Motion Tracking in an Acoustic Point-Measurement Current Meter

Albert J. Williams 3rd [1], Fredrik T. Thwaites [1], Archie Todd Morrison III [2], John M. Toole [1], and Richard Krishfield [1]

[1]Woods Hole Oceanographic Institution
98 Water St.
Woods Hole, MA 02543 USA

[2]Nobska Development, Inc.
PO Box 308
Woods Hole, MA 02543 USA

Abstract*-Measurements of velocity structure in the water column under Arctic ice from an Ice-Tethered Profiler (ITP) employed an acoustic point-measurement current meter, MAVS (Modular Acoustic Velocity Sensor) [1]. With the velocity sensor it becomes the Ice-Tethered Profiler with Velocity (ITPV). The profiler, containing a Seabird CTD, MAVS, batteries, an inductive modem, and a wire crawling engine, integrated by McLane Labs, was constrained to be deployed through a 24" diameter hole drilled in the ice. The anchor to the ice via a buoy with a satellite transmitter fixed the top of the mooring to a drifting but GPS tracked location while the profiler descending to a depth of 800m measured velocity relative to the moving mooring and the climbing profiler. A large current-orienting alignment fin was not possible on the ITP due to the limit of the ice hole diameter yet it was known that vortex shedding by the profiler body in the current would cause the instrument to swing and the current sensor to measure horizontal velocities due to the rotation of the profiler around the center of gyration of the package. To remove this platform motion from the current measurement, an inertial sensor, Analog Devices ADIS 16355 [2], was added to the MAVS current meter and three axes of angular velocity and three axes of linear acceleration were added to each data record of time, velocity, temperature, three-axis magnetic vector components and two axes of tilt. From the rate gyro value of angular velocity around the vertical axis, the platform rotation is determined and using the distance that the velocity sensor is displaced from the axis of rotation the horizontal current sensor velocity can be subtracted from the horizontal velocity measured by the sensor. This ITP was deployed in October, 2009 and data from the first profile indicates expected and unexpected performance.

I. Introduction

Thinning of Arctic ice and the possibility of an ice-free Arctic Ocean within the decade motivates studies of heat exchange and mixing beneath the ice from intrusions of warm ocean water, from internal wave mixing of this water towards the surface, and of other turbulent exchanges of heat and salt that impacts ice from below, even while atmospheric studies show impact of warming from above. Long-term measurements over the upper water column that can resolve the intrusions, internal wave mixing by shear instability and breaking, and turbulent mixing resulting from such events are needed to constrain these estimates and to predict important processes that will affect the climate through Arctic melting. The Ice-Tethered Profiler was developed and deployed for these studies.

II. Instrumentation

In the Arctic, the magnetic lines of flux are very steep; at the magnetic pole, they are vertical. Compasses measure the horizontal components of magnetic flux and as the magnetic pole is approached, the horizontal components get small and measuring the heading becomes difficult. If the profiler undergoes horizontal accelerations, a simple compass measurement becomes corrupted when the horizontal is determined by linear accelerometers. A combination of accelerometers and angle rate gyros can be used to improve the tilt and heading measurements.

The moored profiler [3] obtains a continuous profile of temperature, salinity, and current over several hundred meters by crawling up and down a mooring. Typically, the mooring is anchored to the sea floor and buoyed by a float sufficiently far beneath the ocean surface to avoid violent wave excitation. Fig. 1 shows the McLane Moored Profiler (MMP) built by McLane Research Laboratory being launched. The object protruding from the cowling of the profiler is an acoustic travel-time current sensor made by FSI.

Fig. 1. McLane Moored Profiler being deployed.

For Arctic work, particularly where the greatest interest is in processes occurring near the surface rather than the bottom, the mooring is inverted and the buoy is frozen into a hole in the ice with the mooring terminated by a 100kg weight hung beneath. The profiler crawls up and down the mooring line from near the surface to the weight. The original ITPs only measured the scalars of pressure, temperature, and conductivity so had no need to measure heading or attitude. The current sensor added to the ITPV measures flow relative to the profiler, and to make this meaningful, this relative velocity needs to be transformed into earth coordinates. To measure the profiler attitude, the MAVS has a three-axis fluxgate magnetometer and an Analog Devices ADIS 16355 inertial sensor that includes a three-axis accelerometer and a three-axis angle rate gyro.

