POST-CRUISE COMPASS CALIBRATIONS FOR NORTH ATLANTIC WOCE LADCP

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Abstract

Heading from the magnetic compass in a lowered acoustic Doppler current profiler (lowered ADCP) can be the primary cause of error in the velocity profile, but heading errors can be difficult to detect and correct. One method relies on a comparison between simultaneous estimates of upper ocean velocity from shipboard and lowered ADCPs. Such a comparison on three similar cruises in the North Atlantic identified compass errors occasionally exceeding 60° on one of the three cruises, but under 10° on another. Corresponding velocity differences between shipboard and lowered ADCP in these instances were over 50 cm s^{-1} and under 5 cm s^{-1} in magnitude, respectively.

Two models of compass error were evaluated: a heading-independent compass correction and a heading-dependent compass correction modeled as a sinusoidal function of measured heading. Both models were used by minimizing the magnitude of the vector difference between shipboard and lowered ADCP velocities rotated according to the model. Both compass error models yielded substantial improvement in the corrected data. The heading-independent error was ruled out because it was not

The origin of the heading error is not clear, but an as yet unidentified source of a magnetic field on the instrument package seems the most likely candidate.

1 Introduction

Concurrent measurements of ocean pressure, temperature, salinity, and velocity form an important and expanding pool of data. Many of these direct velocity measurements come from a lowered acoustic Doppler current profiler (LADCP). This sonar device is mounted on the rosette frame along with sampling bottles and sensors and measures the velocity past the package as it is lowered on station. Package attitude (heading, pitch, and roll) is one of the measurements used to determine the ocean velocity sampled. A correct attitude measurement is critical to the velocity determination, yet attitude accuracy is usually unknown.

During a cruise in the North Atlantic (Nov 1997) on board the R/V Knorr, LADCP data became completely unrealistic (figure 2): the heading recorded by the LADCP was determined to be at fault. During the 13 month period from November 1996 through December 1997, the R/V Knorr made five hydrographic cruises of approximately one month each in the north Atlantic, with three of the cruises repeating much of the same cruise track (figure 1). The Nov 1997 cruise was the last of these. LADCP data were collected at nearly every station, and shipboard ADCP data were collected throughout. The three “repeat” cruises in the eastern North Atlantic were used to test heading error models in an effort to correct the data and understand the cause of the erroneous heading measurements.

A compass error may be a constant offset, regardless of heading, or it may depend on heading. This document gives a short description of the geometry and velocity signals associated with heading-independent and heading-dependent compass errors, the calculations used to model these errors and correct the LADCP profiles. A scenario is presented which accounts for most of the properties of the ADCP - LADCP comparison for all 5 cruises.

2 Geometry and Velocity Signals of Heading Errors

2.1 Geometry of Heading-Independent and Heading-Dependent Compass Errors

The simplest compass error is a constant. The most obvious way of generating a heading-independent compass error is to reassemble the LADCP with the compass oriented incorrectly relative to the transducers. If the compass is mounted correctly, its error is then likely to vary with heading.

At least two plausible physical mechanisms could cause heading-dependent compass errors. (1) The presence of a (real or apparent) constant magnetic field associated with the package could be caused by a magnetized LADCP component, another instrument on the rosette, or from the electric current in a cable. (2) The electronics of the magnetic flux gate compass could be faulty. During these cruises, two flux gate compass designs were present among the various instruments. These compasses (KVH and TCM2) measure the horizontal component of the three-dimensional magnetic field vector in slightly different ways. The KVH compass is fluid-gimbaled and measures 2 orthogonal components: “horizontal” is determined through gimbaling. The TCM2 compass is strapped down and measures all 3 orthogonal components: “horizontal” is determined using tilt sensors. An amplifier associated with one of the compass components can have a gain or an offset error. An offset error in a horizontal amplifier generates an error in the measured heading that is indistinguishable from a constant horizontal spurious magnetic field in package coordinates.

Figure 3 shows the geometry creating the heading-dependent error for the case of the horizontal spurious magnetic field. The rosette is shown with two headings (50° and 135°) relative to earth's magnetic field (which is pointing north). In this example, the spurious magnetic field is oriented along the axis of the LADCP. The spurious magnetic field distorts the earth's magnetic field, thus inducing an error in the LADCP measured heading.

The erroneous headings generated by this geometry are modeled well by a sinusoidal function of measured heading (figure 4). The model breaks down if the strength of the spurious magnetic field approaches the horizontal strength of the earth's magnetic field.

Two reasonable physical explanations for a heading-dependent error have been mentioned, both of which are well-modeled by a sinusoidal function of measured heading. There is also empirical evidence for this model. A particularly good example is shown in figure 5, which shows the velocity past the package measured by the LADCP and the angle of that flow (in magnetic earth coordinates) inferred by the LADCP for a portion of one cast with a mean ship speed of 0.4m/s. The best fit of a sinusoidal function of measured heading to this segment of velocity directions is superimposed on the top panel. In all casts during the three "repeat" cruises when the package was being towed at greater than 0.2m/s and was spinning rapidly (1.2-3 minutes/revolution), the angle of the measured velocity past the package oscillated in this manner. Data collected on other cruises indicate the oscillation is not solely due to oscillatory package motion, thus a heading-dependent error is indicated.

2.2 Velocity Signals

2.2.1 Velocity signatures for any heading error

Errors in velocity due to incorrect headings are proportional to the motion of the package through the water, which is in turn related to sampling conditions. Any error in heading corrupts the velocity measured by the LADCP because the instrument assigns the measured velocity (i.e. the flow past the package) to an incorrect direction. The final ocean velocity calculated from the LADCP data is obtained using the measured velocity past the package and the shear calculated from this velocity. The barotropic (depth-independent) component of the ocean's velocity comes primarily from the integrated measured flow past the package and the ship's average velocity during the cast. The baroclinic (depth-dependent) component of the ocean's velocity is calculated by integrating vertically gridded shear. (This shear also makes a small contribution to the barotropic velocity). Errors in the measured velocity past the package affect both the barotropic and the baroclinic components of the final LADCP velocity profile.

The largest velocity error generated by a compass error generally comes from the calculation of the barotropic component of flow, because this is related to the integral of the directly-measured velocity. Since the magnitude of the flow past the package is frequently dominated by the speed over the ground rather than the currents (figure 2), this velocity error is related to the average on-station velocity.

Figure 6 shows the extent to which the on-station ship's velocity exceeds the local oceanic barotropic velocity for the three "repeat" cruises. The bottom panel is the cumulative probability distribution of the ratio of average on-station ship speed to ocean barotropic flow for all stations from the three cruises. This panel shows that ship's speed exceeds the ocean's barotropic signal in about 70% of all stations, and exceeds the ocean's barotropic signal by over 2$\times$ for approximately 50% of the stations. Thus in a majority of casts, the average on-station ship velocity (as opposed to the ocean's local barotropic signal) dominates the flow of water past the package.

The combination of any heading error and a high on-station ship's velocity results in an error in measured velocity. The average on-station velocity is related to the local weather and sea state. The ship usually steams into the wind, which may be in the same direction for many stations in a row. If the there is a strong correlation between the heading of the LADCP and its direction of travel through the water (i.e. the package is "kiting" or "weathervaning" rather than rotating during a cast), then the LADCP will be measuring a very similar flow past the package for these stations due to the similar on-station steaming direction. The corresponding barotropic errors therefore will be similar in direction. Such a bias in measured velocity could exist in several groups of casts, with each group having a different bias resulting from different dominant towing (and hence kiting) directions.

Figure 7 shows both the variability and the coherence of the on-station ship's velocity for the three "repeat" cruises. Of particular note in this figure is the strong grouping of casts with the same on-station direction in the Nov 1997 cruise. These groups correspond to a series of storms.

2.2.2 Velocity signatures for heading-independent compass error

A heading-independent error is constant and hence will result in a measured heading which is only a phase-shifted version of the actual heading. Similarly, the measured velocity $(u + iv)$ will also be a phase-shifted version of the correct velocity (viewed as a function of heading). If the distribution of sampled package headings and velocities past the package was uniform for a given cast, the average velocity error would be zero. However, it is more likely that the velocity past the package will be somewhat directional (due to the ship steaming on station and the weathervaning of the package), so the range of sampled headings will be limited. This would lead to a slight bias in $u + iv$. The bias may change from station to station depending on the dominant package heading and direction of water past the package. Over the course of a cruise, there may or may not be an overall bias in u or v.

2.2.3 Velocity signatures for one heading-dependent compass error

If the heading-dependent error is a sinusoidal function of measured heading, there will probably be a bias in $u + iv$. Figure 8 uses the same geometry introduced in figure 3 to illustrate the cause of the bias. The top panel shows the heading correction plotted as a function of measured heading (gray) and of actual heading (blue). The dots represent the same two examples shown in figure 3. The middle panel shows the measured and actual headings for the examples (plan view). In order to demonstrate the effect of this heading-dependent error on velocity we will assume an ocean at rest, a ship towing the package through the water at 1m/s, and the heading of the package to be identical to the direction of towing. The last assumption is merely convenient: if there really is a weathervaning effect, the package should maintain the same orientation relative to the towing direction regardless of the towing direction. The lower two panels show the geometry of the measured and actual velocities for the two examples. The actual velocity of the water past the package ("W") is induced by the towing ("tow"), and the package heading is aligned with the towing direction. The measured velocity is indicated in the two examples.

The shaded region indicates the headings for which there is a positive compass correction: the actual heading is clockwise of the measured heading in the shaded region and counterclockwise of the measured heading in the unshaded region. Looking at the velocities in the lower two panels of figure 8, this means that in the shaded region the actual velocity is *counterclockwise* of the measured velocity and in the unshaded region it is *clockwise* of the measured velocity. Because the boundary between shaded and unshaded regions is oriented in the North/South direction, there will be a bias in the v component of velocity: the actual v will always be greater than the measured v. Figure 9 shows this by plotting actual and measured u and v as a function of actual package heading (which is aligned with towing direction for this example). Again, the dots represent the two examples from figures 3 and 8.

The phase of the heading-dependent correction will determine the direction along which the bias in $u + iv$ will occur. In this example, over the course of a cast, the error in u may happen to average out, but the error in v will not. In reality, the bias may vary from cast to cast for several reasons: the collection of sampled headings may require little correction, the flow past the package may be small, or the amplitude and phase of the heading-dependent error may slowly change over the course of a cruise.

The velocity signatures of other heading-dependent compass errors are not explored here.

3 Testing Compass Error Models

There are few methods available to evaluate LADCP velocity data directly. The most obvious is to compare LADCP data with shipboard ADCP data where they overlap. Comparisons were made between the shipboard and lowered ADCP data for each station whenever possible. For each station compared, data were extracted from the shipboard database to form three virtual casts for comparison with the lowered ADCP's three virtual casts: "down-cast" (first 20 minutes), "up-cast" (last 20 minutes), and "mean-cast" (average for cast duration). The on-station time was determined by the start time and end time recorded by the LADCP. Corrections were attempted for all 5 cruises using both heading-independent and heading-dependent (sinusoidal function of measured heading) compass error models. The calculations involved and the results for the three "repeat" cruises are detailed in the remainder of this section.

3.1 Heading-Independent Error

For each cast, for headings ranging from 0° to 360°, the difference between LADCP and ADCP velocities was calculated. The "best" heading-independent error for any given cast was the constant heading offset that minimized the magnitude of the ADCP - LADCP velocities.

