

Accurate Ocean Current Direction Measurements Near the Magnetic Poles

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ABSTRACT

Ocean current direction measurements through the Canadian archipelago have required development of a strategy that uses specialised instrumentation to cope with the small horizontal component of the earth's magnetic field in this region. Subsurface instrumented moorings collecting bihourly data through yearlong deployments, use precision heading reference systems to measure the orientation of Acoustic Doppler Current Profilers mounted in streamlined buoyancy packages. Current directions are then corrected for the significant fluctuations in magnetic declination occurring near the magnetic pole, using data from a nearby geomagnetic observatory.

Concurrent observations of current speed and direction from independent moored measurement systems are shown to be in good agreement.

KEY WORDS: current direction measurement, low magnetic field, polar, Arctic mooring instrumentation, magnetic pole

INTRODUCTION

Current measurements near the magnetic poles require special strategies and instrumentation to adequately resolve direction. This is because of the small horizontal component of the earth's magnetic field there that renders compasses in commercially available current meters ineffective, and also because of the requirement to correct for the variation in magnetic declination that occurs there. (Magnetic declination is the angle between true north and magnetic north.) A third difficulty is that the weak horizontal field increases the potential for contamination of direction measurements by magnetic mooring hardware.

A field program to quantify heat and salt fluxes through Barrow Strait was started in 1998. Barrow Strait is one of three main connections between the Arctic Ocean and the Northwest Atlantic. The program required the development of a methodology to collect yearlong current rate and direction data only 700 km from the North Magnetic Pole (see Fig. 1), where the dip angle (the angle that the magnetic field vector makes with the horizontal) is 88.2° . Here, the force imposed by the horizontal component of the magnetic field is

insufficient to reliably overcome the friction in the pivot of a conventional compass. While some commercially available current meters have conventional compasses, others employ a gimballed 2-axis fluxgate magnetometer to measure the horizontal component of the earth's magnetic field. Where the horizontal field strength is low, insufficient precision of the fluxgate sensor or inadequate tilt compensation, results in substantial errors in the computed direction.

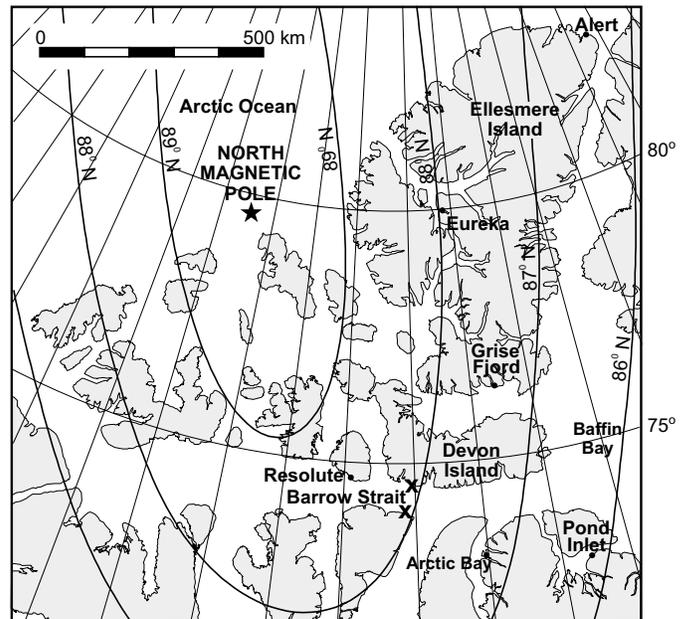


Fig. 1 The northern half of the Canadian Arctic Archipelago. The contours centered around the North magnetic pole indicate the dip angle (the angle of the magnetic vector relative to the horizontal). Mooring arrays are deployed at each of the "X"s in Barrow Strait. This Figure has been extracted with permission from a larger map, "Magnetic Inclination Chart of Canada 2000", Larry Newitt, Geological Survey of Canada, NRCAN.