Fig. 2 shows the buoy in place, plugging the hole and ready to transmit by satellite the data inductively telemetered from the profiler to the surface. In this installation, ITP35, the mooring line is 800m long and the profiler is operated on a pattern profiling schedule between 7 and 760m depth each day. Launch on October 8, 2009 was on a 2.6m thick ice floe in the Beaufort Sea at 77°4.5'N, 135°25.8'W.

Fig. 2. Ice Tethered Profiler buoy frozen in the Arctic ice.

The MMP has a fairing over the housing that points the sensor of velocity into the flow. But the ITP has a restricted hole in the ice through which it must pass that limits the chord length of the housing or fin that might keep the sensor stably pointed into the flow. Fig. 3 shows the ITP entering this hole and Fig. 4 illustrates its lowering.

Fig. 3. Ice Tethered Profiler entering the hole in the ice.

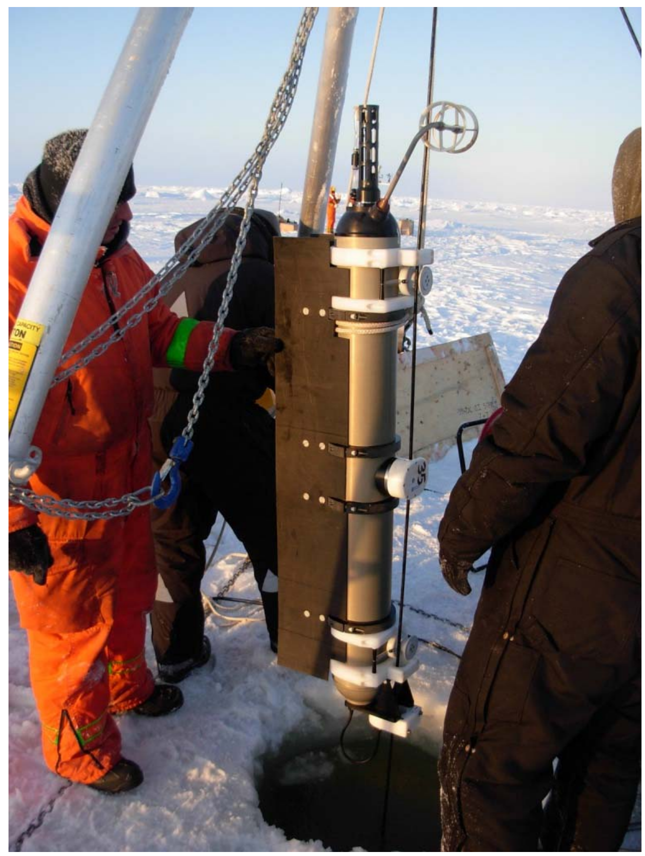

Fig. 4. Ice Tethered Profiler being lowered into the hole in the ice along the mooring line. The short split fin to reduce swinging and Strouhal oscillation has been clamped to the housing. All systems for the profiler are inside the aluminum housing except the crawler motor and roller and the inductive modem transformer.

The short split fin secured to the housing to reduce swinging and Strouhal oscillation that might be excited by current relative to the ice is shown in Fig. 4. The CTD sensor for conductivity and temperature is inside the cage extending up from the endcap and the pressure sensor is ported through the endcap while the MAVS velocity sensor is the pair of rings that support 8 acoustic transducers on the bent tube extending out in front of the mooring line.

In addition to the short split fin, concern that sensor motion would contaminate the velocity observation required that there be an inertial motion package to correct the current measurement from the sensed profiler motion. The Analog Devices ADIS 16355 three-axis rate gyro with three-axis linear accelerometer was incorporated to capture these motions. As indicated above, the angular velocity around the vertical axis can be used to estimate the circumferential velocity of the velocity sensor for subtraction from the measured transverse current.

