Current Measurements under Ice

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***Abstract*- Current measurements under ice face some challenges not present when measuring current in open water and water free of ice. There is the problem of getting the current meter through a hole in the ice, which limits the horizontal dimensions of the instrument package such as fins that might provide directional stability in open water. Then there is the issue of damage to the sensor from contact with ice in the hole, a problem that is generally less threatening in open water, so for ice deployments protection against this may be required. The small chunks of ice in the hole may interfere with the measurement, certainly a major concern with mechanical sensors, but also an issue with acoustic sensors. Finally, a mooring anchored to the moving ice surface must be tracked for recovery if data are to be only recorded internally. If the data are to be telemetered ashore there must be a data connection to the surface through the mooring line.**

I. Introduction

There has been experience with one current meter, MAVS (Modular Acoustic Velocity Sensor) [1], in three under-ice applications. The first was as a self-contained current meter in ice in a lake in Kazakhstan. The second was in the Arctic on an Ice-Tethered Profiler with stored internal energy [2]. The third was from a mooring providing power from the surface and receiving data there from the under-ice sensor for satellite telemetry for the British Antarctic Survey. Each of these applications had distinct requirements and each provided lessons for the MAVS designer.

II. MAVS

The current meter, MAVS, was developed to provide a fluid velocity measurement to accompany other marine samples or observations as a modular sensor. In practice, it has almost never been used in this way. Rather, there has been demand that it be a more or less stand-alone current meter with internal battery power and on-board data logging. The flow measuring technique in MAVS is differential acoustic travel-time where oppositely directed bursts of 1.8 MHz sound cross a measurement volume of 10cm diameter simultaneously and the difference in time of arrival of the sound at the opposite transducers is proportional to the component of velocity along the acoustic axis [3]. Four axes are excited sequentially to obtain a 3-D velocity vector. Resolution in velocity is 1mm/s and the noise level for single measurements is typically 0.7mm/s. Zero-point variations from one deployment to the next are typically 3mm/s and a careful zero-point calibration before each deployment is recommended. Angular resolution in current direction is limited by the internal compass to 3º in the horizontal. In the horizontal plane, the freedom from obstruction in the sensor, exhibited in Fig. 1, results in an ideal cosine response, whereby the two components of horizontal flow, U and V, vary with the cosine of the angle between the X and Y axes and that of the current vector [4]. In the vertical plane, obstruction from the transducer-supporting rings is minimized by fairing in the acoustic axis direction so that at the worst elevation angle, 45º, the along-axis velocity defect is 15% [5]. Full scale range in velocity is 180cm/s although increased ranges have been provided as special order to 10 kn (500cm/s) with only slight increase in noise to 2mm/s. Measurements can be taken as rapidly as 20 Hz although 2 Hz is normally recommended for power and data storage conservation. In the 10-cm diameter of the sensor volume, 2-Hz sampling satisfies the Nyquist criterion for speeds less than 20cm/s. Spectral content of many flows significant for measurements supporting experiments other than turbulence studies are "red" meaning that energy is concentrated at low frequency so that under sampling at greater flow speeds is not a serious source of elevated noise in the spectrum. For higher speeds and for turbulence measurements, the higher measurement rate is recommended but burst sampling can conserve energy and data storage. In at least one case, burst sampling at a high measurement rate with averaging over the burst may be necessary to remove the oscillatory velocity fluctuations due to a von Karman vortex street behind the sensor tube from forced motion of the MAVS sensor that contaminates the flow to be measured.

Fig. 1. The MAVS velocity sensor measures the vector flow components along four acoustic axes between transducers supported in faired plastic rings. Flow in the plane of the rings is measured without deviation from ideal cosine response but may be contaminated by a vortex street from the sensor tube supporting the rings. Vertical cosine response is good with the worst velocity defect at 45º elevation at 15% reduction from ideal cosine response.

III. KAZAKHSTAN

An analog output version of MAVS [6] was delivered to a client for deployment in Kazakhstan. Later it was revealed that this MAVS was deployed through a hole in the ice in a lake. E-mail correspondence including data from MAVS showed a set of velocity traces not normally seen in open water deployments. A section of one of these traces is shown in Fig. 2. The traces displaced from zero velocity are typically the result of a missed cycle in the received acoustic pulse. For purposes of logging in the users existing data logging equipment, the output of MAVS for this client was converted from digital words to analog voltages and one analog channel is presented. The current along this axis after removal of the bad points is shown in Fig. 3.