Even with an accurate compass, variation in pole position results in significant changes in magnetic declination when the measurement site is near the pole. While movement in the earth's molten core accounts for gradual change in pole position over the years, interaction between charged particles emitted from the sun and the earth's magnetic field cause the pole to trace a roughly elliptical path around its mean position during a day. The rate of change of position and the maximum daily displacement varies with the magnitude and nature of the solar activity, but displacements of up to 80 km and significant changes over a 1-hour period frequently occur (Newitt, 1998). The magnitude of the resulting variation in declination depends on the distance from the pole. This variation in declination must be corrected for, to get an accurate direction relative to true North.

Another consideration is the potential introduction of errors with magnetic mooring components not accounted for in the compass calibration. Where the horizontal field strength is low, the introduction of ferrous materials, and the distance at which these materials can have an impact, must be considered.

The strategy described here uses a combination of commercially available equipment to overcome the near-pole direction measurement problem. The orientation of an Acoustic Doppler Current Profiler mounted in a streamlined buoyancy package is measured with a precision heading reference system. The measured magnetic heading is adjusted for the varying declination with measurements from the Natural Resources Canada (NRCAN) geomagnetic observatory in Resolute to obtain direction relative to true North.

METHODOLOGY AND INSTRUMENTATION

Year long deployments of instrumented subsurface moorings have provided uninterrupted, bihourly time series of current, temperature and salinity data on both sides of Barrow Strait starting August, 1998. The area is ice-covered for 10 months of the year, and with the probability of ice ridging and bergs, the moorings are designed not to extend into the top 25 m of the water column. While this reduces the chance of losses due to ice it does not eliminate the possibility, so instrumentation is distributed over four moorings at each of the Northern and Southern sites. In this way the higher risk, near-surface CTD (conductivity, temperature, depth) measurements can be made from moorings supporting a single instrument only (see Fig. 2).

To measure water speed and direction, a buoyancy package supports an Acoustic Doppler Current Profiler (ADCP) and heading reference system. By combining these three commercially available components into a single, manageable package (see Fig. 3), there is now a reliable and convenient strategy for measuring currents in areas where the horizontal component of the earth's magnetic field is too low for conventional instrumentation to be useful.

The System Components

The Acoustic Doppler Current Profiler (ADCP)

The ADCP being used is the RD Instruments Workhorse Sentinel, WH-300. This instrument measures currents out to a 100 m range by transmitting sound pulses and listening for frequency-shifted reflections from particles in the water column. This technology makes it possible to avoid the risk of penetrating the near-surface area to collect current information. Used in an upward-looking configuration with "bottom-tracking" mode on to provide the ice drift speed as well as current speed, it measures and stores bihourly profiles for a full year on its own internal battery.

The compass in the RDI Workhorse is a floating fluxgate magnetometer. The specified uncertainty in heading is $\pm 5^\circ$ at a dip

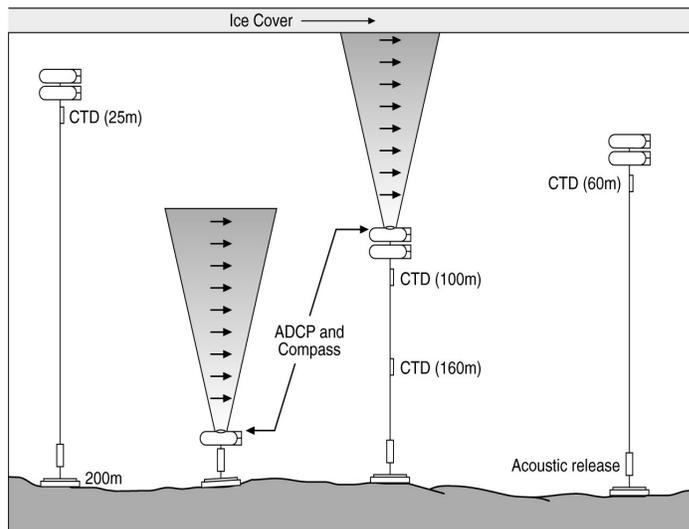


Fig. 2 Mooring array deployed at each of two sites in Barrow Strait. Currents, temperatures and salinities are sampled every 2 hours throughout each yearlong deployment.