In principle, the other motions of the profiler can be subtracted from the current measurements as well by using the rate gyro outputs from the two horizontal axes of rotation. In addition, the linear accelerations can be used to remove vibrations and uneven climbing rates from the velocity measurements. The main correction to the velocity signal is the removal of vertical velocity from the rate of pressure decrease (or increase) as determined by the CTD measurement. Variations about the mean ascent rate (or descent rate) are removed as well. It is of significance that in the Arctic Ocean, close to the magnetic pole, ordinary compass measurements, as determined by the three-axis magnetic sensor used for determining the azimuthal orientation of the current, are too noisy to give a good estimate of angular rotation and, thus, rate gyros were chosen to remove the angular oscillation. Fig. 5 shows the top endcap of the ITP with the housing removed. The inertial sensing package is mounted between the two chassis plates and wired to the TT8 μP controller of the MAVS.

The ADIS 16355 inertial package is shown in a testing condition in Fig. 6. It is about 2.5cm on a side and connected to the digital I/O lines of the TT8 μP of MAVS where it is controlled as an SPI device. The configuration is set at the start of every deployment with a setup and configure command and for this experiment was set to 150º/s full scale for the rate gyros. The gyro chip samples the accelerometer and rate gyro axes at 150 Hz into a 12 bit ADC, and low-pass filters these measurements digitally with a 64 tap FIR filter. Current drain was about 40ma from 5v, and a switching DC-DC converter to produce the 5v efficiently from the 12 v supply caused enough electronic noise to degrade the velocity measurement. Consequently, a series regulator, LM7805, was substituted for the DC-DC converter and that restored the high quality to the velocity measurements. In the end, power drain in the ITP drew an extra 37ma to run the gyro, which is on continuously while profiling, and this, added to the average of 18ma for MAVS, produced 55ma. A final 3ma was required to power the LM7805 linear voltage regulator. Even though the efficiency of the DC-DC converter in producing 5v from the 12v supply had a somewhat lower power drain, the degradation of the velocity measurement from the electronic noise of the switching circuits was unacceptable and the series regulator was used instead. The flying LM7805 of Fig. 6 was subsequently mounted to the chassis plate just below the ADIS 16355.

Fig. 5. MAVS, CTD, and top endcap of Ice Tethered Profiler. MAVS velocity sensor is the white rings. A 3-axis rate gyro is mounted to the chassis.

III. Performance

Satellite telemetry recovered engineering data and temperature and salinity from under the ice from the first Arctic profile that is presented in Fig. 7. This up-trace profile also shows motor current and battery voltage. Because the housing is less compressible than seawater and the upper ocean is stratified, it takes force to keep the profiler near the surface. This is shown by the increase of motor current and the drop in battery voltage as the profiler rises.

Profiles are executed daily and the data are internally logged and also inductively coupled up the mooring cable to the buoy at the surface for satellite transmission. Satellite transmission has continued from deployment October 8, 2009 but no additional profile data have been returned. There is a possibility that the ITP will be recovered in summer 2010 and that all of the data will be stored and be available. So far there is no explanation why profile data are not part of the satellite transmissions.

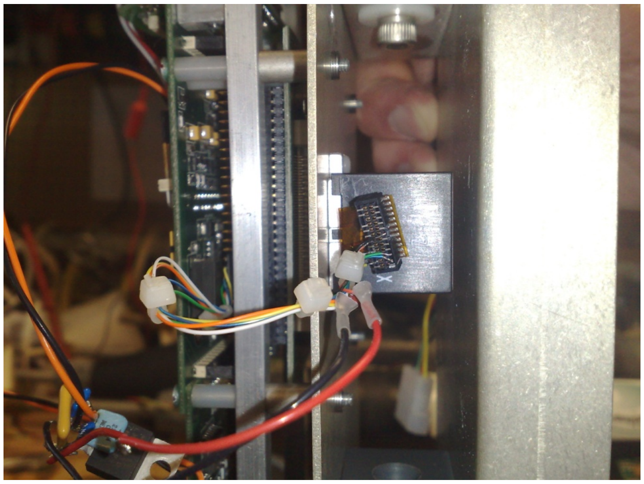

Fig. 6. The black cube between the two chassis plates is the rate gyro wired to the TT8 μP with the colored wires. The red and black wires are power connected to an LM7805 linear 5v regulator for testing.