3.2 Heading-Dependent Error

The heading-dependent correction ($C = \theta_A - \theta_M$) was approximated by a sinusoidal function of measured heading

$$C = a\cos(\theta_M) + b\sin(\theta_M),$$

where (θ_M) is measured heading and (θ_A) is actual heading. In order to find the best rotation parameters (a and b) to calibrate a given compass on a given cruise, a simple 4 degree gridding of parameter space was used. For each station, for each a and b on this grid, a new "rotated" LADCP cast was calculated using the heading-dependent correction specified by a and b on the grid. By comparing the magnitude of the velocity offsets in u and v between shipboard and lowered ADCP, a grid of velocity error magnitudes was obtained for each station.

Ideally, for each station, there would be a clear minimum in the values on the grid of (a, b) parameters indicating a "best" heading-dependent correction for each cast. Not all stations showed a clear minimum. Stations that did show a clear minimum had two characteristics. First, the rosette must have undergone several rotations during the cast: this ensured that all headings were sampled sufficiently. Second, the ship should have been moving while on station so there was flow past the package. These two characteristics together generally resulted in a clear minimum in the ADCP - LADCP velocity magnitude. Unfortunately, they rarely appeared together. Strong on-station steaming was correlated with a tendency for the package to "kite" (i.e. the package was stabilized against rotation). The one exception to this general rule was when the rosette was deployed on a new wire. In this case the tendency for the wire to unwind was high, and package rotation occurred at higher ship speeds than would normally be the case. In an effort to allow time- (or space-) dependent variations of (a, b) yet still obtain a well-defined minimum in ADCP - LADCP velocity magnitude, a and b were chosen from a running mean applied to the velocity error magnitude grids. A series of (a, b) parameters was calculated in this manner for each cruise.

4 Effectiveness of Correction

ADCP and uncorrected LADCP data were compared prior to correction: the magnitude of this velocity difference is shown for the three "repeat" cruises in figure 10. Clearly, the comparison between the original LADCP and ADCP data is best for the May cruise, with an average ADCP - LADCP magnitude of 2.6 cm s^{-1}. The first November cruise shows a slightly worse comparison, with an average ADCP - LADCP magnitude of 4.8 cm s^{-1}. The second November cruise is much worse with an average ADCP - LADCP magnitude of 10 cm s^{-1}. Approximately 15% of the casts on this cruise have a error magnitude greater than 15 cm s^{-1} with some casts exceeding 50cm s^{-1}.

The LADCP data were corrected for all casts on all five cruises using both heading-independent and heading-dependent error models and were compared with shipboard ADCP values. Little correction was possible for the two meridional lines in the western North Atlantic. The results for the three "repeat" cruises in the eastern North Atlantic are discussed below.

4.1 Heading-independent Correction

The values of the heading-independent correction for the three "repeat" cruises are plotted against station number in figure 11. The correction possible for the May 1997 cruise was minimal and nearly constant for the entire cruise, reducing the magnitude of the ADCP - LADCP velocity from 2.6 cm s^{-1} to 1.7 cm s^{-1}. The correction for the Nov 1996 cruise was more substantial and varied slowly over the duration of the cruise. The magnitude of the ADCP - LADCP velocity was reduced from 4.8 cm s^{-1} to 2.7 cm s^{-1}. The correction for the Nov 1997 cruise was extreme, changing by as much as 60° in 10 days. Velocity error reduction for this cruise was substantial. Comparisons between cruises and error models are shown in table 1.

4.2 Heading-dependent Correction

In this section the results of applying a heading-dependent correction modeled as a sinusoidal function of measured heading to the LADCP data are shown for each of the three North Atlantic cruises. In the third cruise, where three compasses were used in sequence, the results are shown separately for each compass.

The results for the November 1996 cruise are shown in figure 12. The bias in the original LADCP u and v were apparent in this cruise (bottom two panels, blue). The compass appeared have a moderate heading-dependent offset, with the amplitude of the correction starting around 10° (top panel), increasing to about 30° between stations 40-60, and decreasing slowly until the end of the cruise. This walk through parameter space changed roughly with the cruise track: although there is no physical meaning for the (a, b) coordinates, their amplitude increased in rough correspondence with increasing proximity to the earth's magnetic pole. After the rotation, the u and v biases were reduced by roughly a factor of ten. Casts with a high remaining bias were generally in regions of high local on-station velocity or were shallow (figures 10 and 12). Casts 56-59 and 62-68 were under 1400m taken in the East Greenland Current. Casts 108-113, 128-135, and 184-190 were all under 1200m. Biases for these casts were improved but remain the areas of worst comparison.

Figure 13 shows the LADCP - ADCP velocity comparisons for the May 1997 cruise. This cruise has the best raw (unrotated) data of all three cruises. The magnitude of the heading-dependent error was under 10° for the entire cruise. Little bias in the LADCP - ADCP velocities was present (-.04 cm s^{-1} and -.03 cm s^{-1} for u and v, respectively). As with the previous cruise, the errors in comparison between ADCP and LADCP were highest in shallow regions or where shipboard velocities were highest.

The results for the November 1997 cruise are shown separately for each of the three compasses. Data collected on this cruise used the small rosette, as did the November 1996 cruise (the May 1997 cruise used a larger rosette). The first third of this cruise used the same LADCP instrument and compass as the May 1997 cruise and traveled approximately the same track. After cast 75, this compass was replaced by the other TCM2 compass in the instrument. After cast 128, the second TCM2 compass, the compass board, and the transducer driver boards were all swapped for the same suite of boards from another instrument.

Results for the first TCM2 compass are shown in figures 14 and 15. Because the Knorr started with two fresh CTD wires on this cruise, there were many casts with substantial package rotation (eg. figure 5). In figure 14 the magnitude of the correction starts near 15 but increases nearly linearly with time until cast

70. Sampling conditions started changing at about cast 40 (figure 15): package rotation all but ceased, and by station 46, the depth decreased to 1500m. These effects are visible in the increasing magnitude of the ADCP - LADCP comparison beginning about station 48 (figures 14 and 15). By station 55, mean on-station ship's speed was about 60 cm s^{-1} for each cast, and the depths were shallower than 1000m (figure 15). The first peak in velocity bias occurs around cast 58 and is correlated with high on-station ship's speed, shallow water, and no rotations. The second peak occurred around cast 70, and was also associated with shallow water and low package rotation. This time, however, the shipboard ADCP velocities are in excess of 60 cm s^{-1} but the ship only went 10 cm s^{-1} on station. The local minimum between the two peaks is due to an increase in water depth (to nearly 2000 m) and a combination of lower on-station velocities and lower upper-ocean velocities. Degradation of heading quality is first seen in stations 25-30 where a strong wind event resulted in high on-station velocities (figure 7, third panel) and led to an increased bias in u.

Figures 16 and 17 show the results of the ADCP - LADCP comparison for the second TCM2 compass. The magnitude of the heading-dependent correction decreased from about 60° to about 40° during the use of this compass. Peaks in LADCP bias appear to be most highly correlated with highest on-station velocity (casts 80-100, figure 17). In addition, there is a decrease in velocity error (primarily in the u direction) over this compass' duration of use as the magnitude of the correction decreased.

The last third of the data were collected using a KVH compass. These ADCP - LADCP comparison improved only slightly with the heading-dependent correction. The results of the compass corrections are shown in figure 18.

5 Interpretation of Results

Two models were tested to correct the heading errors: heading-independent and heading-dependent (modeled as a sinusoidal function of measured heading). The data do not support a heading-independent error for the following reason. The most reasonable physical explanation for a heading-independent error is a misalignment of the transducers relative to the LADCP chassis. This implies that the heading correction is constant for all package orientations and for the duration of the installation. Figure 11 shows the rapid changes in the heading-independent correction over time in the Nov 1997 cruise. These changes are not compatible with the physical explanation for a heading-independent error. Therefore, the error must be heading-dependent.

Arguments made in section 2.1 give plausible physical explanations for a heading-dependent error. Emperical evidence (section 2.1) indicates that modeling the heading-dependent error as a sinusoidal function of measured heading captures most of the signal. Another way to evaluate this model of heading-dependent error is to note that the mean ADCP - LADCP difference in each of the u and v components decreased: a small bias remaining indicates that an error is still present in the heading.

The sinusoidal function of measured heading was chosen for the final data correction. However, in order to improve the model, one must answer the unresolved question: "What caused the extreme degradation of the heading measurements in the LADCP during the November 1997 cruise?". The two best explanations are a spurious magnetic field fixed in package coordinates, and a failure of the TCM2 compasses (eg. calibration or electronics). Both of these problems give similar signatures in the heading distortion. Evidence we can use to help make a distinction includes the empirically determined heading correction, sampling conditions, compass type, rosette used, and the earth's magnetic field.

Over the cruise track, changes in earth's magnetic field and the amplitude of the heading correction are highly correlated. Figure 20 shows this for the three "repeat" cruises: it is clear that in general corrections are highest closer to the magnetic pole. Figure 19 shows the total magnetic field strength, the inclination (the dip of the magnetic field in degrees down from horizontal), and the horizontal field strength. A miscalibrated compass or a spurious magnetic field will distort the measured headings because of the interaction between the local total magnetic field and the spurious magnetic field. A constant strength spurious magnetic field will have a much stronger effect on the heading error near the magnetic pole because of the relatively weak horizontal field strength.

The erroneous headings in the Nov 1997 cruise could not have been due to proximity to the magnetic pole. Figure 21 shows a comparison of identical station locations sampled by the same instrument on the two 1997 cruises. Although the on-station ship speed is high for both cruises, the magnitude of the corrections is radically different. The model used (sinusoidal function of measured heading) corrects the data from the bad compasses (blue and green, right panel, figure 21) to a similar level of comparison with the ADCP data (seen in the May 1997 cruise (red)).

The erroneous headings in the Nov 1997 cruise could not have been due to a compass failure. Although the amplitude of the heading correction is highest overall for the two TCM2 compasses used at the beginning of the Nov 1997 cruise, those two compasses were thoroughly tested after the cruise and revealed no problems. The instrument itself has been used subsequently and gave no indications of failure.

The erroneous headings in the Nov 1997 cruise could not have been due to the type of compass alone. The data collected that required the smallest amplitude correction were also collected with the same TCM2 compass.

The best explanation for the patterns of heading-dependent correction seen in figure 20 is the presence of a spurious magnetic field on the small rosette. This explanation is consistent with the following observations. (1) The data collected on the small rosette were worse than the data collected on the larger rosette. (2) Data collected using the TCM2 compasses were worse than data collected with the KVH compass, and yet the best data collected with a TCM2 compasses. The TCM2 compasses use three directional sensors, whereas the KVH compass uses two external tilt sensors and the compass itself is gimbaled. If a spurious magnetic field on the package were not horizontal, the TCM2 compasses would measure a larger projection of the (now incorrect) vertical field component onto the horizontal than would a KVH compass. (3) The TCM2 compasses were sent back to the company for evaluation after the cruise and showed no problems. (4) data collected with the small rosette on the two meridional lines in July and August 1997 (in the midlatitude western North Atlantic, far from the magnetic pole) needed no correction.