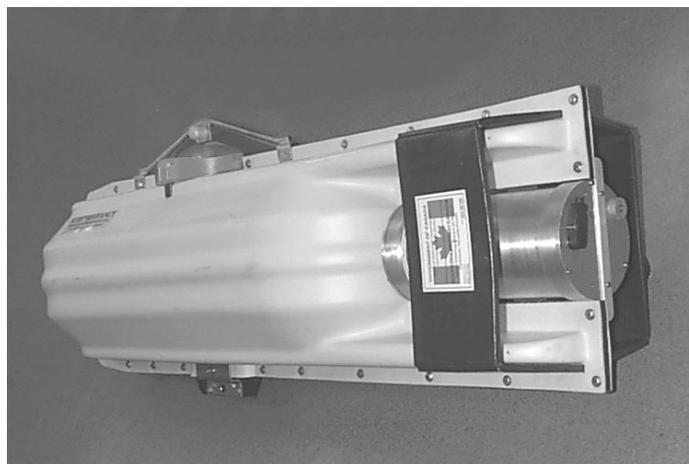


Fig. 3 The instrumented SUB assembly used to measure current speed and direction near the magnetic pole. The instrument mounted vertically through the SUB is an Acoustic Doppler Current Profiler. The instrument in the tail measures the SUB heading.

angle of 60° . Tests in a laboratory generated magnetic field (NRCAN Geomagnetic Laboratory at Ottawa) show that for a dip angle of 82° (as occurs at the South end of Baffin Bay, and the western edge of the Beaufort Sea, for example), errors in heading of 10° can be expected. In a magnetic field corresponding to the field at our mooring site where the dip angle is 88.2° , the ADCP compass performance is inadequate giving errors of over 30° (see Fig. 4). Performance may in fact be worse in an actual deployment than shown in Fig. 4 owing to the potential impact of any instrument motion or variation in tilt, which were not simulated in the laboratory tests.

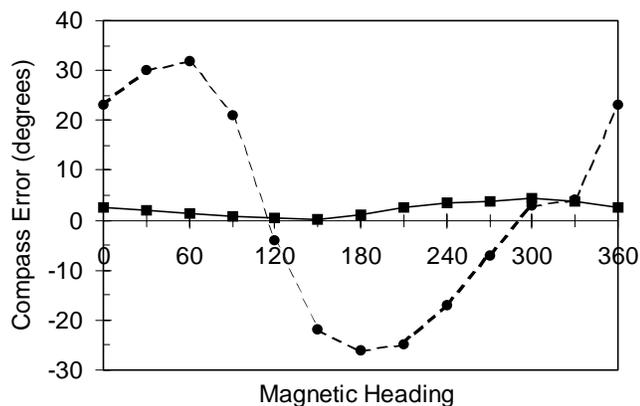


Fig. 4 Compass performance at the magnetic dip angle expected at the mooring site (88.2°). The dashed line is for the ADCP floating fluxgate magnetometer, while the solid line is for the Watson heading reference. Tests were done with an assembled SUB unit (Fig. 3), at the Ottawa NRCAN Geomagnetic Laboratory.

The Heading Reference System

The compass chosen for this low horizontal field strength application is a Watson Industries, Inc Strapdown Heading Reference System (SHR-360); a 3-axis fluxgate magnetometer with patented precision tilt indicators. The tilt information is used for co-ordinate transformation of the magnetometer outputs, rather than reliance on a gimbal to keep the sensors level. The strapdown sensor method has an advantage in calibration. Heading sensor calibration can compensate for any magnetic influences from the overall assembly into which the sensor is installed. With the strapdown sensor, its orientation relative to the system into which it is installed will not change. A calibration that involves "swinging" the entire assembly will therefore minimise the impact of any magnetism in the assembly.