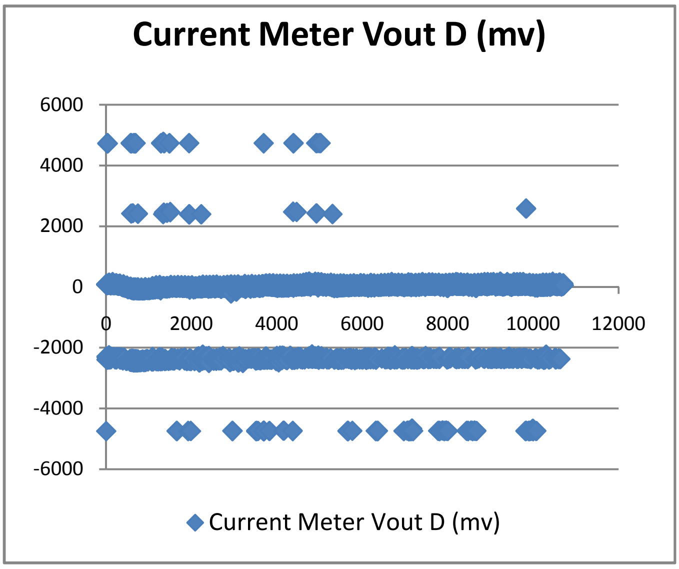

Fig. 2. Analog output voltages from MAVS acoustic axis D under ice in Kazakhstan exhibit many spurious values due to missed cycles in the receiver. Despite these bad points, the velocities were extractable by filtering these points out.

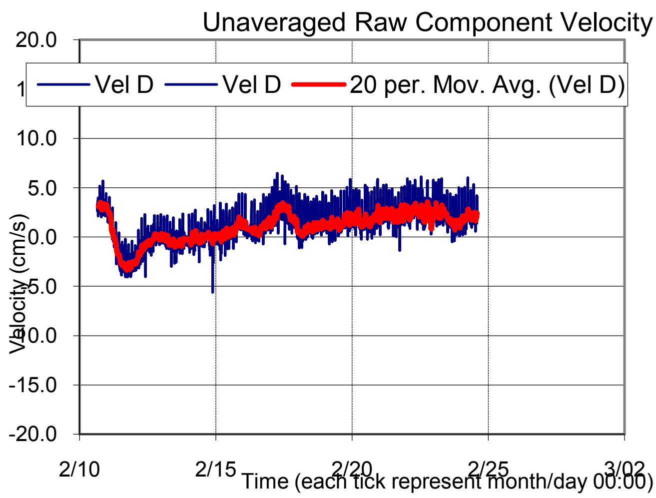

Fig. 3. After bad points were removed, the analog voltages from Kazakhstan MAVS were converted to velocity components. Axis D is shown here.

A. *Missed Cycle Issue*

There are several variations on the missed cycle issue. To provide the background for understanding the behavior of the problem, it is necessary to explain how the differential travel-time measurement is made with such precision. Electrical excitation of the piezoceramic transducers with a square wave in voltage causes the thickness of the transducer to change in response to the electrical stress and to create a pressure wave in the fluid at the face of the transducer. The mechanical resonance of the ceramic results in a slow buildup of amplitude over several cycles. In fact, the Q of the transducer is about 5, meaning that at the fifth cycle, the amplitude has increased to $(1 - 1/e) = 63\%$ of the steady state. The transducer that is receiving the acoustic pulse has a similar slow buildup reflected in an asymptotic increase in voltage toward the steady state value. As the amplitude increases, the slope of the voltage from the receiving transducer becomes steeper where it crosses zero. Electronic Johnson noise is added to the voltage present at the comparator but when the voltage slope is steeper, this noise contributes less to the timing noise that is critical to the differential travel-time measurement. With signal amplitude of 3v, the 10mv voltage noise translates to a time noise of 50ps. So 15 cycles are transmitted and the 14^{th} negative-going zero crossing of the received signal is detected by a Schmitt trigger voltage comparator to define the arrival time of the acoustic pulse. The Schmitt trigger is used to reject electronic noise below the trigger threshold and the countdown to the 14^{th} cycle only commences when the received signal becomes greater than that threshold. But it is the negative-going zero crossing that is detected and used to start the time integrator for determining the differential travel time. Zero crossings are independent of amplitude.

Counting to the 14^{th} cycle requires that the first positive-going cycle be detected unambiguously. Typically, this first cycle is about 150mv while the electronic noise that must be rejected is 10mv. So the Schmitt trigger is set to 50mv, generally a safe and stable level far removed from the low level noise but well below the first positive cycle to be detected.