6 Conclusions

If there is no error in the heading, then there should be no consistent difference between ADCP and LADCP velocities. If there is a compass error then the combination of package headings, velocities measured, and the nature of the compass error will probably lead to a bias in the velocities. In comparing ADCP and LADCP velocities, this would be revealed as a nonzero bias in u or v over a collection of casts. The presence of such a bias is an indication of a compass error. If a bias persists in the presence of rotating packages and a variety of on-station velocities, it is possible a heading-dependent error is the cause.

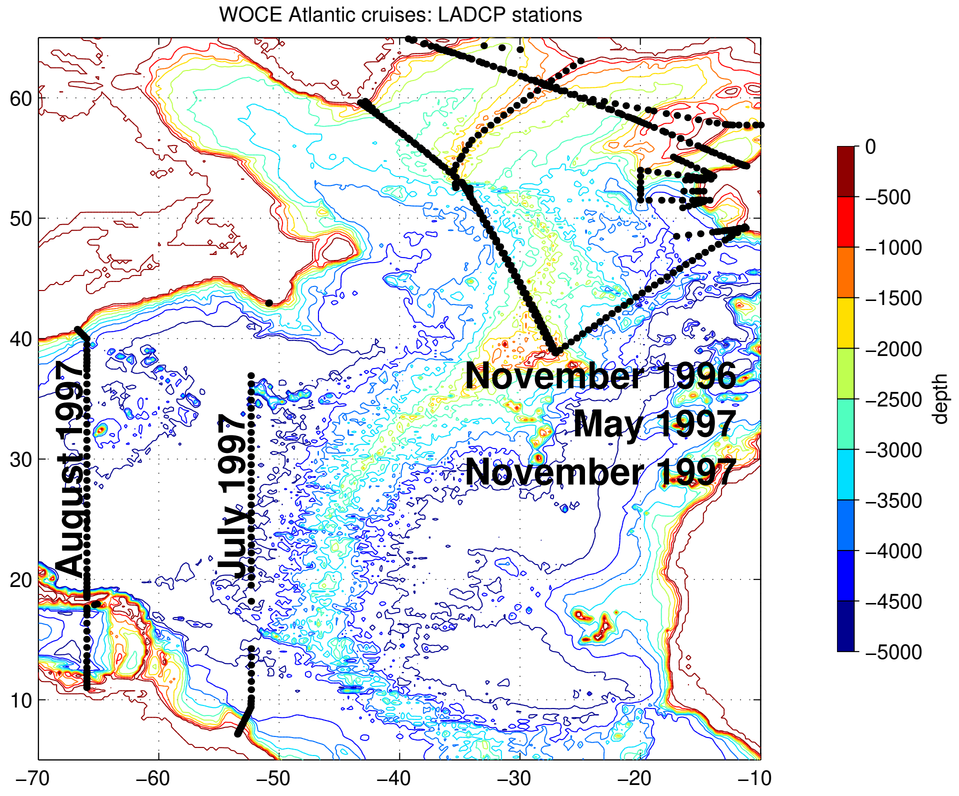


Figure 1: Locations of LADCP samples taken during five North Atlantic WOCE cruises of the R/V Knorr. Approximate cruise dates are labeled.

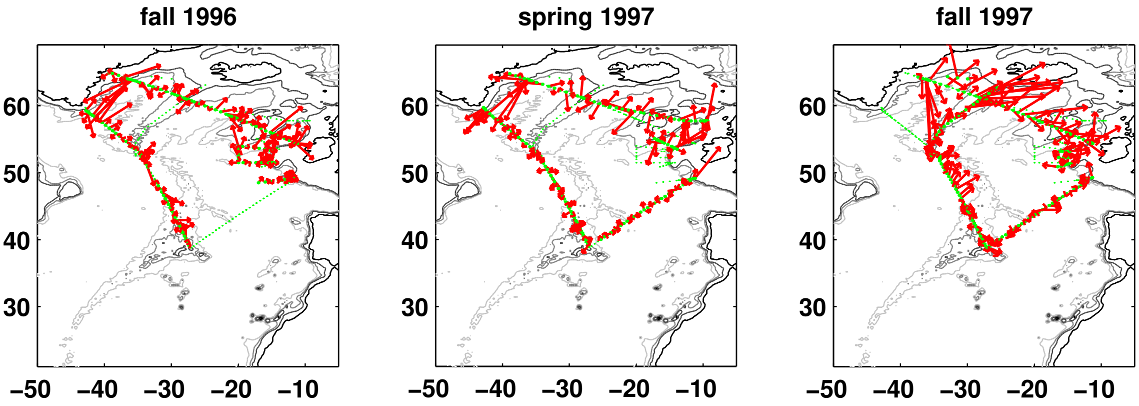


Figure 2: Barotropic velocities measured by the LADCP during the three Atlantic cruises (shown in red arrows) overlaid on bottom topography and the total collection of station locations (in green). Although there is strong flow against Greenland and near Great Britain, and marked variability in the northernmost line, the LADCP the barotropic velocities in the northern half of the fall 1997 cruise are clearly not realistic.

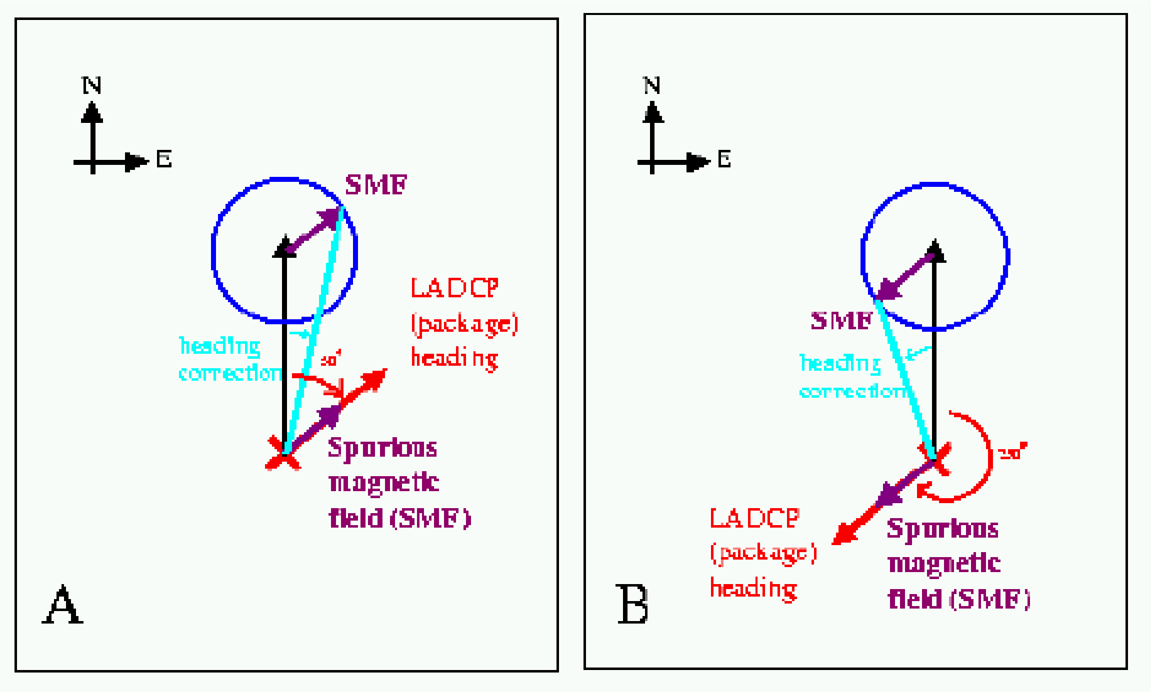
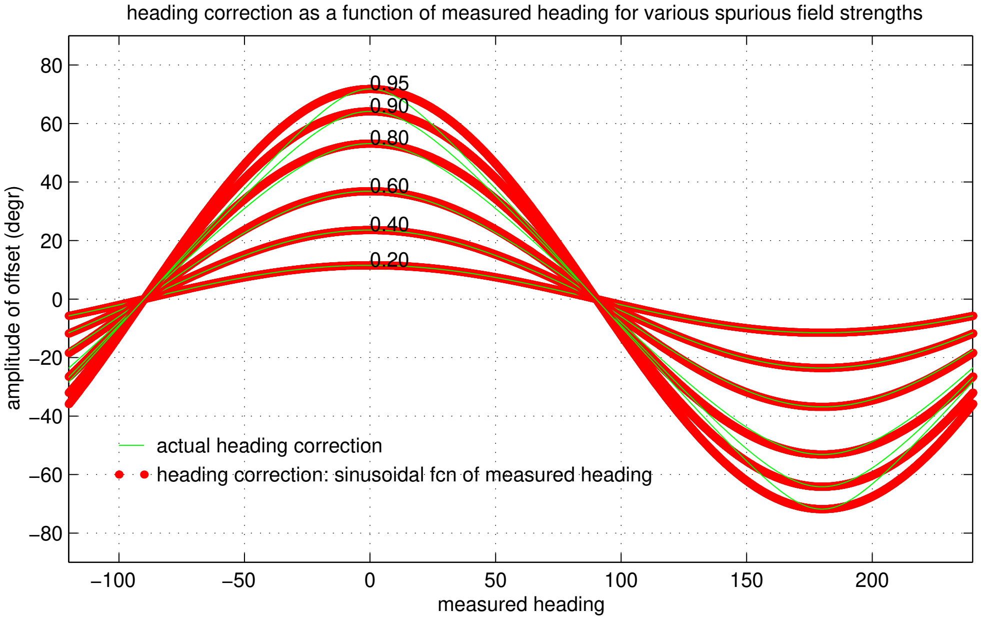


Figure 3: Plan view schematic showing the geometry of a heading-dependent error due to a spurious magnetic field that is constant in the package coordinates. Package coordinates are shown in the red axes; earth's magnetic field is shown in black (aligned with the compass rose). Correct heading is the sum of measured heading (in red) and heading correction (shown in light blue).



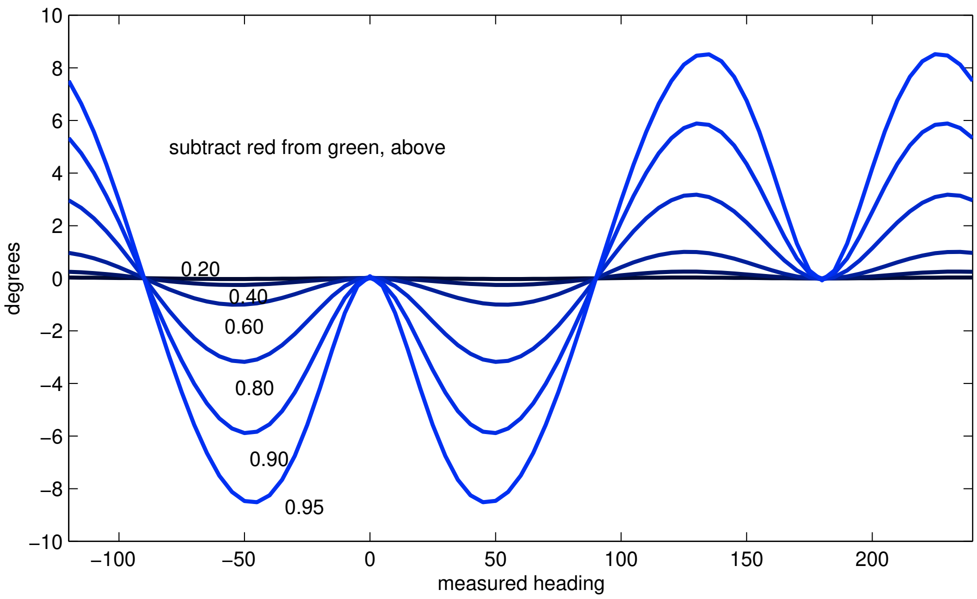


Figure 4: Heading-dependent error modeled as a sinusoidal function of measured heading. Top: heading-dependent error for different horizontal strengths of the spurious magnetic field (as a fraction of earth's magnetic field) plotted as a function of measured heading (green) and modeled as a sinusoidal function of measured heading (red). Bottom: difference between heading-dependent error as a function of measured heading and the sinusoidal model.

