of eqn (2) we get

$$e^{-i\gamma} = 1 - i\gamma - \frac{\gamma^2}{2!} + \frac{i\gamma^3}{3!} + \mathcal{O}(\gamma^3) \tag{5}$$

Substituting γ from equation (4) into equation (5) and grouping terms in terms of r^n, we get:

$$
\begin{aligned}
1 &= 1 \\
-i\gamma &= -i(b_0)r + b_1 r^2 + \mathcal{O}(r^3) \\
-\frac{\gamma^2}{2!} &= -(\frac{(b_0 r + b_1 r^2}{2!} + \mathcal{O}(r^3))^2 \\
\frac{i\gamma^3}{3!} &= \mathcal{O}(r^3)
\end{aligned}
\tag{6}
$$

and hence

$$
e^{-i\gamma} = -ib_0 r - ib_1 r^2 - \frac{b_0^2 r^2}{2} + \mathcal{O}(r^3). \tag{7}
$$

Finally, substituting equations (3) and (7) and into equation (2), grouping terms as to their order (r^n), and matching real and complex parts, we get:

	overall	real	complex
r	$-ib_0 = a_0 - e^{i\hat{\theta}}$	$a_0 = cos(\hat{\theta})$	$b_0 = sin(\hat{\theta})$
r^2	$-ib_1 - b_0^2 = a_1$	$a_1 = -b_0^2$ $a_1 = -sin^2(\hat{\theta})$	$b_1 = 0$

... so that to order $(dr)^2$:

$$
\gamma = r\ sin(\hat{\theta}) + \mathcal{O}(r^3)
$$
$$
\hat{r} = 1 + r cos(\hat{\theta}) - r^2 sin^2(\hat{\theta}) + \mathcal{O}(r^3),
$$

i.e. to $\mathcal{O}(r^3)$ the error in heading (-γ) is a sinusoidal function of measured heading ($\hat{\theta}$).

References

Fischer, J., and M. Visbeck, 1993: Deep velocity profiling with self-contained ADCPs. *J. Atmos. and Oceanic Technol., 10*, 764–773.

INSTRUMENT CONFIGURATION ON THREE NORTH ATLANTIC CRUISES

chief sci (LADCP person)	WHOI cruiseid	LADCP cruiseid	start,end info	LADCP used	rosette used	compass name
McCartney (Hummon, Donohue)	kn147_2	kn9611	WHOI-Azores-Southampton Nov 1996	TC	WHOI(s)	KVH1
Talley (Firing, Chen)	kn151_2	kn9705	WHOI-Azores-Halifax May 1997	EF	ODF	TCM2(orig)
Curry (Hummon, Donohue)	kn154_1	kn9710	WHOI-Azores-WHOI Oct 1997	EF EF EFTJ	WHOI(s) WHOI(s) WHOI(s)	TCM2(orig) TCM2(repl) KVH(repl)

INSTRUMENT AND COMPASS: KEY

initials	instrument	compass	firmware
"EF"	Eric Firing	TCM2 compasses	v5.x
"TC"	Teri Chereskin	KVH compass	v5.x
"TJ"	Terry Joyce	KVH compass	v4.x
"EFTJ"	Firing instrument	Joyce KVH compass and xducer boards	v5.x

Table 1: LADCP instrument, compass type, and rosette used.

Statistics of Shipboard ADCP and LADCP Velocity Comparison

	MEAN (cm/s)			RMS ERROR (cm/s)	
	u	v	mag	u	v
original LADCP	-1.45	-2.44	4.81	4.03	3.57
corrected LADCP	0.02	-0.34	3.32	2.89	3.12
kn9611, KVH	n = 175				
original LADCP	-0.04	-0.03	2.61	2.59	2.13
corrected LADCP	-0.14	0.02	2.38	2.27	1.92
kn9705, TCM2	n = 148				
original LADCP	-10.80	-3.17	12.85	14.91	4.63
corrected LADCP	-0.30	-0.36	2.74	1.87	2.62
kn9710, TCM2	n = 74				
original LADCP	-8.11	-2.74	10.48	6.18	5.58
corrected LADCP	-0.35	-0.14	2.90	2.53	2.03
kn9710, TCM2	n = 50				
original LADCP	-0.46	-1.65	3.59	2.80	2.73
corrected LADCP	-0.25	-0.81	3.48	2.76	2.95
kn9710, KVH	n = 36				