A microprocessor/data logger provides the interface to the Watson heading reference. The sensor, microprocessor/data logger and a non-magnetic, 11 Volt lithium battery pack are all housed in a 35 cm long, 6-inch diameter aluminium pressure case. The assembled case is neutrally buoyant so that it does not alter the balance of the buoyancy package on to which it is mounted. Care has been taken to avoid magnetic components in this case. It is worth noting that 316 stainless steel can have a magnetic signature.

The performance of the Watson heading reference in a magnetic field corresponding to that expected at our mooring site is also shown in Fig. 4.

The Streamlined Buoyancy Package

The ADCP and compass are mounted in an "A2-SUB" streamlined buoyancy package, manufactured by Open Seas Instrumentation, Inc. SUBS were developed at the Bedford Institute of Oceanography to improve data quality in instrumented subsurface moorings (Hamilton et al, 1997). The model A2 is designed specifically to house an RD Instruments WorkHorse ADCP. It provides a stable, low-drag instrument platform over a range of flow speeds. The only required modification is a cut-out in the tail to allow for mounting the compass case along the central axis of the SUB. The stabiliser on the tail is designed to maintain alignment into the flow and minimise changes in pitch with flow speed. A constant alignment relative to the flow is

critical in our application. This will be discussed in the next section.

The use of the SUB also provides for 0.5 m separation of the heading sensor from the ADCP. A compass calibration that involves swinging the entire instrumented SUB package will compensate for the magnetic signature of the ADCP, but as the ADCP battery discharges, this field may change. Increased separation will minimise any potential heading error created by this effect. The compass is also more than 0.5 m from any mooring hardware. Although shackles and swivels used are 316 stainless steel, the mooring wire and shackle seizing wire are magnetic. The separation also prevents magnetic contamination from this source.

All fasteners and hardware on the SUB are from 316 stainless steel, and individually tested for magnetism.

Sampling Scheme

Current speed and direction are measured every 2 hours over the yearlong deployment. Synchronisation of the ADCP and compass samples is straightforward, using the trigger pulse output capability of the RDI ADCP (the RDS³ interface) and a hard wire connection to the compass.

To obtain the desired resolution in the measurements of water speed, 100 ADCP measurements are averaged over a 5-minute period at the required sample interval of 2 hours. If instrument heading changes significantly over the 5-minute period, a means of obtaining a representative direction from the compass must be devised. An obvious approach is to sample direction over the entire 5-minute period and compute an average to combine with each ADCP average, but the battery requirement to run the compass for the full 5 minutes is too great.

In the system described here, the SUB ensures a constant alignment relative to the flow. Typically, flow direction will not change significantly over 5 minutes and a compass measurement in the middle of the ADCP sample period is sufficient. At the start of each 5-minute ADCP sample then, an RS485 pulse is sent to the compass controller to initiate the compass sample sequence. Following a 135 s delay to center the compass measurement in the middle of the ADCP sample, the compass is powered up to sample and log compass outputs (heading, the 3 magnetometer outputs, and tilts) for 30 s. The compass controller time is also logged for each sample to facilitate merging of the compass and ADCP data after mooring recovery. Time stamping the data is crucial if the slaved compass happens to miss the occasional synchronisation pulse from the ADCP, although this has not been a problem.