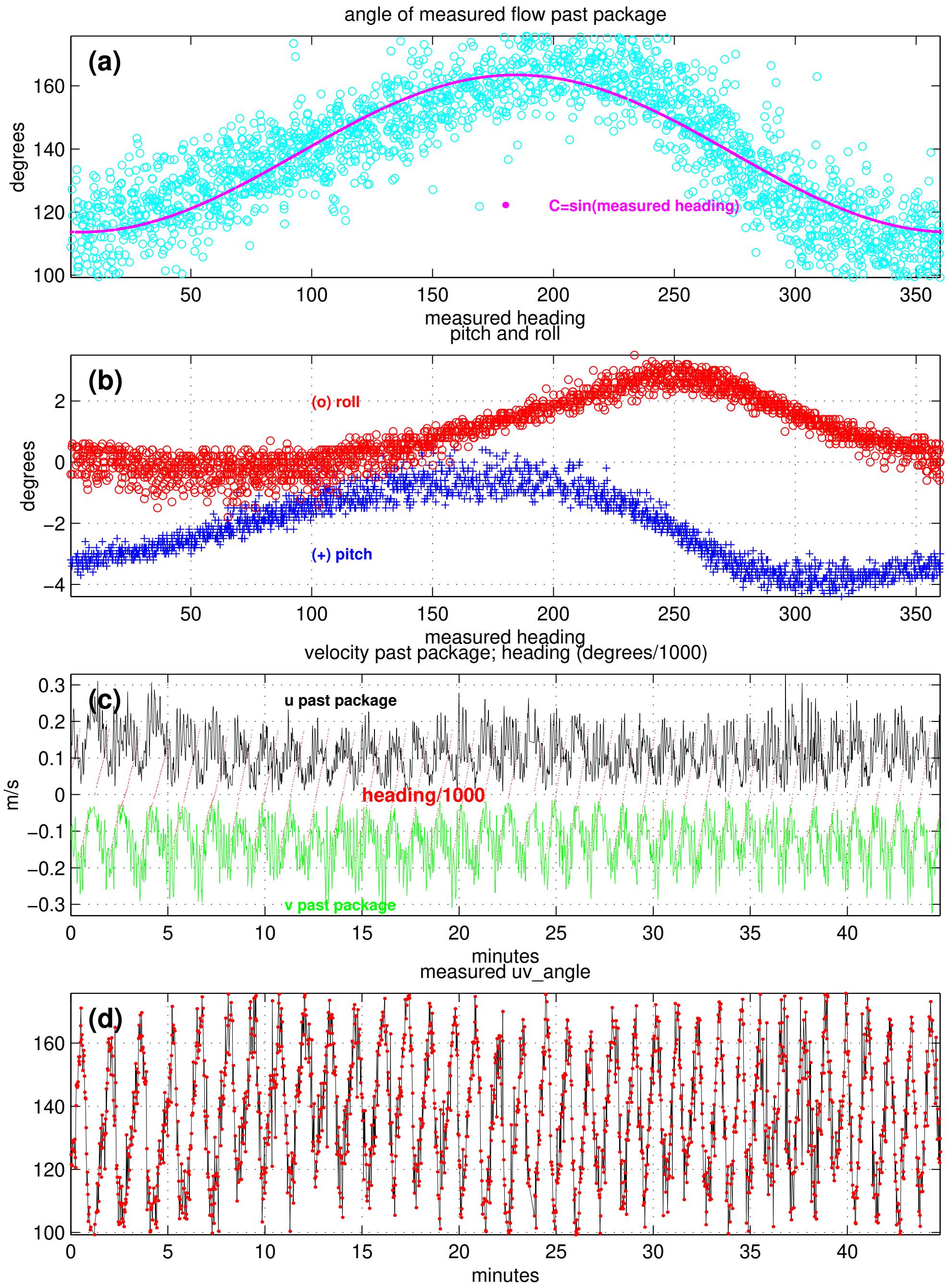
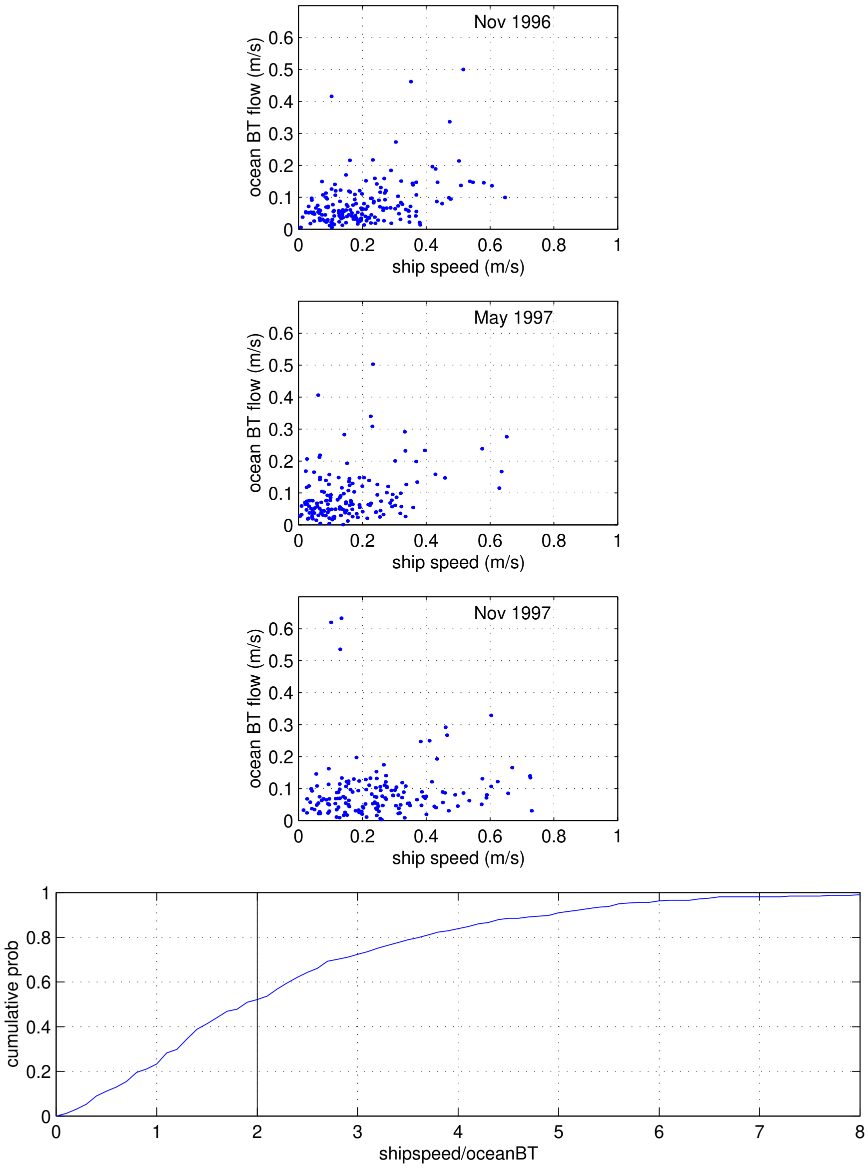


Figure 5: Cast 21, Nov 1997 cruise; (a) measured heading of velocity past the package during a time of strong package rotation (4.9deg/sec); (b) pitch and roll sensor output recorded by the instrument (these are in package coordinates) (c) velocity past the package (m/s) and scaled heading (same as measured heading in the upper two panels) (d) measured heading. The wobble in the measured direction of flow past the package is in part due to the tilt and rotation of the package, but also illustrates the effect of a heading-dependent error on measured velocity.



on–station steaming speeds and ocean barotropic signal

Figure 6: Top 3 panels: average on-station ship's speed (magnitude) plotted against oceanic barotropic flow for the three "repeat" cruises. Bottom panel: cumulative probability for ratio of ship speed to oceanic barotropic signal for all three cruises. Note that approximately 50% of all stations have a ship's speed greater than 2× the local barotropic value.

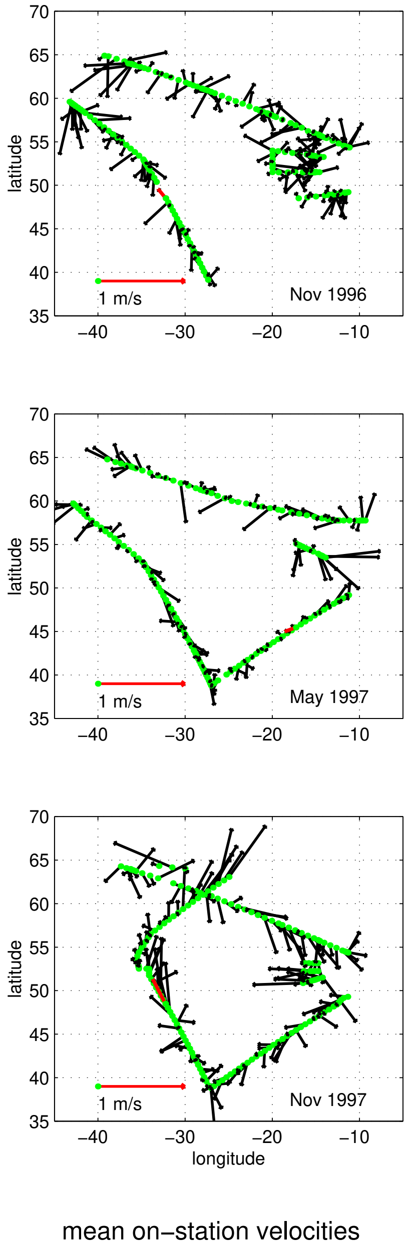


Figure 7: Vectors representing mean on-station ship's velocity for each of the 3 "repeat" cruises. Note that the magnitudes are larger on the two November cruises than the May cruise. This is consistent with the generally higher wind speeds during the November cruises. The third panel reveals coherent groups of vectors: these are associated with strong and sustained wind events which determined the speed and direction of on-station steaming.