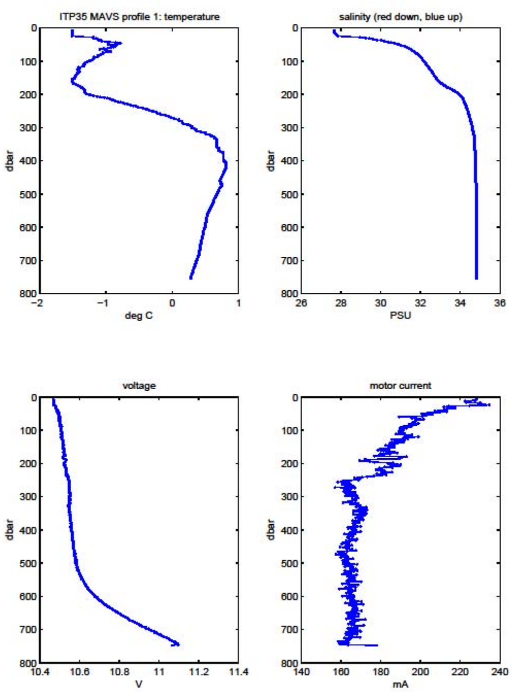

Fig. 7. Engineering and environmental data from the first profile of the ITPV under the ice. The upper left shows temperature; upper right is salinity; lower left is voltage during the profile up; lower right is motor current.

Uncorrected velocity data from this first up profile is illustrated in Fig. 8. MAVS currents are presented as U, V, and W velocities for the velocity into the sensor in the horizontal, the current across the sensor in the horizontal, and the current vertically up into the sensor. The rising of the profiler at 25cm/s results in a vertical velocity (W) of -25cm/s after the profiler starts to move. Magnetic field direction cosines (magnetic components normalized by the total magnetic field) reveal, as expected, that the local magnetic field is nearly straight down as this region is close to the magnetic north pole. The two horizontal components, however, still can resolve the heading of the profiler during this up profile and a small horizontal current has veered to point the profiler into different headings during the 20min up profile.

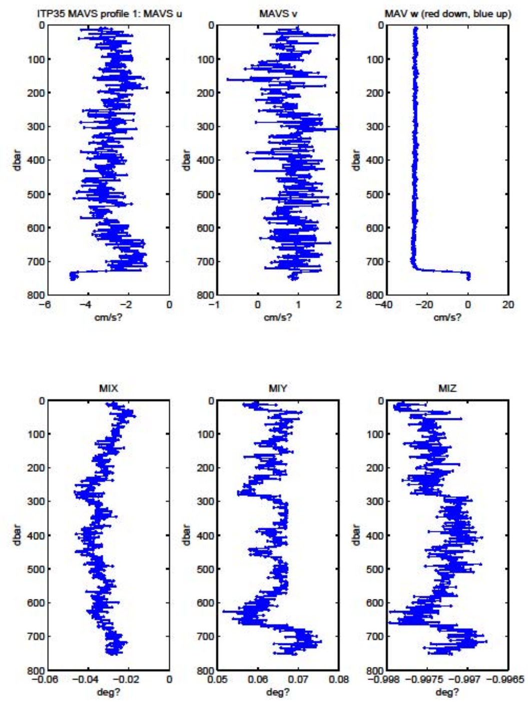

Fig. 8. MAVS data from the first up profile of the ITP under the ice. The top row shows velocity into the sensor, velocity across the sensor and vertical velocity. The lower row shows three components of earth magnetic field direction cosines.

IV. Inertial Processing

Processing raw data into corrected current uses the three MAVS velocity components in addition to pressure rate from the CTD for vertical velocity, integrated rate gyro for the horizontal current, and magnetic direction cosines with the integrated rate gyro for heading. The pressure rate is constant despite the variation in motor current indicated in Fig. 7 and the pressure curve is presented in Fig. 9.

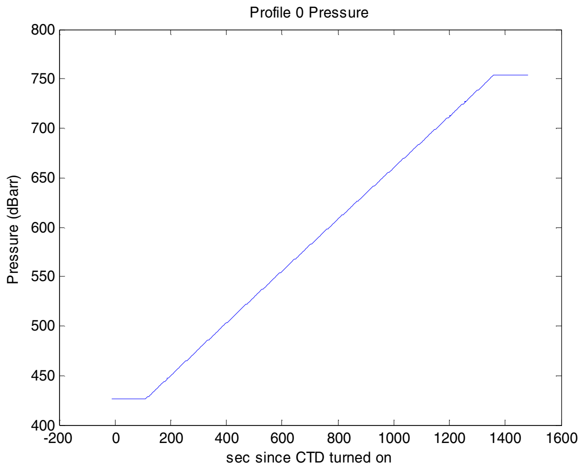

Fig. 9. Pressure from the CTD during a profile of the ITPV under the ice.