It is possible that the period of internal waves, if they are present, can be short enough that they can potentially cause a current direction change over 5 minutes. However, the current speeds associated with internal waves are typically too low (0.05 m/s; Garrett and Munk, 1979) to alter the net flow direction in the presence of a moderate mean flow and/or tidal flow. Nonetheless, in a tidal flow there can be short intervals of slack water when internal waves, if present, could dominate the flow, and this is a potential error source for the sampling scheme described. An examination for any trend in the 30 s compass sample can reveal whether there is a rapidly varying current direction change. Alternatively, 10 s compass samples can be taken at the start, middle and end of each 5 minute ADCP sample, and any direction change over the 5 minutes evaluated. This sampling strategy was in fact used in a recent deployment. Over a year long data record, only 2% of the time was the standard deviation of the 3 direction measurements over the 5 minute sample greater than 10° , and these occurrences were always when the current speed was less than 10 cm/s.

Assembly and Calibration

The materials and hardware used in the instrumented SUB assembly are selected to be non-magnetic, but some magnetism cannot be avoided. Watson recommends that there should be no magnetic masses within 10 cm of the SHR-360 sensor. Therefore the use of any magnetic components in the compass pressure case has been avoided. All fasteners and hardware on the SUB are also non-magnetic.

The ADCP is located in the SUB 0.5 m forward of the compass. The case is non-magnetic and the magnetic signature of the internal electric components is low, except for the alkaline battery pack. A horizontal field strength of about 20 nT (nanoTeslas) was measured as the field generated by the ADCP battery pack at a distance of 0.5 m in laboratory tests. This is approximately 1.5% of the magnitude of the horizontal component of the earth's magnetic field at the mooring site. To replace the 42 V battery pack with non-magnetic batteries is expensive, and unnecessary given that the Watson compass calibration can be done with the entire instrumented SUB assembly, ADCP battery included. The Watson calibration routine will compensate for magnetic masses whose field strength, and orientation relative to the compass, do not change as long as they are at least 10 cm from the sensor. A concern is that the magnetic signature of the alkaline battery pack may change as it discharges, but the 0.5 m separation from the compass will help to minimise any impact.

It should be noted that degaussing of the batteries is not necessarily an appropriate strategy to reduce the magnetism of masses near the compass. It is quite possible that as a pack discharges (or simply as time passes), the change in magnetism of the degaussed pack will be greater than for a battery pack that was not originally degaussed. The calibration procedure can compensate for unchanging magnetic masses, but if the field produced by a mass close to the compass changes significantly over the course of the deployment, heading errors will result.

The goal of the calibration procedure is to compensate for magnetic masses that will be part of the moored system, while avoiding magnetic contamination from laboratory sources. Calibrations were done on a turntable at a non-magnetic hut specially built and located for compass calibrations. The instrumented SUB assembly was rotated through 4 known compass points following a simple procedure with Watson sensor software. The computer needed to interface with the compass package during the calibration, and all other required tools were kept at least 5 m from the instrumentation.

Breiner (1973) provides some useful information for assessing potential sources of contamination during the calibration procedure, or in the field. The magnetic field produced by a ferrous mass falls off with the cube of the distance from it, if the object is small relative to the distance. Breiner's (1973) Figure 46 shows the approximate relationship between distance from source and field intensity for different quantities of iron. As an example of the application of this information, consider the 300 kg iron train wheels used for the moorings discussed here. Based on Breiner's curves, the anchor at 5 m will cause an anomaly on the order of 150 nT, which is about .25% of the strength of the earth's magnetic vector. At 15 m the anomaly caused by the anchor is around 5 nT. Given that Breiner warns that his estimation method is only approximate with potential errors of as much as a factor of 5, our practice is to use special non-magnetic anchors when the instrumented SUB is within 15 m of the anchor.

FIELD RESULTS

An array of 4 moorings was deployed on both sides of Barrow Strait in approximately 200 m depth, to collect the required current,

temperature and salinity data. Over-the-side tests with an ADCP before the actual mooring deployments indicated that, for the desired profile detail, a realistic maximum range of only 80 to 85 m could be expected in the clear Arctic waters. (A more typical range is 100-110 m). Two instrumented SUB packages then, were moored closely together on separate moorings at 80 and 160 m depth, to provide current speeds from 160 m to the surface.