But if the sound is attenuated and the first positive cycle is missed, the count will be off by one, assuming the much larger second positive cycle is not missed. Then the 14^{th} negative-going zero crossing will actually be the 15^{th} and delayed a full cycle from what it should have been. This is so late that the differential time integrator for that channel (say channel A) saturates and gives a full scale voltage to the A/D converter. This value is stored temporarily awaiting a reversed measurement. In MAVS, to remove slow electronic drift, the electronic comparators and integrators are switched between transducers and the measurement is made again. This reversed measurement results in a second A/D conversion and the two values, the first and the reversed, are subtracted to get the net differential travel time. Actually the travel time value is doubled while the drift signal is canceled.

There are two possibilities for the reversed measurement. In the first case, for the reversed measurement, channel A does not miss the first positive cycle so that the 14^{th} negative-going cycle is detected by both Schmitt trigger comparators. Then the reversed measurement gives a modest value to the A/D converter which, when subtracted from the first value, leaves a large value, near half scale or 2500mv. There are such values in the trace in Fig. 2. The second possibility is that the same missed first positive half cycle occurs but this time with the same Schmitt trigger comparator receiving the reversed signal, channel A. This would give a full scale value to the A/D convertor and when the second full scale value is subtracted from the first full scale value, the result will be zero or near to zero. Fig. 2 shows many points in the trace that are at or very close to zero. There is also a third case in which the other Schmitt trigger comparator, channel B, misses the first positive cycle for the reversed measurement while the original Schmitt trigger comparator, channel A, does not miss and in this case, the A/D converter is given a large negative value to subtract from the first value and this is an even larger value, about 5000mv and these can sometimes be seen in Fig. 2.

All of these can be negative if the first Schmitt trigger comparator, channel A, gets the correct count while the second, channel B, misses the first positive cycle. To summarize these cases, the values may be 0mv, 2500mv, 5000mv, -2500mv or -5000mv. All of these are wrong and do not show what the current actually is. These are tabulated in Table I. But there is a further subtlety when both channel A and channel B miss the first positive cycle and both trigger on the 15^{th} negative-going zero crossing instead of the 14^{th} negative-going zero crossing. Due to slightly different propagation delays in the electronics, instead of exactly matching, there is a slight offset and I have indicated that in the table as 2550mv half scale for a missed count on channel A and 2450mv half scale for a missed count on channel B. When they are both missed, there is thus a 100mv measurement (assuming there is no actual current). Current is added to these values. So the full complexity of the trace in Fig. 2 is current added to these values in five bands plus the actual Good measurement that may be close to zero but may not be on top of zero.

TABLE I
MEASUREMENT RESULTING FROM POSSIBLE MISSED FIRST CYCLE

A Normal	A Reversed	B Normal	B Reversed	Measurement
OK	OK	OK	OK	Good
Missed	OK	OK	OK	2550mv
OK	OK	Missed	OK	-2450mv
Missed	OK	Missed	OK	100mv
OK	Missed	OK	OK	-100mv
Missed	Missed	OK	OK	0mv
OK	Missed	Missed	OK	-5000mv
Missed	Missed	Missed	OK	-2450mv
OK	OK	OK	Missed	2450mv
Missed	OK	OK	Missed	5000mv
OK	OK	Missed	Missed	0mv
Missed	OK	Missed	Missed	2550mv
OK	Missed	OK	Missed	-100mv
Missed	Missed	OK	Missed	2450mv
OK	Missed	Missed	Missed	-2550mv
Missed	Missed	Missed	Missed	0mv

B. Cause of Missed Cycle

Attenuation of the acoustic signal or loss of sensitivity of the acoustic transducers both cause the first positive cycle to drop below the Schmitt trigger threshold. Since this was experienced under the ice in a lake in Kazakhstan, the conclusion is that ice in the acoustic path attenuated the acoustic signal. This can be by absorption, scattering, or refraction out of the beam. Air bubbles in the ice would be responsible for scattering and also for blocking transmission of the sound. Air bubbles in breaking waves are not a problem until the bubble fraction is greater than 10%, attenuation then being something like 10%, which is not enough to cause the first positive cycle from being counted. Refraction is another possibility where shards of ice with a different speed of sound from water cause the acoustic beam to leave the path and reduce the sound pressure level at the opposite transducer. Placing a finger in the acoustic path will disrupt the signal if the bone in the finger is on the acoustic axis. Flesh does not directly interfere with acoustic transmission. But attenuation by scattering or refraction seems to be the most likely cause of the missed cycles.