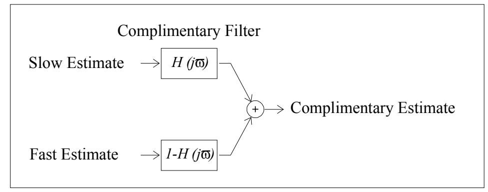

Fig. 10. Block Diagram of a Complementary Filter. Often a better estimate of a variable can be made from redundant imperfect sensors. In the above, if the slow estimate is good at low frequencies and the fast estimate is good at high frequencies, summing a low-pass filtered slow estimate with a high-pass filtered fast estimate results in a significantly more accurate estimate.

The calculation of profiler attitude uses redundant measurements and a complementary filter to improve the attitude estimates. In a complementary filter, the sum of two transfer-function magnitudes is one at all frequencies. In Fig. 10, if one estimate, called the slow estimate, is accurate at low frequencies and noisy at high frequencies, and if the second estimate, called the fast estimate, is poor at low frequencies and accurate at high frequencies, adding a low-pass filtered slow estimate to a high-pass filtered fast estimate can result in a much more accurate estimate [4]. This processing was done in the lab on a PC in the Matlab environment. The low-pass filter is a four-pole Butterworth run both forward and backward over the sample to avoid phase changes. This results in an eight-pole zero-phase filter. The cutoff frequency was 0.05 of the one Hertz Nyquist for a 20-second period. A smaller cutoff frequency filter resulted in excessive end transients. The slow estimates of roll and pitch are inverse tangents of the horizontal acceleration divided by the vertical acceleration. The slow estimate of heading is the inverse tangent of horizontal components of magnetic flux. These slow estimates are noisy at high frequencies with least significant bit noise. The fast estimates of angles are from integrating the angle-rate gyro axes which are inaccurate at low frequencies due to zero offsets and slowly changing biases.

A portion of the roll angle estimates is shown in Fig. 11. The blue line is the slow estimate of roll from the inverse tangent of horizontal over vertical acceleration and is noisy at high frequency with least significant bit noise. The green line is the high-pass filtered integrated rate gyro. This has a mean of zero from the high-pass filtering. The red line is the low-pass filtered slow estimate. The black line is the sum of the two and is the best estimate of roll. In the figure, only a short period of one profile is plotted to show the detail. The motion of the profiler on its mooring was quiet. The figure is plotted in degrees, but the angles are calculated and kept in radians.

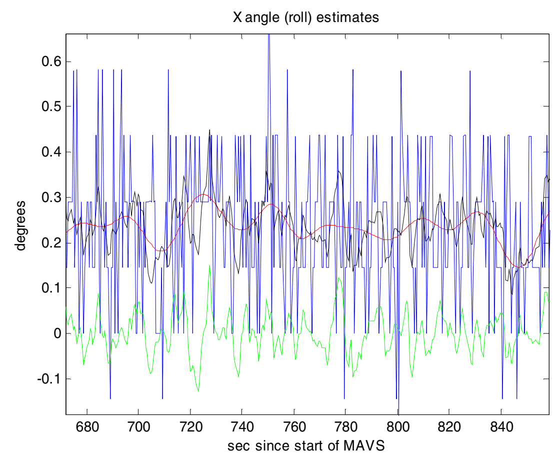

Fig. 11. Estimates of Profile 0 Roll Angle. The blue line is the slow estimate of angle from the arctangent of horizontal and vertical acceleration and the red line is this data low-pass filtered. The green line is the high-passed integrated angle rate gyro. The black line is the sum of the low-passed slow estimate and the high-passed integrated rate gyro. This graph plots a small section of the record to show the finer detail.