Magnetic declination at the mooring site must be applied to the collected current data to get direction relative to true North. This can be calculated from the declination at Resolute, which is measured continuously at a NRCAN Geomagnetic Observatory located there. Declination (D) at a particular site is computed from the Resolute data using

$$D = \arctan (Y+\Delta Y_0)/(X+\Delta X_0), \quad (1)$$

where X and Y are the instantaneous horizontal components of the earth's magnetic field as measured at Resolute, and ΔX_0 and ΔY_0 are the differences between the mean values at Resolute and mean values at the particular field location. These mean field component values can be computed for any location using the NRCAN "CGRF" mathematical model (Canadian National Geomagnetism Program web site, http://www.geolab.nrcan.gc.ca/geomag/eng_main.html). Shown in Fig. 5 is a sample of the typical variation in declination at the Southern mooring site as computed from Eq. 1, using the 1 minute Resolute data, $X_0=183$ nT, and $Y_0=-497$ nT. Although the location is 700 km from the magnetic pole, there are still significant declination changes ($\pm 12^\circ$) over the course of a day that need to be taken into account.

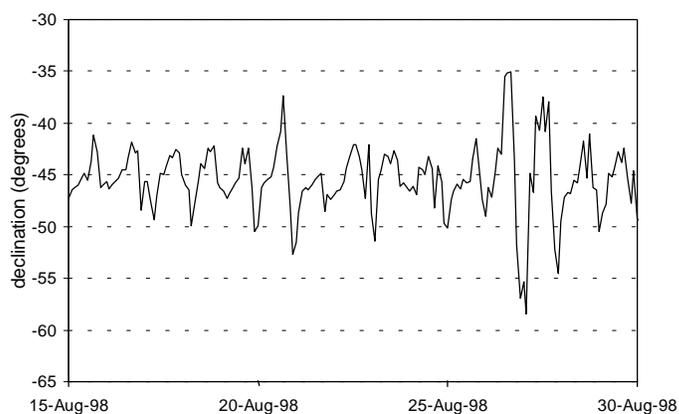


Fig. 5 Declination at the Southern mooring site calculated from Eq. 1 using declination data from the Resolute observatory.

Shown in Fig. 6 are selected data from the instrumented array that was moored on the South side of Barrow Strait from Aug, 1998 to Aug, 1999. The velocity data, from which the along-strait and cross-strait components have been calculated, have been corrected for the variation in the magnetic declination. The diurnal and semi-diurnal tidal signals have been removed from all of the data records in processing. Note that the predominant direction of motion is along-strait, as expected. Mass, heat and salt transports through Barrow Strait are being calculated from these records.