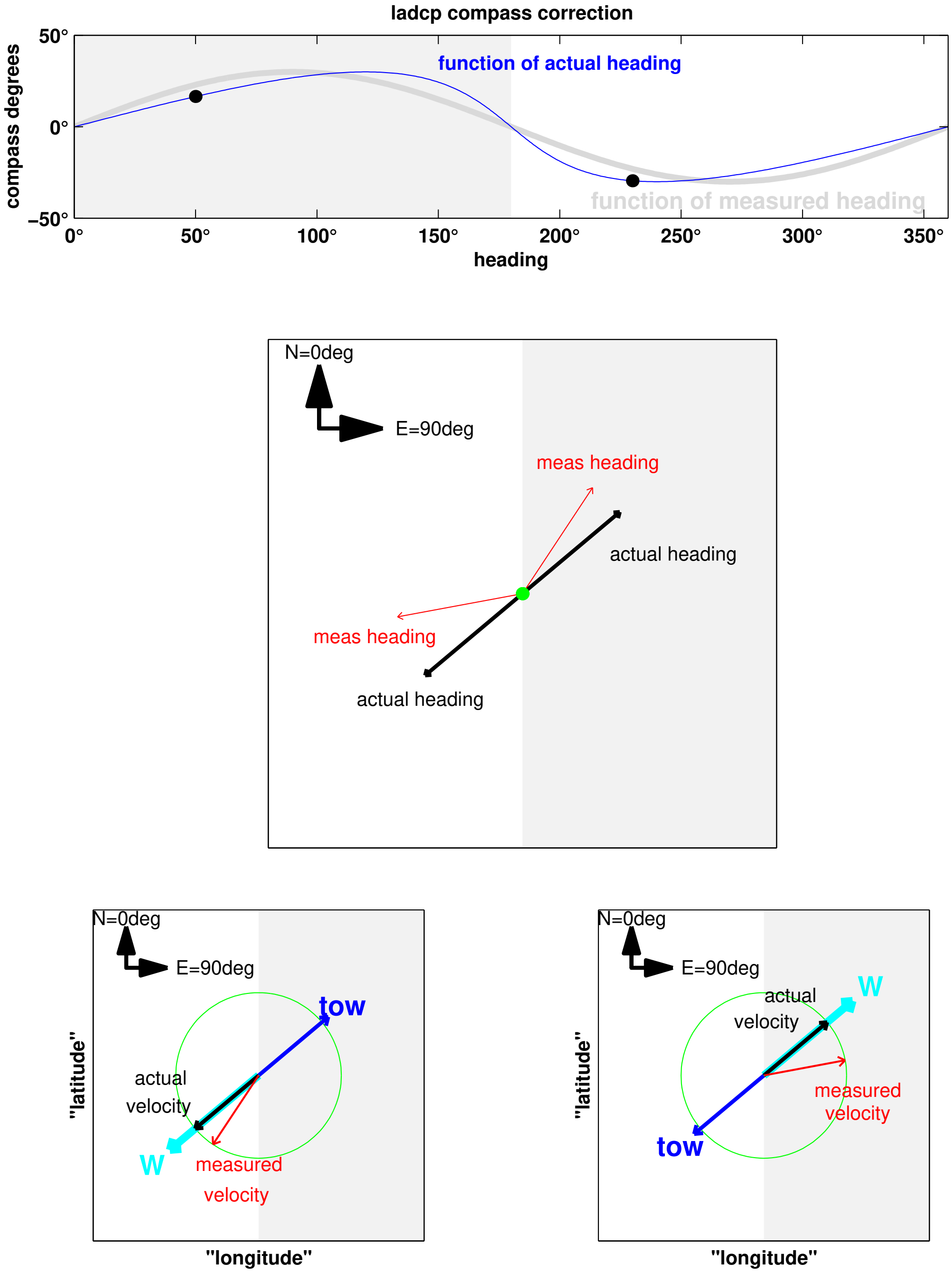


Figure 8: Two examples of heading correction (with the same geometry as figure 3) are used to illustrate the effect of a heading-dependent error on measured velocity. The top panel shows the heading correction plotted as a function of actual heading. The points marked “A” and “B” indicate the two configurations “A” and “B” shown in figure 3. The middle panel shows the same two examples in plan view. The effect on measured velocity for these two examples is shown in the bottom panels. In this example, velocity past the package is a result of towing the the package through quiescent water. The towing direction is assumed (for convenience) to be identical to with the actual package heading.

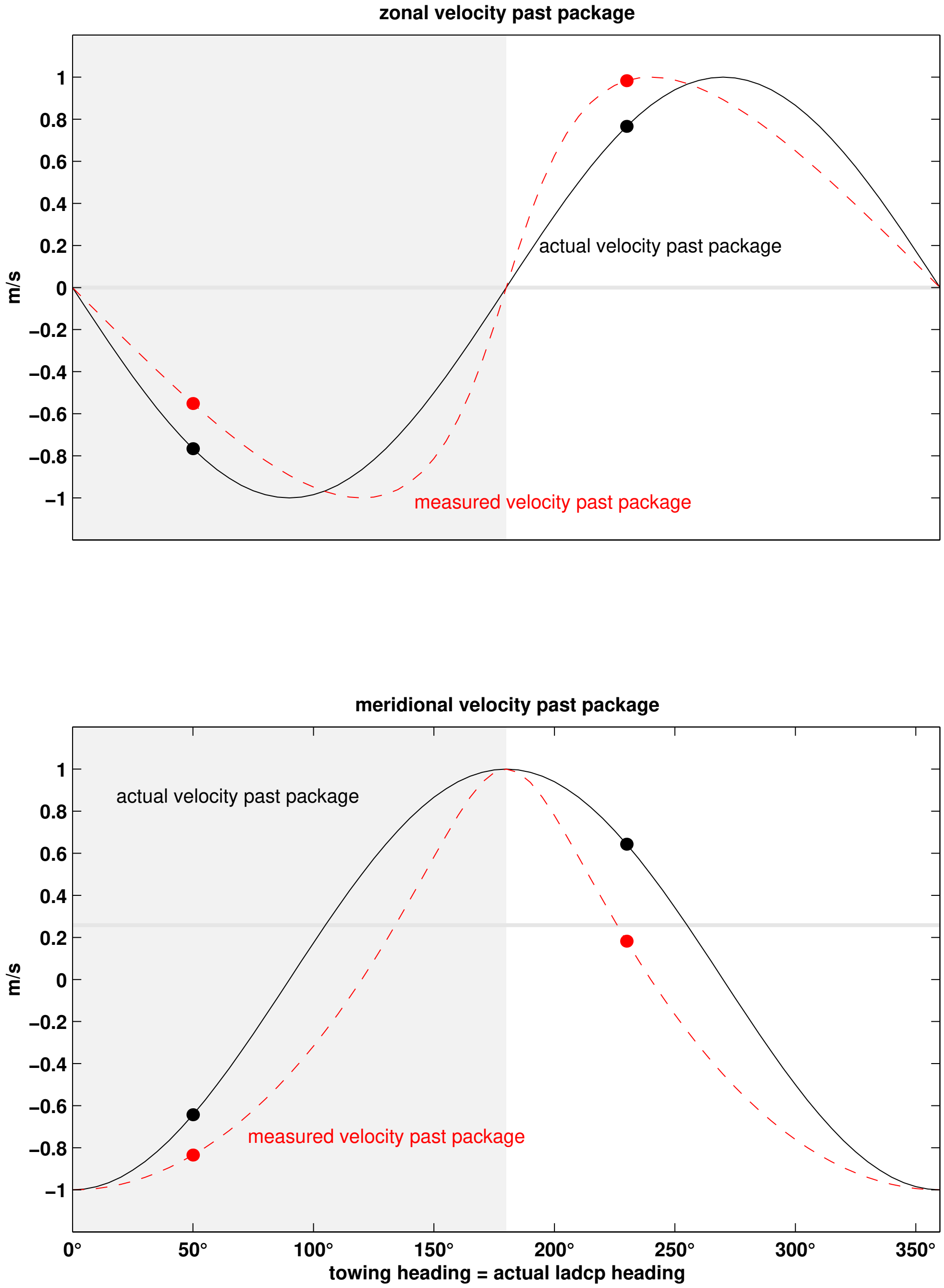


Figure 9: Effect on velocity of a heading-dependent error modeled as a sinusoidal function of measured heading. The heading-dependent correction used in figure 8 (top panel) was applied to all package headings with the flow past the package coming from towing at 1m s^{-1}: the package was assumed to be heading in the same direction as it was towed. The resulting measured and actual zonal and meridional velocities are shown. The dots indicate the same actual headings shown in figure 8, "A", and "B". Note that the bias in v exists for all headings.

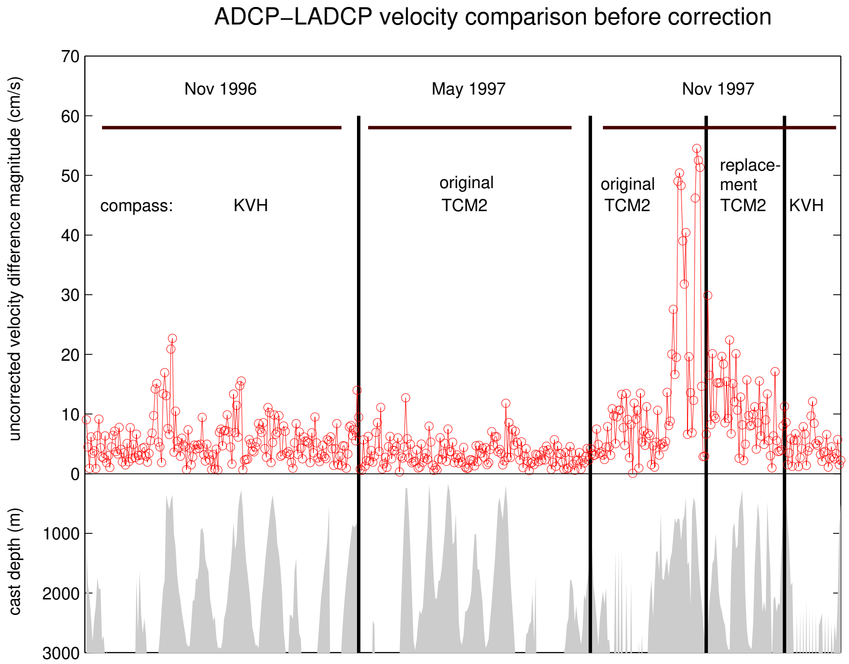


Figure 10: ADCP - LADCP velocity error magnitude for the three eastern North Atlantic "repeat" cruises: (top) velocity error magnitudes shown in red; (bottom) cast depth in meters (gray: cast depth generally followed topography). Compass type is labeled for each cruise. Additional cruise information is contained in the Appendix.