Table 2: magnitude of velocity difference (shipboard ADCP - LADCP)

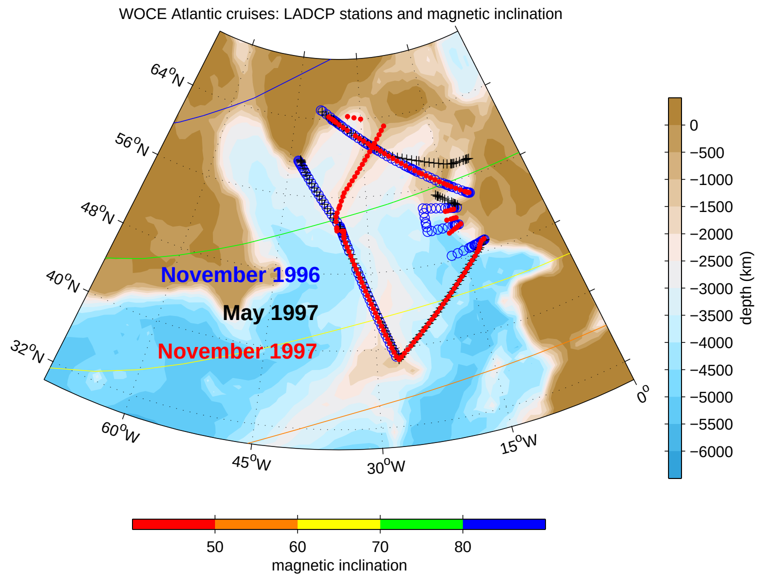


Figure 1: Cruise track for the three North Atlantic cruises shown in three colors. Magnetic inclination (degrees below horizontal) is also contoured

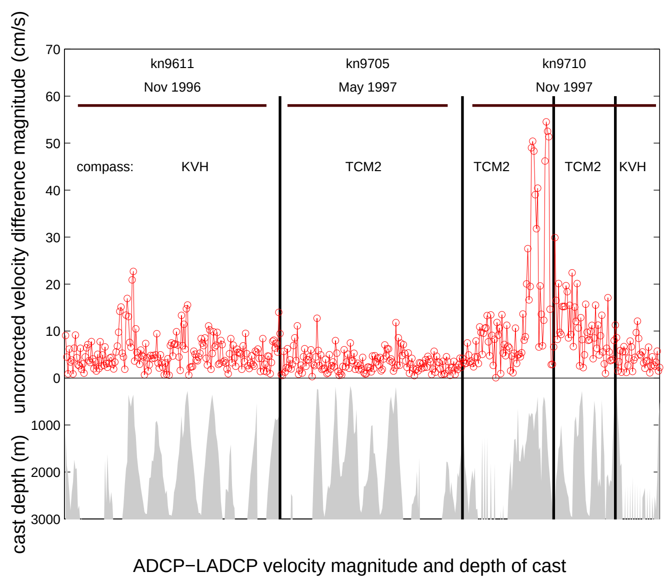


Figure 2: Magnitude of shipboard ADCP minus LADCP velocity for each cast (red), and depth of cast (gray). Compass type and dates are also noted.