C. Physical Damage to the Sensor

If there is ice in the sensor volume sufficient to attenuate the sound and cause missed cycles, there is also a risk of physical damage to the sensor. The support rings are injection molded ABS plastic that has been machined for the transducer seats. The piezoceramic elements are glued to the seats and then enamel insulated solid copper wires are led along channels cut into the ABS rings to near the transducers. Silver braid conductors connect the copper wires to the silvered ceramic transducers. The wired rings with four transducers in each ring are over molded with low viscosity epoxy in RTV molds. Strands of fiberglass roving are laid in the molds in the vicinity of the machined seats to increase the strength of the sensor in its most vulnerable part. Still, the rings are plastic and have been broken when impacting a ship hull, ship propeller, or wire rope. Ice might well be a hazard as well. Fig. 4 illustrates a design of a wire whisk that can protect the sensor from floating debris such as loose ice and can even deflect the sensor from hard impact with the sides of the hole through the ice without interfering with the flow to the measurement volume.

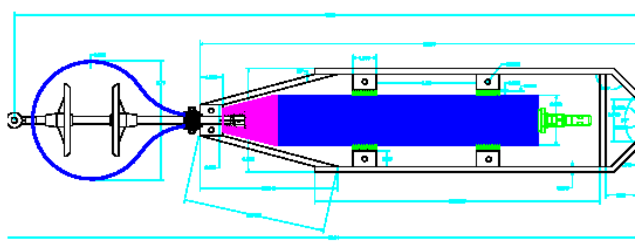

Fig. 4. MAVS can have a wire whisk-shaped protector over the sensor to protect it from ice and from impacts with the side of the ice hole. This drawing includes a mooring frame that picks up mooring tension carried through the sensor tube from the eyebolt at the end of the sensor tube to the inboard weldment of the tube where it enters the housing.

IV. ICE-TETHERED PROFILER

The moored profiler, produced by McLane Labs as the McLane Moored Profiler or MMP, runs down and up a mooring and measures temperature, conductivity, and pressure for durations as long as a year and at depths as great as 5000m [7]. Current measurements have been added to the MMP so that not only the depth, time of passage, and contrast of frontal features can be recorded but also the velocities associated with these features. In the Arctic, a version of the MMP that is anchored to a hole in the ice instead of to a weight on the bottom is the Ice-Tethered Profiler or ITP [2]. In 2009, one of the ITPs was equipped with a MAVS to determine the turbulent velocities important for estimating mixing of salt and heat while the ITP was stationary in between taking profiles of temperature, salinity, and velocity. Fig. 5 shows this ITP being inserted into a hole in the ice with the MAVS sensor and the SeaBird CTD sensors at the top. It is noteworthy that there is a short fin to stabilize the profiler since body motion of the profiler would contaminate the observation of fluid motion under the ice.