The overall attitude processing is shown in block diagram form in Fig. 12. The processing is based on a linearized 3, 2, 1 Euler angle system [5]. Pitch and roll are calculated with complementary filtered measurements from the accelerometer and rate gyro axes. Pitch and roll angles are used to rotate the measurements of magnetic flux into a horizontal reference frame. These in turn are used to form the slow estimate of heading which was combined in a complementary filter with the integrated vertical rate gyro to estimate the corrected heading.

An example of the heading processing is shown in Fig. 13. The blue line is the complementary filtered estimate of heading ignoring tilt. The green line is the slow estimate of the inverse tangent of magnetic fluxes in the horizontal plane and shows least significant bit noise. The cyan line is the fast estimate of high-pass filtered integrated rate gyro. The zero mean results from the filtering. The red line is the sum of low-pass filtering the green line and the cyan line. A small portion of the profile is plotted to show finer detail. In this profile, the tilt was less than a degree while the magnetic lines of flux were four degrees from vertical resulting in a modest difference between uncorrected heading and heading compensated for tilt. If the profiler is deployed closer to the magnetic pole, if tilts are larger, or if horizontal accelerations are larger, not compensating for tilt will result in a larger error.

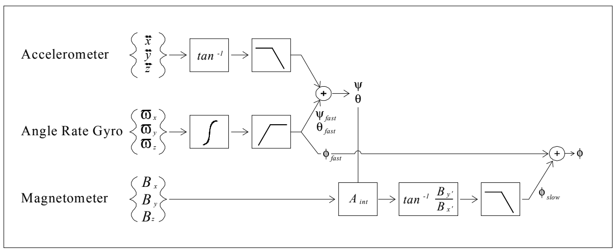

Fig. 12. Block Diagram Showing Processing of Profiler Attitude.

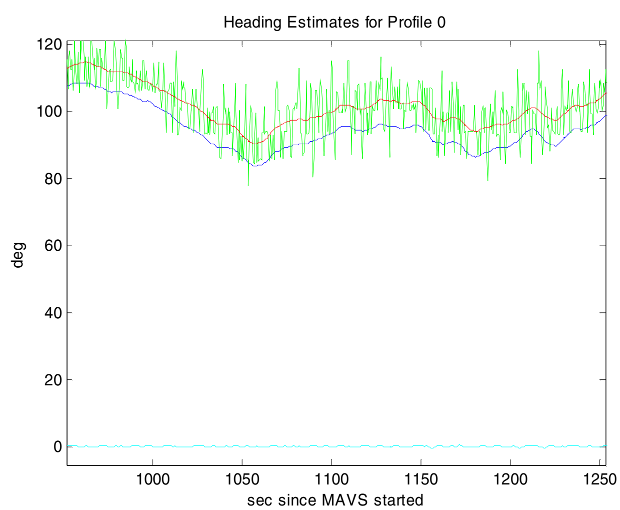

Fig. 13. Four Estimates of Heading during Profile 0. The blue is a complementary filtered estimate using the profiler based magnetometer and rate gyro. The cyan is the fast estimate of heading, the high-passed vertical rate gyro. The green line is the slow estimate of heading from the inverse tangent of magnetometer components rotated into a horizontal reference frame. The red line is the complementary filtered estimate using the green line low-passed and summed with the high-passed integrated vertical rate gyro. A small portion of the profile is shown to show the finer detail.

V. Velocity Processing

The modular acoustic velocity sensor measures water velocity along four different paths. These four paths are transformed into a three-axis vector in profiler coordinates of X, Y, and Z as defined in Fig. 14. The X axis is upstream, the Y is to port, and Z is up. This view looks at the side of the profiler top end-cap. The measured relative flow velocities for profile zero are shown in Fig. 15.

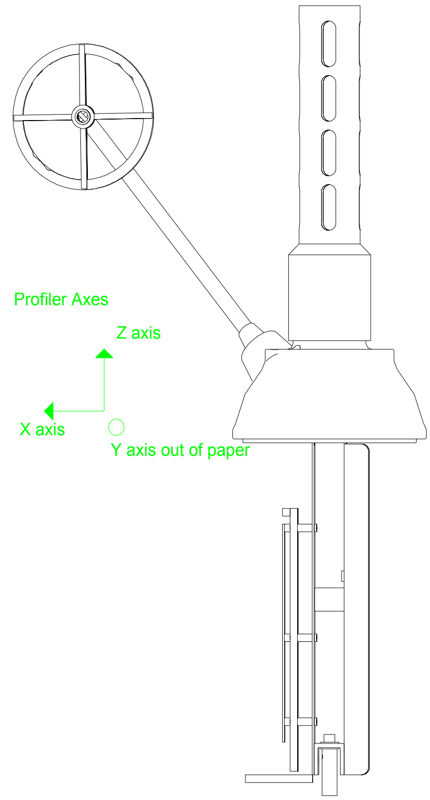

Fig. 14. Definition of Profiler Axes.