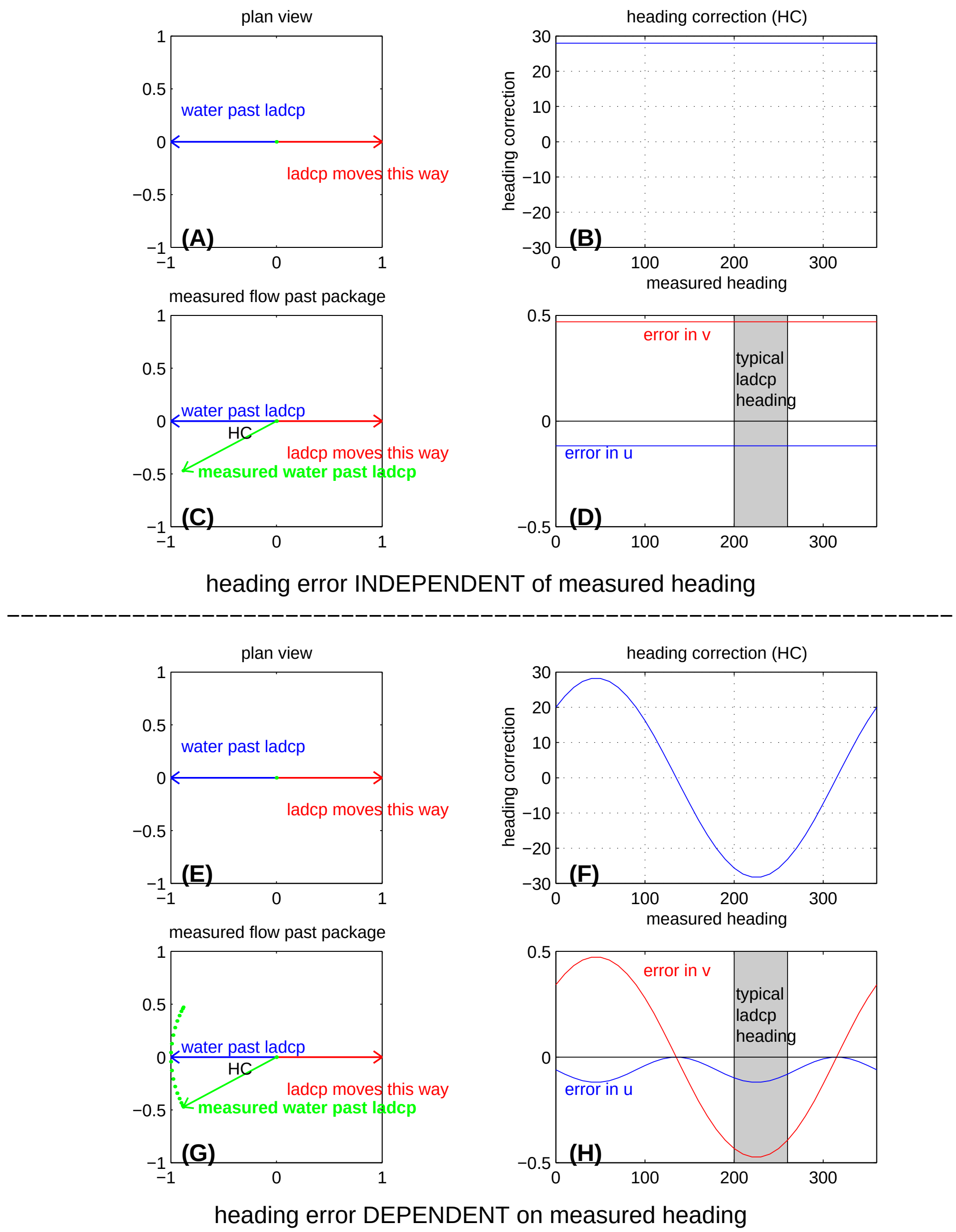


Figure 3: The velocity error resulting from flow past the LADCP for a heading-independent and a heading-dependent heading error contains a bias which is dependent on sampling conditions.