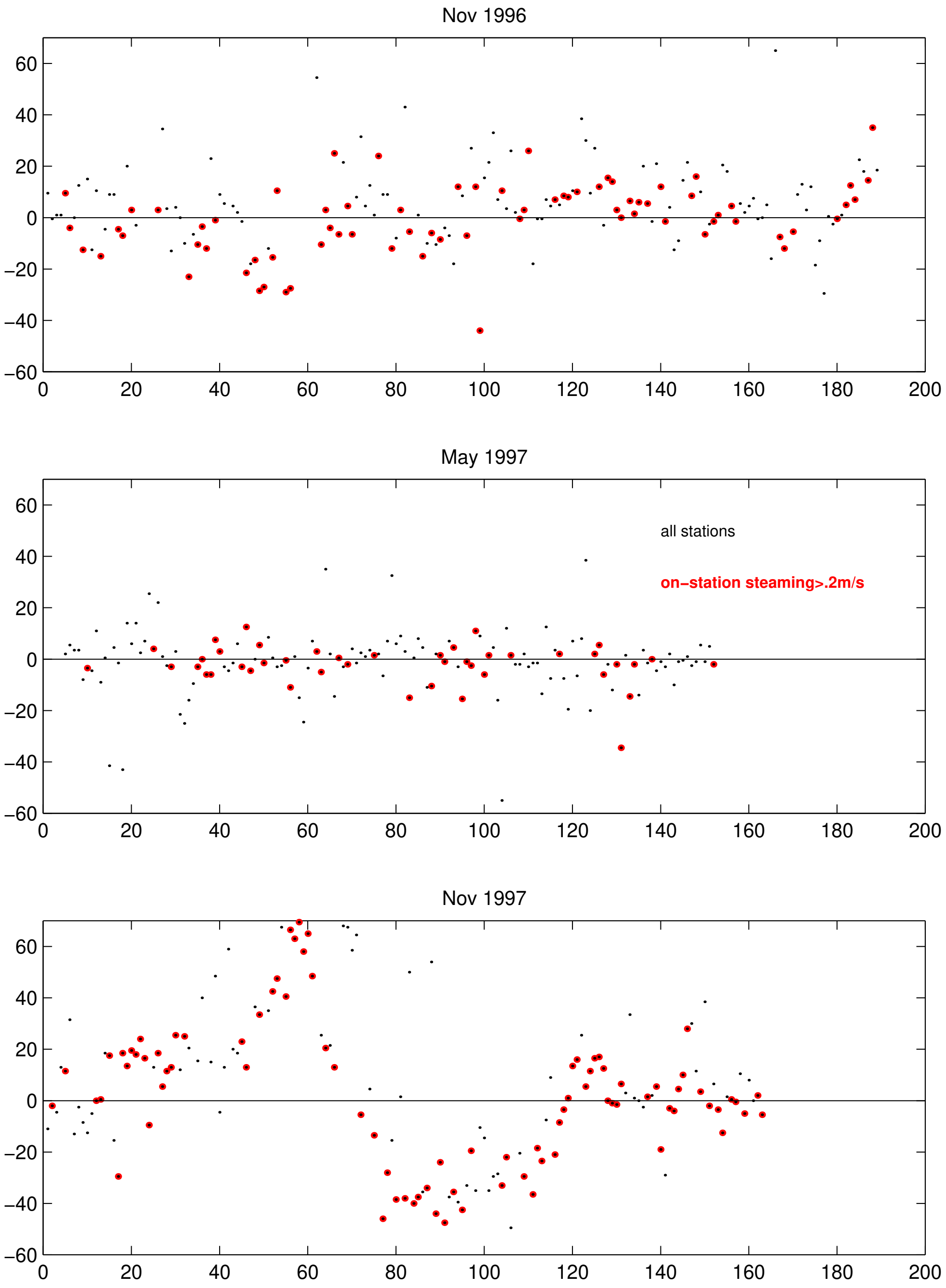


Figure 11: Heading-independent correction which minimizes the difference between LADCP and ADCP data, plotted as a function of cast number. Red dots indicate stations during which on-station steaming exceed 0.2m s^{-1}. Note the extremely high amplitude and rapid variation of calculated correction in Nov 1997. This indicates that modeling the heading error as constant is incorrect.

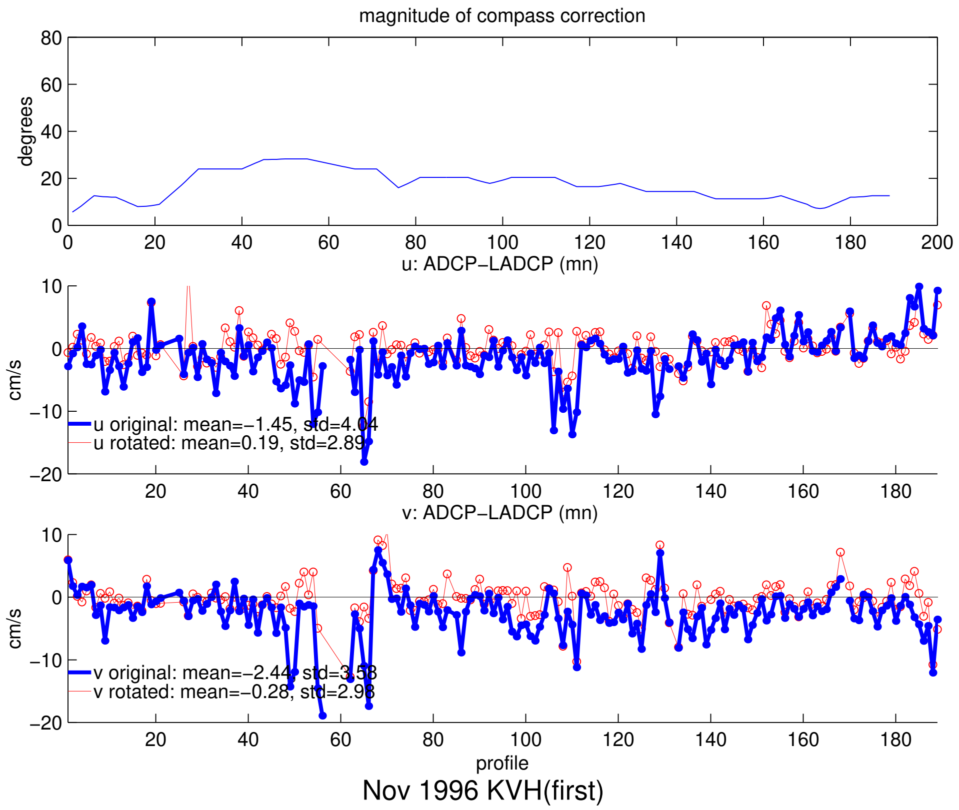


Figure 12: Comparison between LADCP and shipboard data for Nov 1996 cruise: velocity difference ADCP - LADCP for original data in blue and corrected in red.

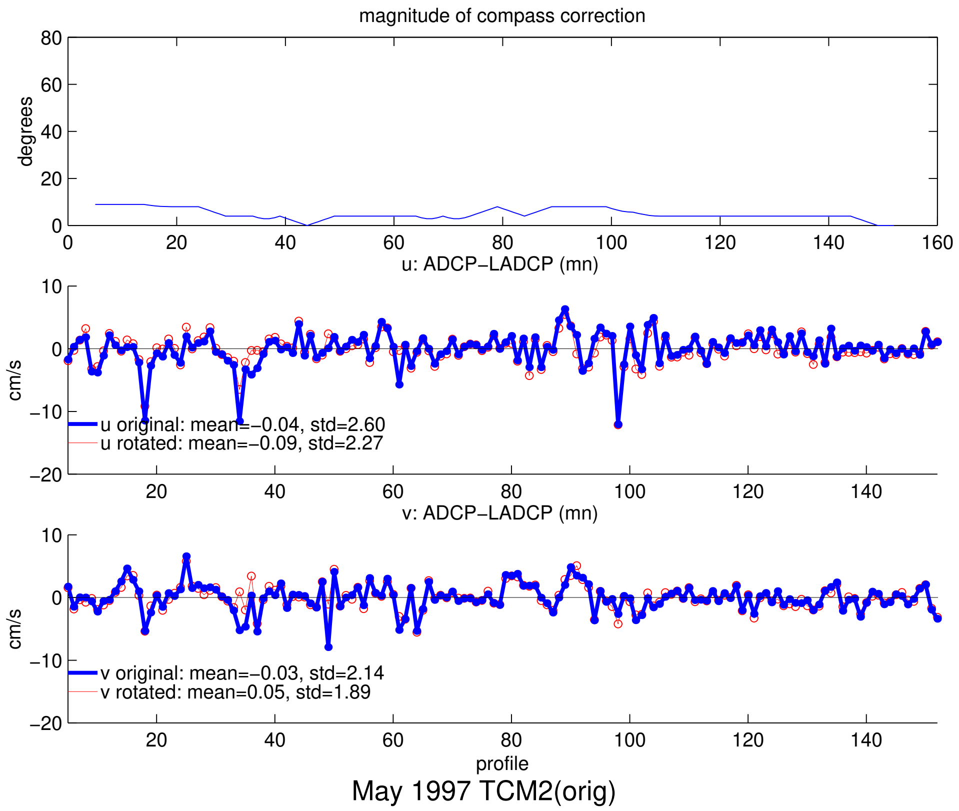


Figure 13: Comparison between LADCP and shipboard data for May 1997 cruise: velocity difference ADCP - LADCP for original data in blue and corrected in red.

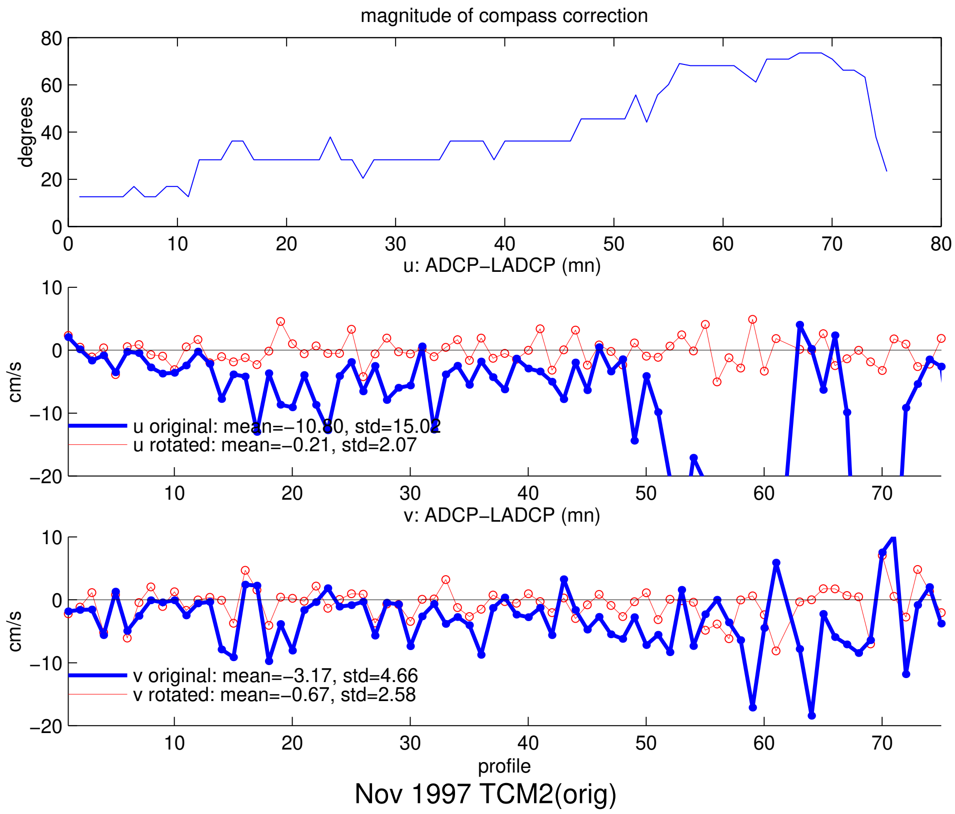


Figure 14: Comparison between LADCP and shipboard data for Nov 1997 cruise casts using the original TCM2 compass: velocity difference ADCP - LADCP for original data in blue and corrected in red.