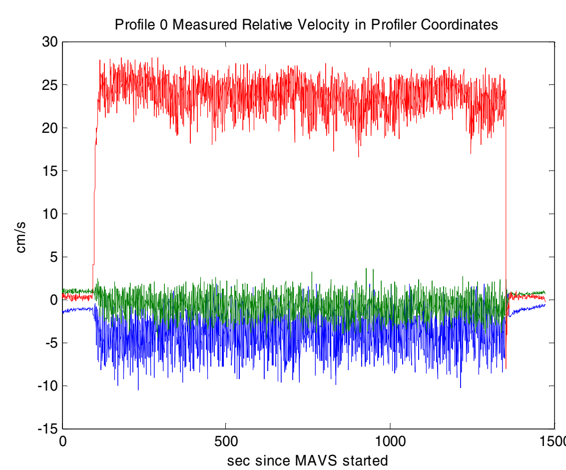

Fig. 15. Measured Relative Velocities Transformed into Profiler Coordinates. Blue is toward profiler, green is across the profiler in the Y direction, and red is vertical up.

The blue line is the X axis which is negative when pointed into a current. The green line is to port, and the red line is vertical. In the example, the profiler motored down from 430 meters to 755 meters depth. The velocities relative to the profiler are rotated into magnetic North, West and Up using the profiler attitude angles.

VI. Results

The system transmitted the first two profiles back via the satellite. Unfortunately, for reasons unknown, the top buoy node stopped accepting the data sent up the inductive modem. We hope that the data is still being recorded in the profiler and we intend to recover the profiler to get the data this summer.

This ITPV was deployed in an area where the magnetic lines of flux are about four degrees from vertical and the profiler tilt was less than one degree. The attitude processing resulted in a more accurate heading than a simple compass and if future ITPVs are deployed closer to the magnetic pole this processing will be necessary.

There is a bias in the X velocity resulting from flow over the profiler. In Fig. 16 the full profiler body is shown with the velocity sensor a little above the upper endcap and offset to the other side of the mooring wire. This location is a compromise between having the sensor far from a flow obstructing body and having the instrument compact enough to fit through the hole in the ice and on a short enough moment arm so that motion of the body is only converted to a small transverse velocity at the sensor. However, there is flow over the housing when the profiler is moving that adds to the current at the location of the sensor. The profiler vertical velocity was much larger than the current in the profiles presented here. The flow around the profiler when descending makes the X component of velocity more negative. On ascent, the X velocity will be more positive. This bias has yet to be modeled for compensation.

The noise in velocity measurements has been about three times the expected noise as extrapolated from tow-tank tests [1]. In Fig. 15, the noise before the profile was very low and the noise with the motor running is significant. The authors believe this is due to motor commutation electrical noise leaking to the MAVS. We will be reducing this noise by better filtering of the MAVS electrical power and communication lines.

The profiler motion has been smooth. Attempts to compensate measured relative flow velocities for profiler motion have been hampered by noise in the rate gyros and pressure sensor. Differencing the pressure sensor measurements results in a noisy signal that has low coherence with the measured relative vertical velocity. The angle rate gyro signals have significant noise relative to the smooth motion of the profiler. There is low coherence between the angle rate measurements and the corresponding relative flow velocities. The rate gyro measurements did, however, significantly improve the profiler attitude estimates.

Applying the heading corrections to the attitude of the profile yields the earth coordinate velocity as shown in Fig. 17.