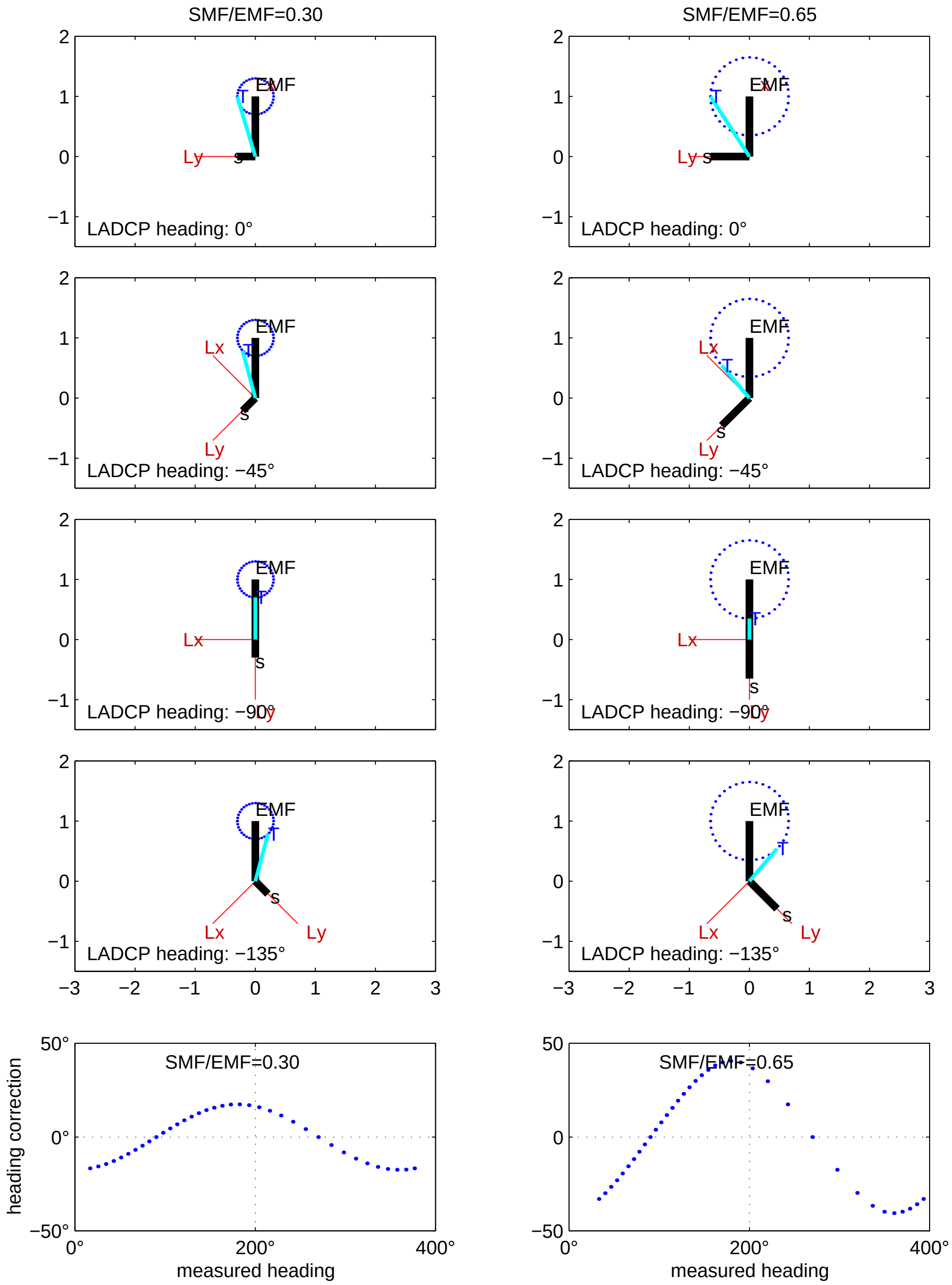
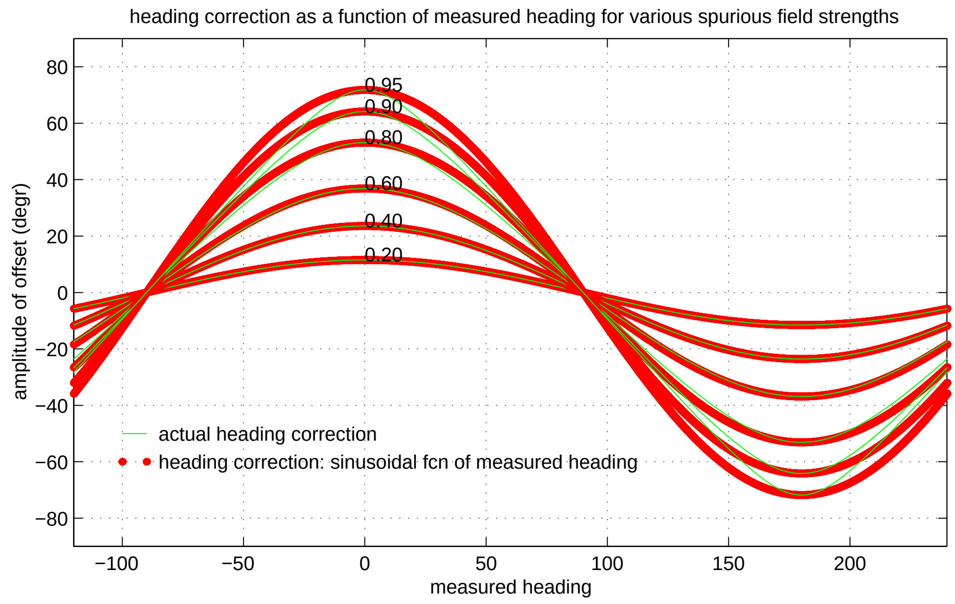