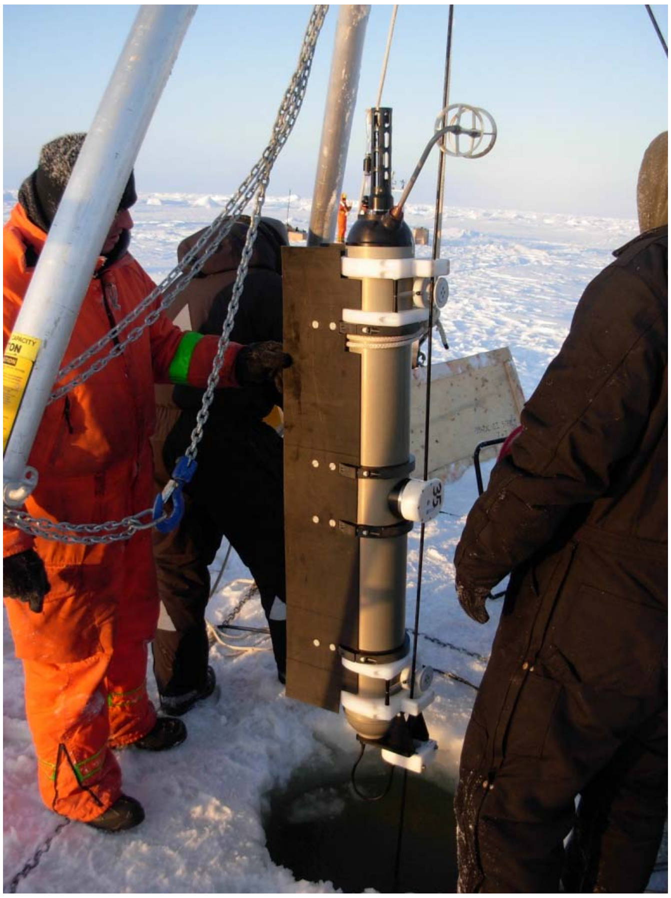

Fig. 5. The Ice-Tethered Profiler is being inserted through a hole in the Arctic ice. Note the small alignment fin. The crawling wheel at the bottom drives the profiler down and up the mooring wire. A buoy at the top will be frozen in the hole and transmit the data that has been inductively telemetered up the mooring from the profiler. The inductive transmitting coil is located at the bottom. The MAVS and SeaBird CTD sensors are located at the top.

A. Motion Tracking

The small fin on the ITP, dictated by the limited diameter of the hole in the ice, does not guarantee that the profiler will point into the current at all times. In fact, there is almost certain to be some oscillation in current that will result in the velocity sensor moving, causing a contaminated measurement of fluid velocity under the ice. MAVS contains a three-axis magnetic compass and solid-state tilt meter [8] from which the motion of the profiler might be determined but for two reasons this was inadequate. First, the magnetic compass for heading of the profiler has a poor signal in the high Arctic due to the proximity to the earth's magnetic pole. Second, the motions that are important are relatively rapid and the averaging that will allow the compass to give a reliable directional estimate is too slow. A solid-state inertial navigation sensor was added to MAVS providing three axes of rate gyro to get yaw rate, pitch rate, and roll rate, and three axes of linear acceleration to estimate the tilt and changes in tilt. Using the magnetic compass, low passed, and adding the inertial yaw rate integrated and high passed gave a good directional estimate of profiler orientation. It was necessary to use the tilts to rotate the rate gyro outputs into earth coordinates by Euler angles [2]. Poor magnetic direction sensing near the earth's magnetic pole may not be an issue at other ice deployment sites but the short-fin problem is likely to be important and data telemetry to a moving buoy in the ice may remain essential. The buoy, in addition to relaying the data by satellite, telemeters its GPS position so that it might be picked up on another deployment mission. Although the data were to have been sent by satellite, they are also logged on the profiler and there was a problem after the first several profiles with the inductive telemetry so these stored data are valuable.

V. ICE DEPLOYED MAVS FOR BRITISH ANTARCTIC SURVEY

MAVS is about to be deployed on a long mooring under ice where it will be powered from the surface with solar panel-charged batteries and where the data will be sent to the surface by an RS422 data link. The mooring will be 450m long. Since the communications will be by ASCII but RS232 is limited in range, RS422 has been used and is half duplex. However, the power to MAVS presents a small but important problem. The resistance of the cable and its inductance limit surge current to MAVS and this is solved by installing a large capacitor at the MAVS end of the cable which can provide this surge while limiting the current demands from the battery at the top. MAVS has a low average power but it achieves this low average current by turning off most of the circuits between measurements. A switching power supply inside MAVS generates 5v and +/-12v when a new measurement is about to be taken. It takes 15ms for the filter capacitors in the circuit to charge and the voltage to stabilize during which time the switching regulator draws about 1a. Then during the actual measurement, the current drops to about 100ma and between closely spaced measurements, the current drops to 12ma, the current needed by the controller. If as long as 10 seconds pass without a measurement, the controller goes into low power sleep drawing only about 700µa of current. However, these low power options were not sufficient for the client and the intention is to turn power off at the surface end of the cable and turn it on only when a new burst of measurements is needed. This ability to turn on the MAVS reliably when it has a large capacitor across the power input is an issue.

The controller on MAVS is a TT8 single board computer made by Onset. It uses a 68332 microprocessor made by Motorola. In order to start reliably, the reset line must be asserted while power is applied forcing program execution at a known location. Slow turn-on voltage, as can happen at the end of a long cable with a capacitor at the end, sometimes hangs the TT8 by the execution starting somewhere else in memory. So a sharp turn-on circuit was added and it is a minor but necessary addition as shown in Figs. 6 and 7.