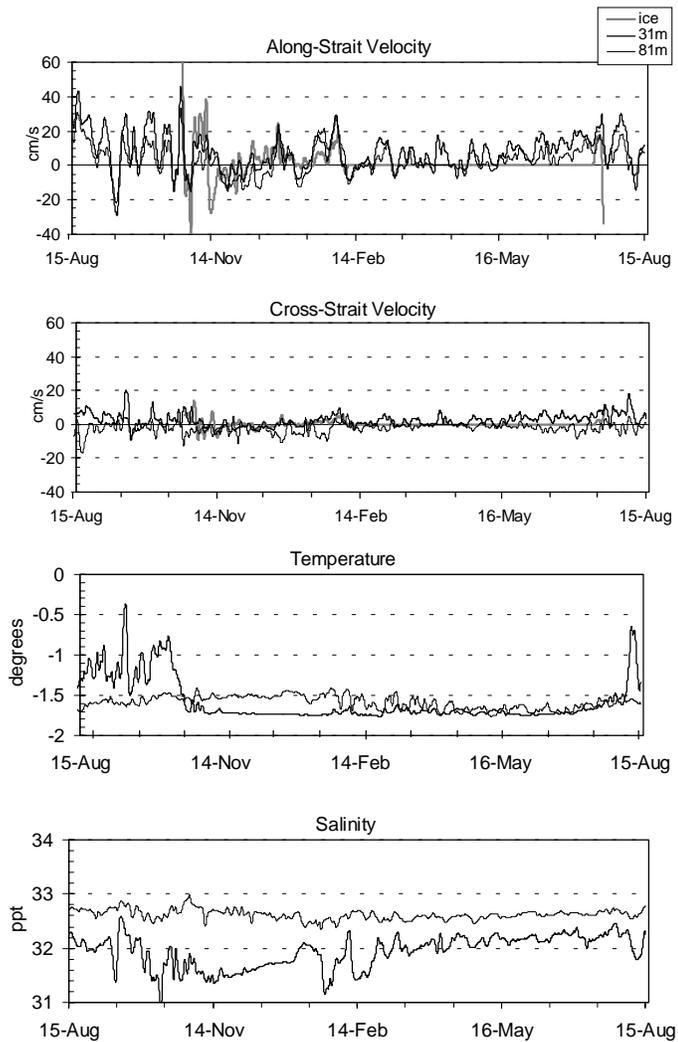


Fig 6 A years data showing ice movement, and currents, temperatures and salinities at the 31 m and 81 m levels on the southern side of Barrow Strait. Semi-diurnal and diurnal tidal signals are removed. A positive velocity indicates easterly motion. Where no ice data are shown (August to October), ice cover is broken or non-existent.

The proximity of the deep (160 m) and shallow (80 m) moored, instrumented SUB packages provides an opportunity to compare the results of 2 independent measurement systems. Shown in Fig. 7 is the along-strait component of the measured current at 75 m depth on the South side of Barrow Strait, comparing data from the top bin of the deep SUB and the bottom bin of the shallow SUB. Considering the 1 km mooring separation, the two independent systems are in good agreement over the depth interval in which there is measurement overlap.

CONCLUSIONS

Current direction measurement near the magnetic poles presents some unique challenges. The new strategy described here provides a straightforward and cost effective approach to overcoming these measurement problems. A key component of the system is a Watson precision heading reference, but just as important is the mounting of

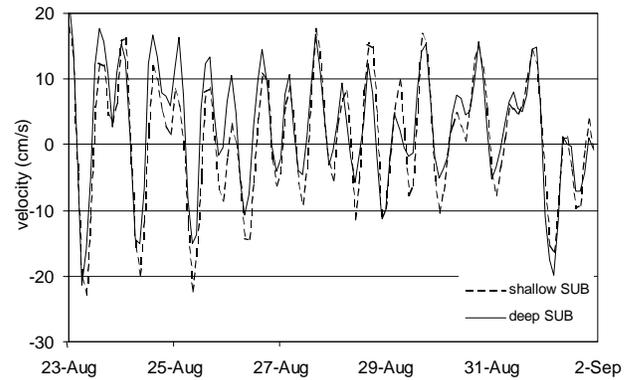


Fig. 7. Comparison of alongstrait currents from independent instrumented SUB packages. Data are from the top ADCP bin of the deep package and the lowest ADCP bin from the upper package. The two moorings are a kilometer apart.

the heading reference and acoustic Doppler current profiler in a streamlined buoyancy package (SUB). By ensuring a constant alignment relative to the flow using the SUB, it is necessary to power the heading sensor for only a fraction of the 5 minute ADCP sampling period. The battery requirement for the heading sensor is thereby drastically reduced. Yearlong records of bihourly, current and direction data can thus be made using compact instrumentation on subsurface moorings where the horizontal component of the earth's magnetic field is extremely low. Field results demonstrate the method is effective and reliable at a dip angle of 88.2° . The upper limit on dip angle for effective use of this new ocean current direction measurement strategy remains to be determined.

Finally, adjustment for variation in magnetic declination can easily be applied to the magnetic direction measurements acquired with this technique, using geomagnetic observatory data available from NRCAN.

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