Figure 4: Top 4 panels: Two-dimensional geometry of a spurious magnetic field (“s”) in the presence of the earth’s magnetic field (“EMF”), on a package free to rotate. The x and y axes of the package are shown in red (“Lx” and “Ly”). The actual heading of the package is the direction of the Lx axis and the measured heading comes from the sum of the earth’s magnetic field and the spurious magnetic field (shown as “T”, light blue) for four actual headings. The The circle of dark blue dots shows the trace of the total magnetic field for one rotation of the rosette. The bottom panel shows the error in measured heading (i.e. the difference between actual heading and direction of the EMF+spurious field) as a function of measured heading.



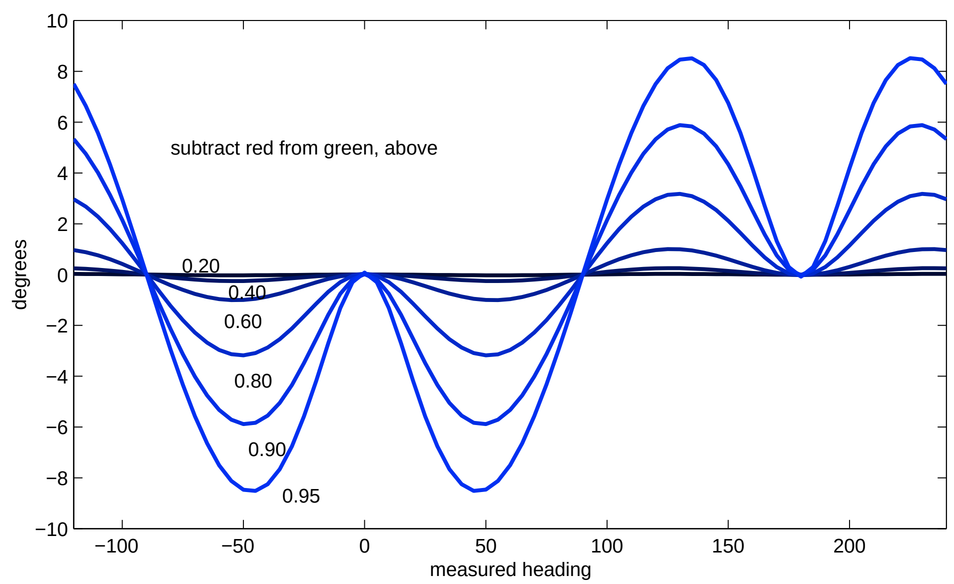


Figure 5: Emerically derived heading-dependent heading error for a spurious magnetic field on a package free to rotate (in green) and the same error modelled as a function of measured heading (red).

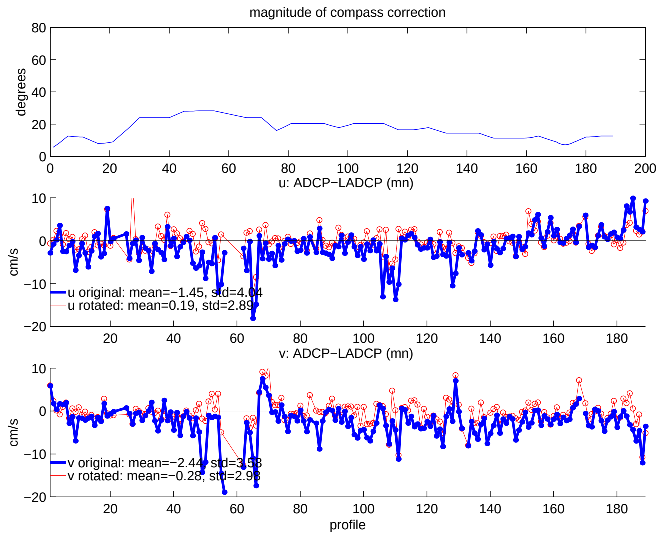


Figure 6: November 1996 cruise: Top panel: magnitude of heading-dependent heading correction applied to the data. Center and Bottom panels: difference between shipboard and lowered ADCP, u and v respectively, before (blue) and after (red) heading correction.