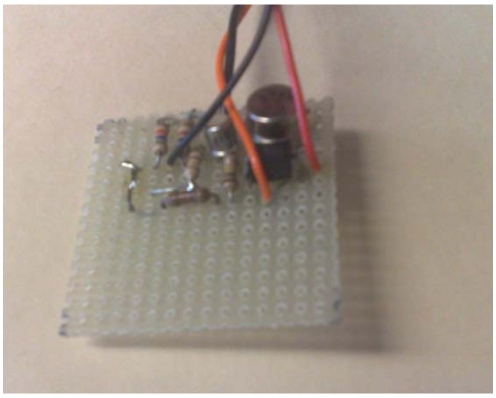

Fig. 6. Schmitt trigger circuit set to switch the capacitor to the MAVS at 9v and disconnect the capacitor from MAVS at 5v. This small piece of perforated circuit board is mounted on the 20,000µF capacitor.

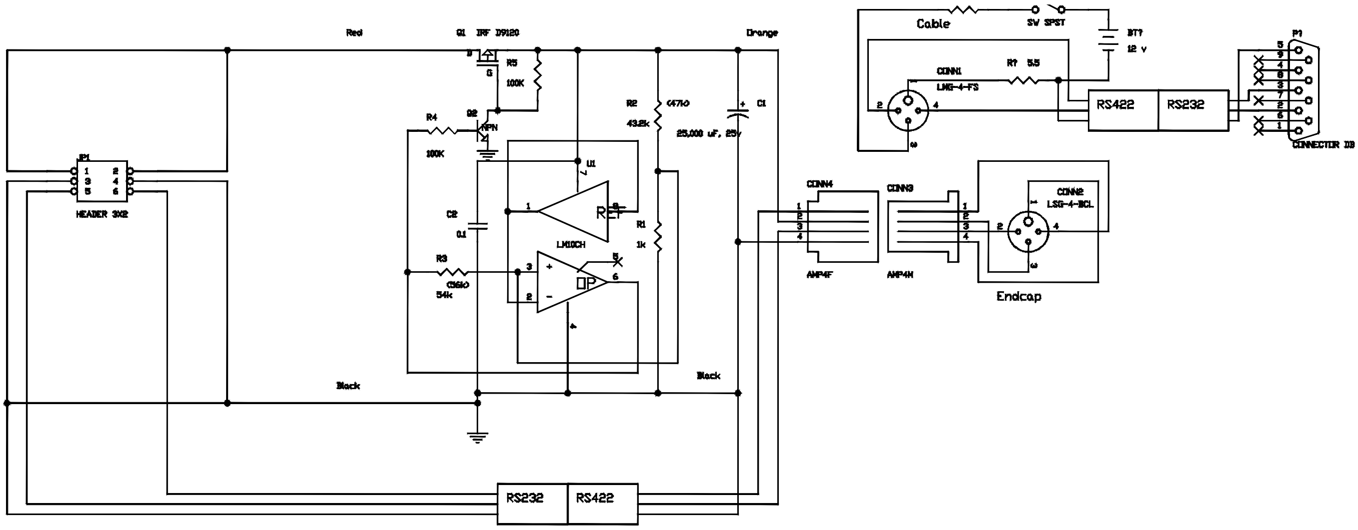

Fig. 7. The schematic drawing for the Schmitt trigger circuit of Fig. 6 shows an LM10 reference voltage and Op Amp circuit with an FET switch and the various connectors used in this circuit for the British Antarctic Survey MAVS.

VI. SUMMARY

MAVS has been deployed in three different applications, under the ice. As a self-contained instrument in Kazakhstan the issues were attenuation of the signal so that there were missed cycles in the receiver that caused spurious measurements that had to be detected and filtered before velocities could be obtained. Keeping out of loose ice bits by keeping well below the lower ice surface and by providing a wire whisk protector may be useful strategies.

When MAVS was deployed as part of the Ice-Tethered Profiler in the Arctic, additional motion tracking was required because the measurement of turbulence required removal of profiler motion from the measurement and this was beyond the capability of the magnetic compass and built-in tilt meter, at least in part because of the high magnetic lattitude. An inertial sensor with three rate gyros and three linear accelerameters was added to provide the high-frequency part of the heading measurement to the low frequency direction information from the compass. Tilt is used to get yaw direction and then the integrated yaw rate is high-passed and added to the low passed compass direction to get accurate instantaneous profiler heading.

The application that the British Antarctic Survey has for MAVS is a long duration deployment at the end of a long cable along which data are transmitted by RS422 and from which power is provided from the solar panel-charged batteries at the surface. Provision for surge current suppression in the cable requires a large capacitor in the MAVS that requires an additional Schmitt trigger switch to apply turn-on power abruptly to have the program start reliably.

Under-ice applications are demanding but can be dealt with if care is taken with instrumentation. There are opportunities for observations in this environment.

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