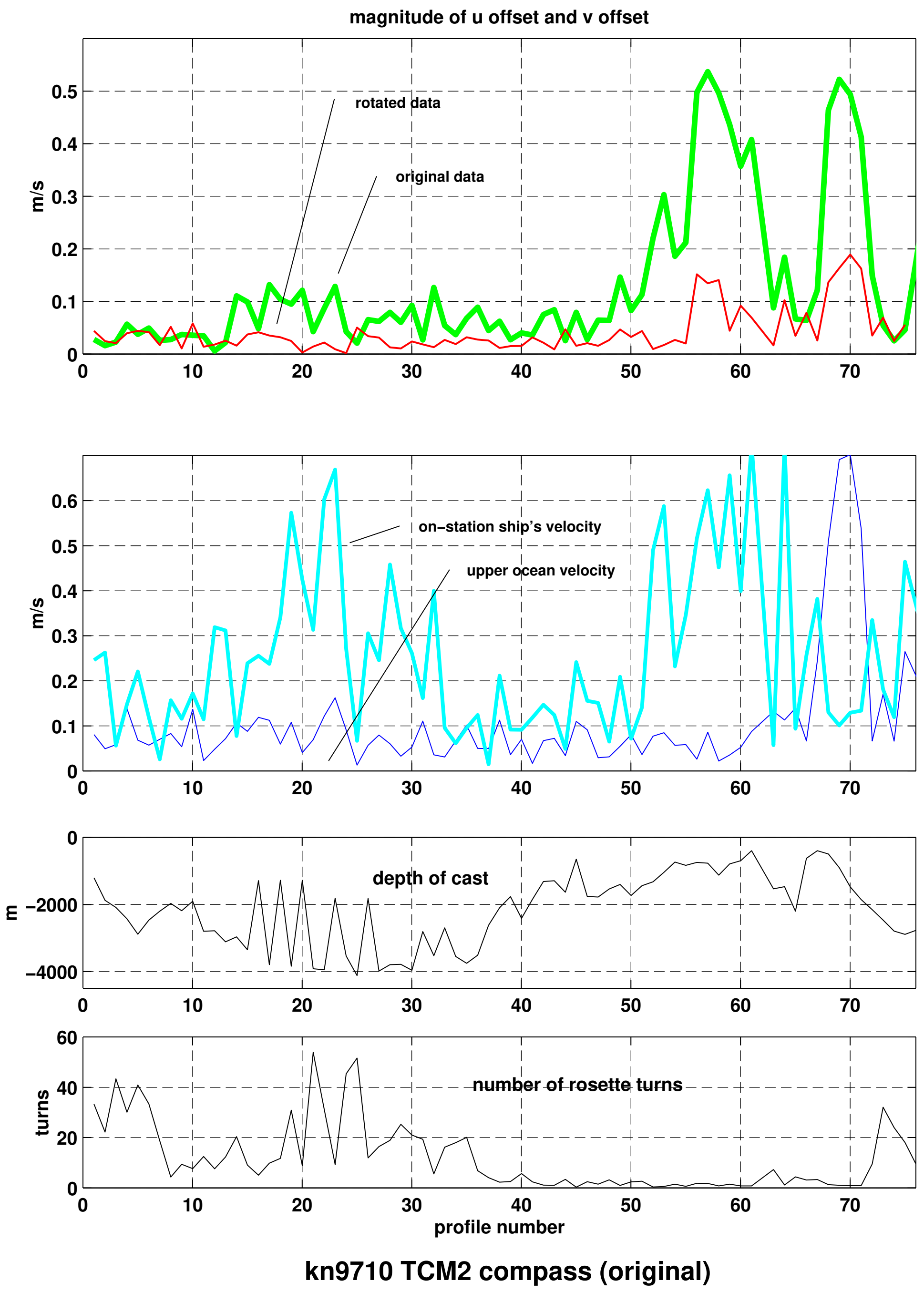


Figure 15: Nov 1997 cruise on-station information for first TCM2 compass. Top panel: magnitude of velocity error before (green) and after (red) correction. Second panel: on-station mean ship's speed and upper ocean ADCP velocity. Bottom two panels: depth of cast and number of rosette turns per cast, respectively.

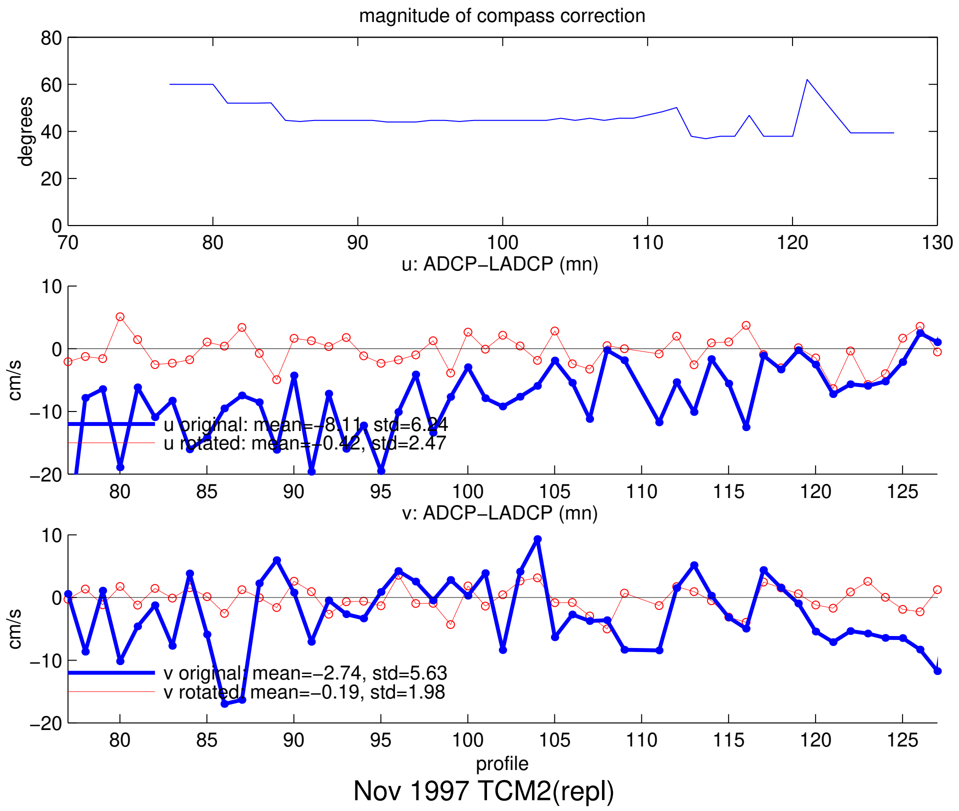


Figure 16: Comparison between LADCP and shipboard data for Nov 1997 cruise casts using the replacement TCM2 compass: velocity difference ADCP - LADCP for original data in blue and corrected in red.

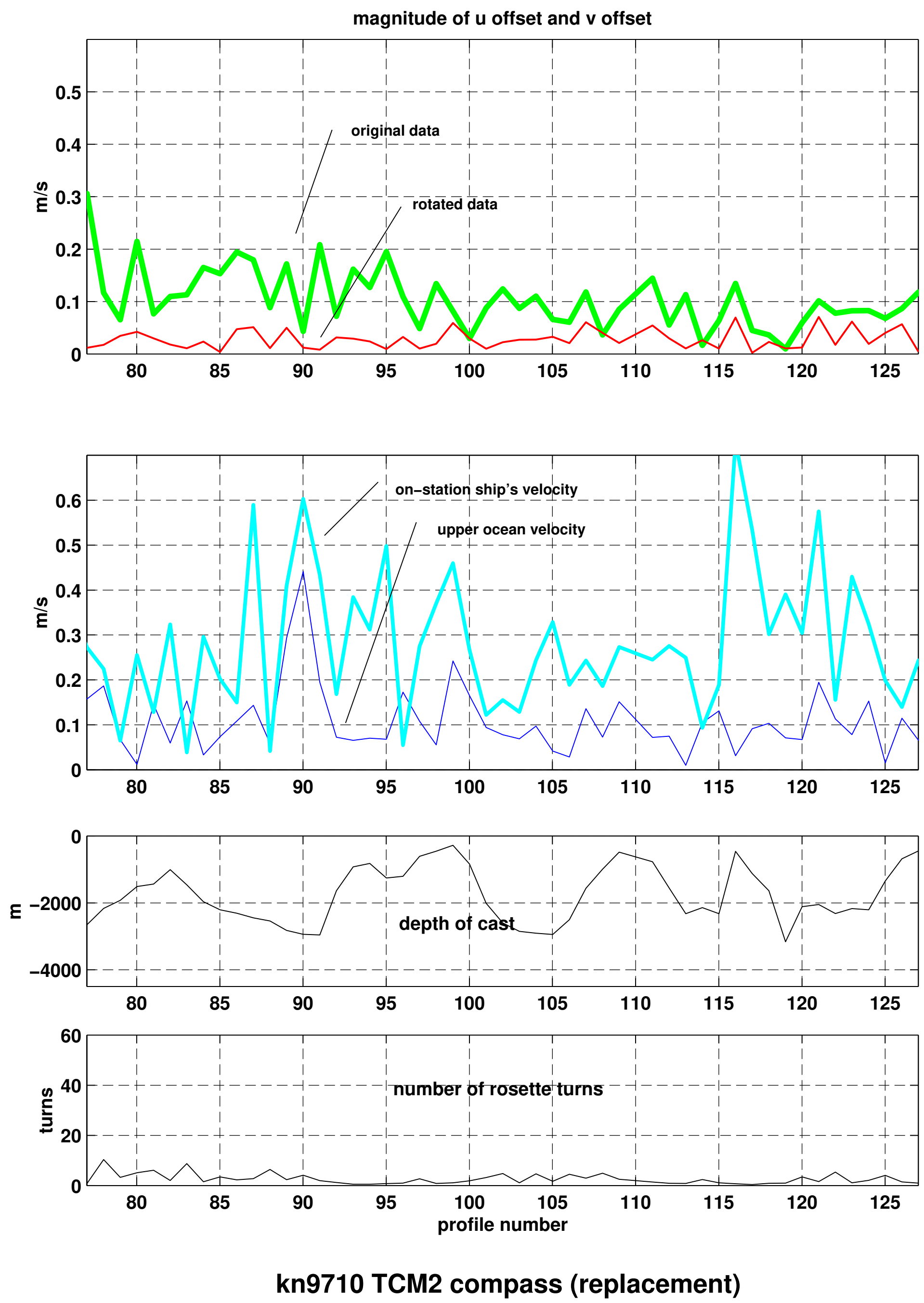


Figure 17: Nov 1997 cruise on-station information for replacement TCM2 compass. Top panel: magnitude of velocity error before (green) and after (red) correction. Second panel: on-station mean ship's speed and upper ocean ADCP velocity. Bottom two panels: depth of cast and number of rosette turns per cast, respectively.