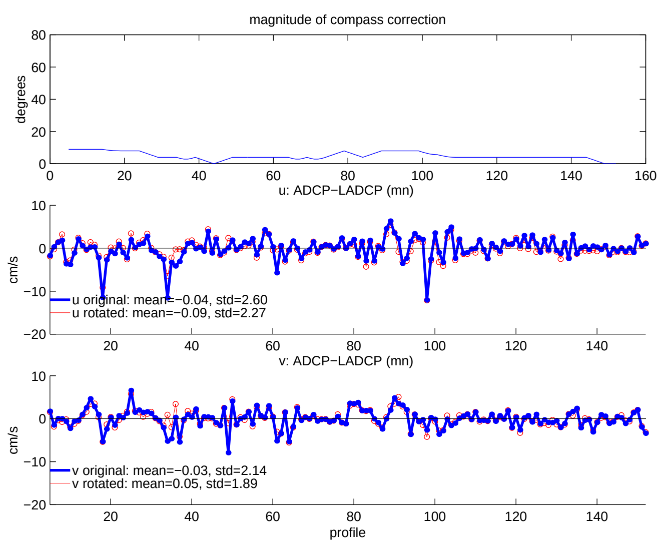


Figure 7: same as figure 6 but for May 1997 cruise.

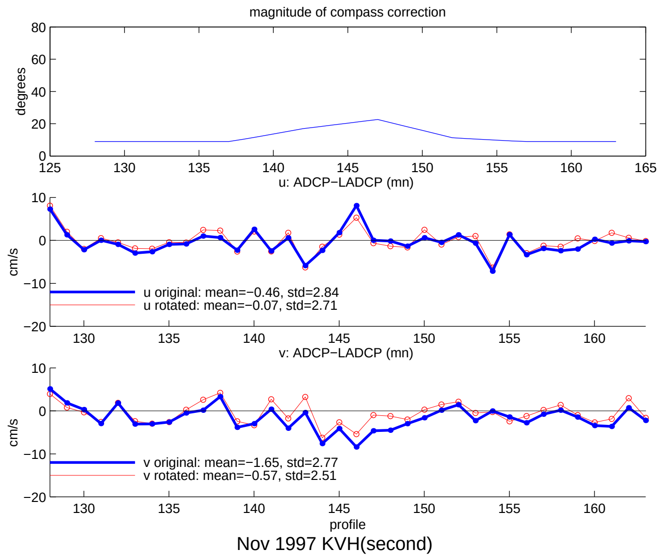


Figure 8: same as figure 6 but for November 1997 cruise, first TCM2 compass.

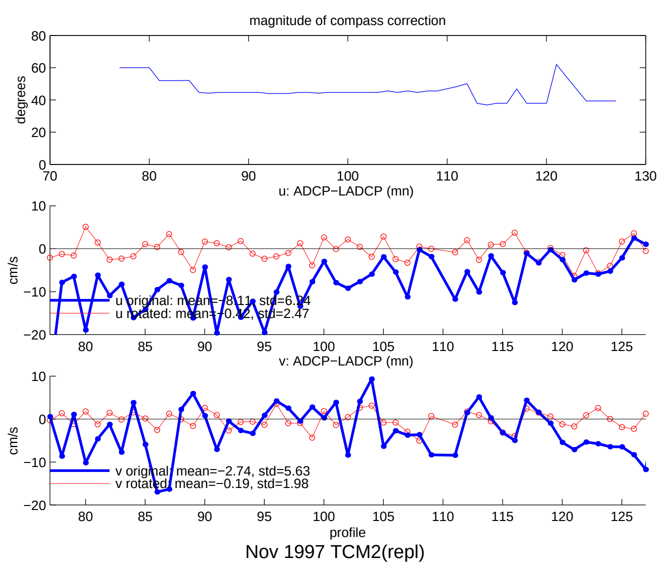


Figure 9: same as figure 6 but for November 1997 cruise, second TCM2 compass.