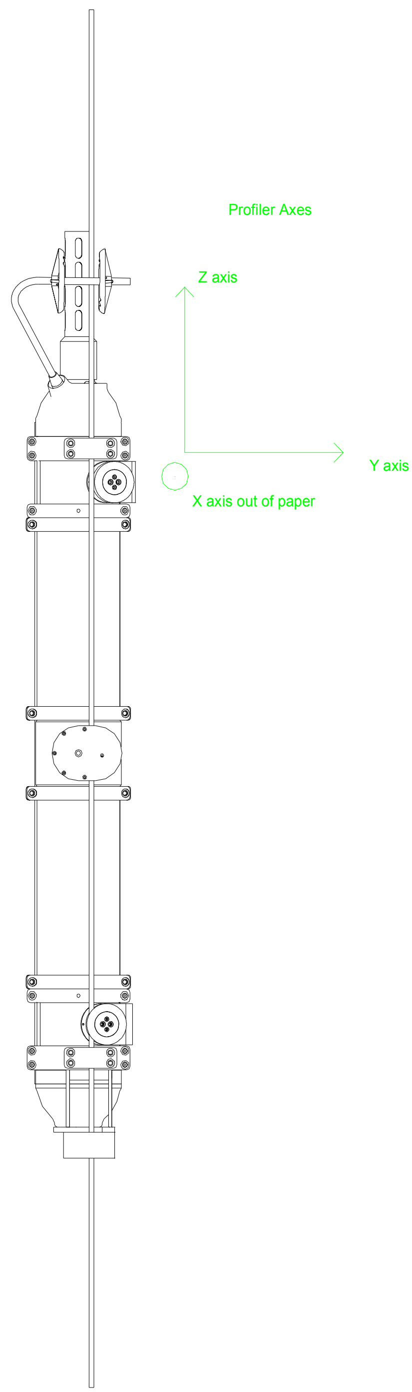

Fig. 16. Definition of Profiler Axes. This view looks at the front of the profiler, X points upstream, Y to port, and Z up.

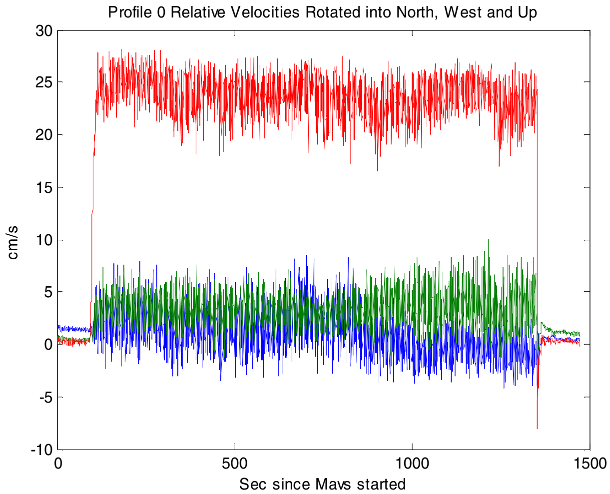

Fig 17. Measured Relative Velocities Transformed into Earth Coordinates. The measured relative velocity rotated into north, blue, west, green, and up, red.

VII. Turbulence Measurement

During a profile, the noise from the electric motor (uncorrected in this first ITPV unit) is noticeable in the velocity measurements. However, when at rest, this noise is gone as at the beginning of the record in Fig. 17. The intention has been that turbulence will be recorded at fixed depths at intervals during the year-long deployment of the ITPV. Unfortunately, the satellite returned records do not give us any of these measurements (although there is hope that they are preserved in the logged data) so we are not able to give estimates of the turbulent kinetic energy here. However, MAVS is capable of providing velocity fluctuation correlations that will show times when there is mixing of momentum towards the ice surface and heat and salt transport from the warmer, saltier water beneath to the ice above.

VIII. Summary

The Ice-Tethered Profiler has been equipped with an inertial sensor for removal/correction of motion of the profiler body. The three axes of rate gyro and three axes of linear acceleration combined with magnetic heading in a complimentary filter corrected the attitude of the profiler. Applying these to the MAVS velocities gives velocity in earth coordinates. Remaining tasks are to remove the pressure rate from the up velocity. Correction for horizontal current must be done by using the vertical rate gyro in body coordinates and this can be done with possible recovered data next summer. For this analyzed profile, the vertical rate was so small that it did not impact the velocity observation.

Acknowledgment

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