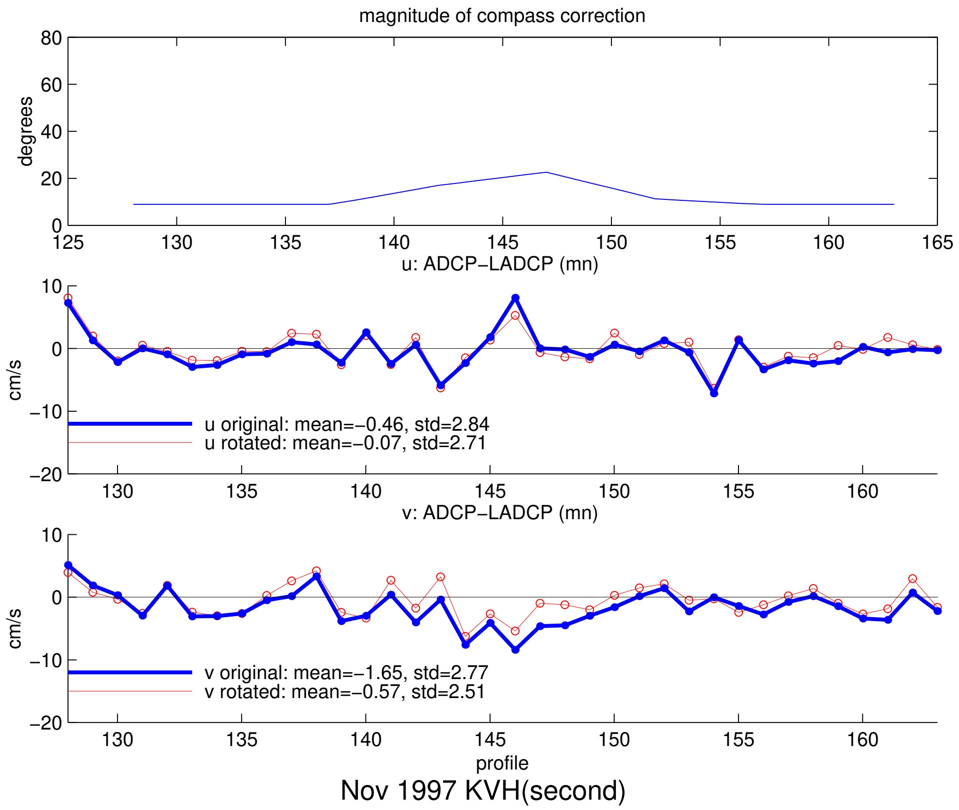


Figure 18: Comparison between LADCP and shipboard data for Nov 1997 cruise casts using the second KVH compass: velocity difference ADCP - LADCP for original data in blue and corrected in red.

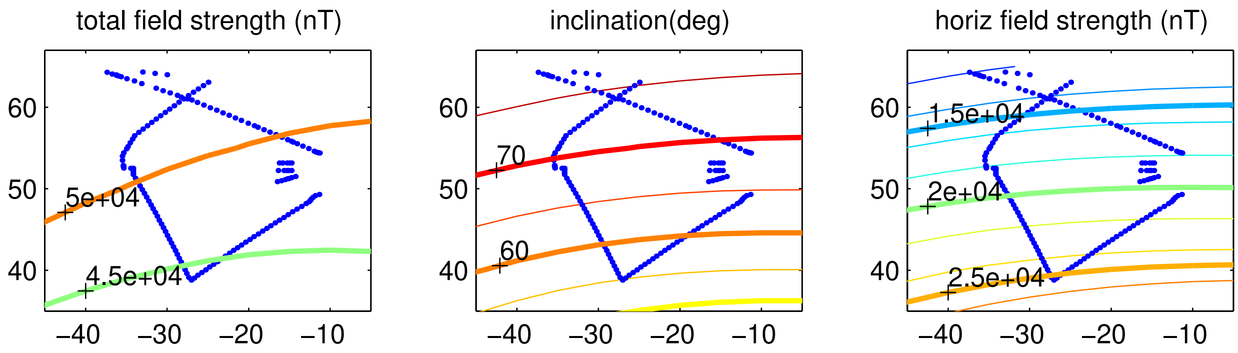


Figure 19: Total field strength (nanoteslas), inclination (dip: degrees down from horizontal), horizontal field strength (nanoteslas) for the North Atlantic. Cruise track (Nov 1997) plotted on top as dots.

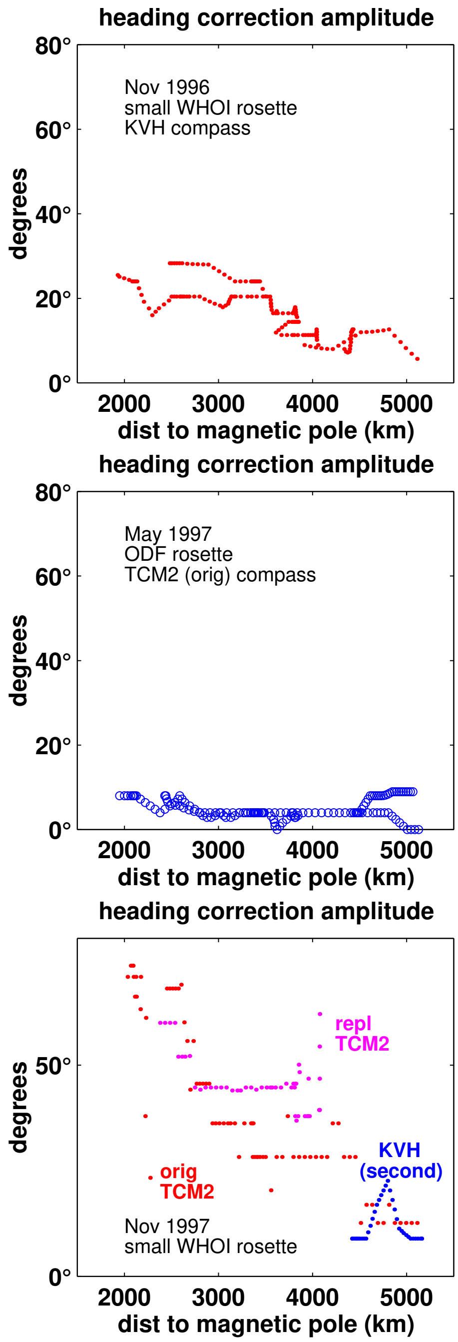


Figure 20: Magnitude of heading-dependent correction (as modeled in figure 3) as a function of distance to the magnetic pole for each of the three cruises. Symbols and colors are used to distinguish between package configurations: dots indicate the small WHOI rosette, circles indicate the larger SIO rosette, red denotes a TCM2 compass, and blue denotes a KVH compass.

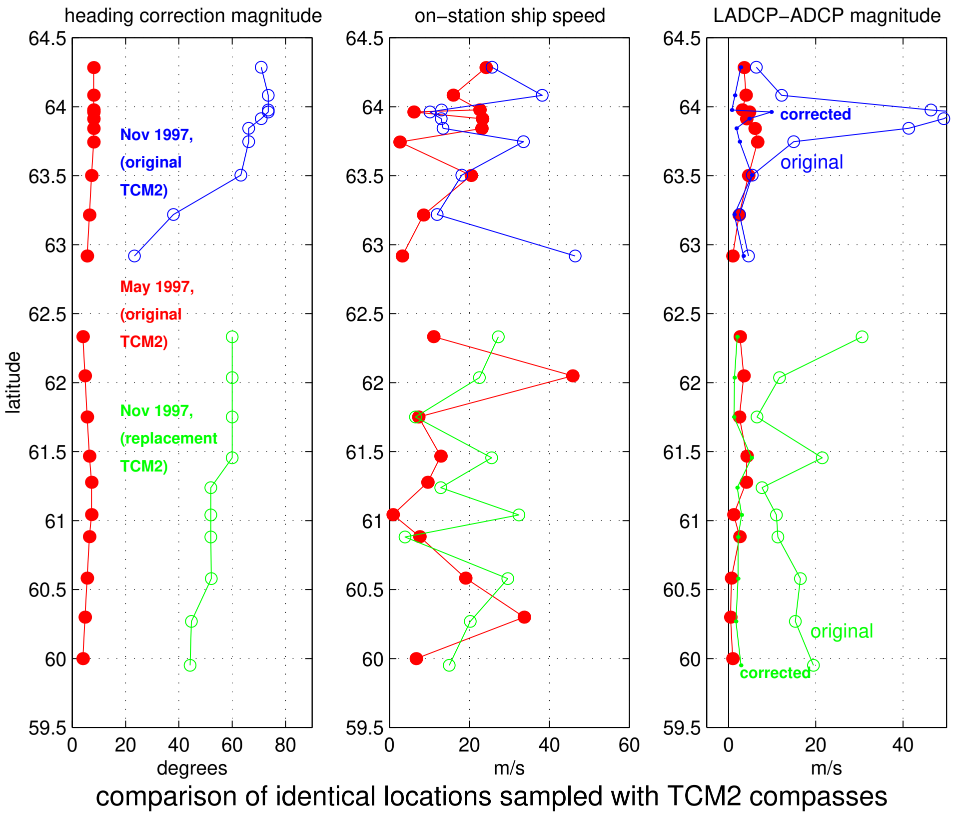


Figure 21: Three panels comparing the magnitude of the heading-dependent correction ($\sqrt{(a^2+b^2)}$), on-station ship speed, and magnitude of ADCP- LADCP vector velocity comparison before and after correction for a group of stations near Greenland during both the May and November 1997 cruises, using the same instrument. The difference between original ADCP - LADCP velocity magnitudes indicates a problem with the LADCP data in the November 1997 cruise.

VELOCITY ERROR (LADCP - ADCP)

	MEAN (cm/s)			RMS ERROR (cm/s)	
	u	v	mag	u	v
orig	-1.45	-2.44	4.81	4.03	3.57
heading dependent	0.02	-0.34	3.32	2.89	3.12
heading independent	-0.59	-0.64	2.73	3.01	2.28
Nov 1996, (KVH (first)):		(n = 175)			
orig	-0.04	-0.03	2.61	2.59	2.13
heading dependent	-0.14	0.02	2.38	2.27	1.92
heading independent	0.07	0.11	1.68	1.61	1.75
May 1997, (TCM2 (orig)):		(n = 148)			
orig	-10.80	-3.17	12.85	14.91	4.63
heading dependent	-0.30	-0.36	2.74	1.87	2.62
heading independent	-1.37	-1.38	3.02	2.66	3.06
Nov 1997, (TCM2 (orig)):		(n = 74)			
orig	-8.11	-2.74	10.48	6.18	5.58
heading dependent	-0.35	-0.14	2.90	2.53	2.03
heading independent	-1.40	-0.46	2.49	2.31	1.95
Nov 1997, (TCM2 (repl)):		(n = 50)			
orig	-0.46	-1.65	3.59	2.80	2.73
heading dependent	-0.25	-0.81	3.48	2.76	2.95
heading independent	-0.46	-1.05	2.62	2.20	2.09
Nov 1997, (KVH (second)):		(n = 36)			

Table 1: Comparison of ADCP - LADCP velocity errors for the three “repeat” cruises. Values are in $\mathrm{cm\ s^{-1}}$.

APPENDIX II

Some summary information regarding these cruises follows:

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)
Pickart (Torres)	kn151_3	kn9707	Halifax–Trinidad	BP EF	WHOI(s) WHOI(s)	?? TCM2(orig)
Joyce (Bahr)	kn151_4	kn9708	Trinidad–WHOI	TJ EF	WHOI(b) WHOI(b)	 TCM2(orig)
(Pickart)	(9/97?)	–N/A–	WHOI–WHOI	EF	WHOI(b?)	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	: compass	firmware
``EF'' Eric Firing	: TCM2 compasses	v5.x
``TC'' Teri Chereskin	: KVH compass	v5.x
``BP'' Bob Pickart	: ? (Transducers failed)	v5.x
``TJ'' Terry Joyce	: KVH compass	v4.x
``EFTJ'' Firing instrument with Joyce compass + xducer driver boards		v5.x