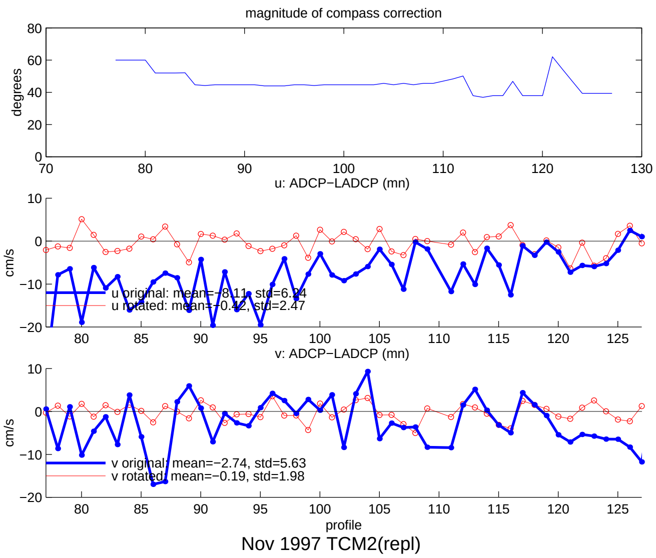


Figure 10: same as figure 6 but for November 1997 cruise, KVH compass.

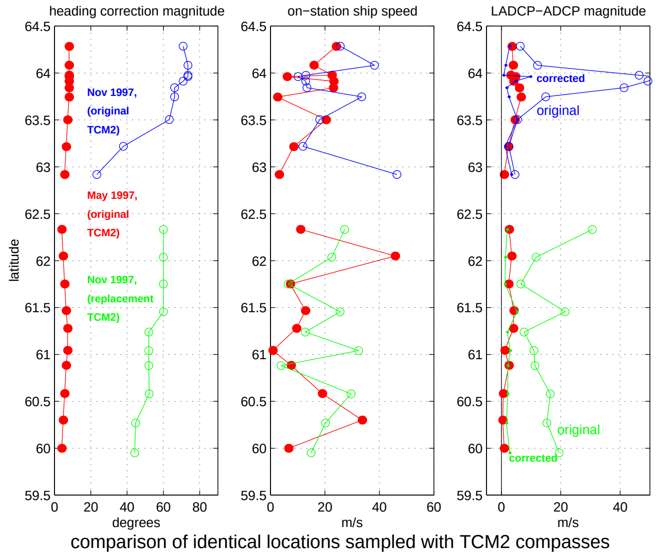


Figure 11: Data collected near Greenland in May, 1997 (plotted in red) and collected in November, 1997 (plotted in blue and green). First panel: the May cruise required very little (under 10°) correction to heading whereas the Nov, 1997 casts generally required a heading-dependent correction with amplitude over 40°. Center panel: a variety of average on-station ship speeds (steaming on station) are shown. Right panel: the magnitude of the velocity error is shown for the May cruise (uncorrected), abd the November cruise (before and after correction).

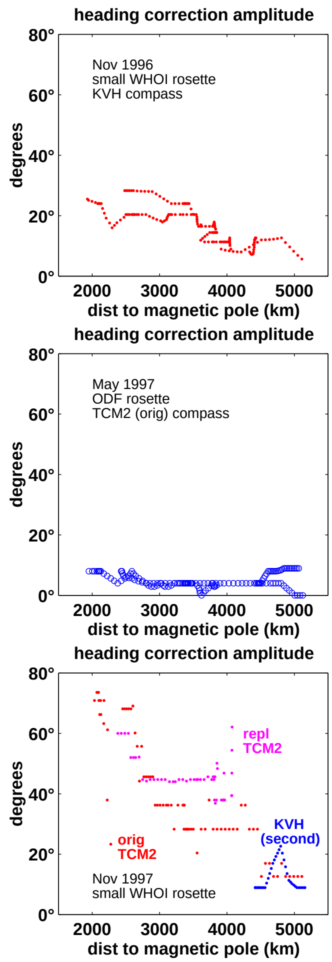


Figure 12: Magnitude of heading-dependent correction plotted as a function of distance to earth's magnetic north pole, all three cruises shown.