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Using the Magnetometer

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Product reference: All VMP Profilers

Introduction

This document explains the operation and use of the PNI MicroMag3, which is a 3-axis magnetometer that is installed on all VMP5500 profilers and is optional on all other profilers.

The purpose of the magnetometer is to indicate the orientation of the profiler with respect to the local geo-magnetic field. This information can be used to discern the rate of rotation of the profiler and the orientation of the relative shear and velocity measurements taken with other sensors on the profiler.

Overview

A 3-axis magnetic sensor module, MicroMag3, part number 12349, manufactured by PNI Corporation (www.pnicorp.com, 133 Aviation Blvd., Suite 101, Santa Rosa, CA, 95403-1084, USA) is used to sense the orientation of a profiler with respect to the earth magnetic field. This is a cost effective, low-power sensor that uses magneto-induction to measure the magnetic field. There are no moving parts. The user must follow the usual precautions regarding the placement of materials that are magnetic or susceptible to magnetic fields and the routing of DC currents. The user manual for the MicroMag3 is available at the PNI web site and a copy is also available from the web site of Rockland Scientific International.

The MicroMag3 is mounted on a circuit board (P032) manufactured by Rockland Scientific International so that its three axes are aligned with the axes of sensitivity of the VMP's accelerometers. Data are retrieved using the Instrument Bus by the same procedures used for the Analog-to-Digital Converter and the Sea-Bird frequency counters. The *x-, y-,* and *z*-axes are assigned, by default, to channels 34, 33 and 32, respectively. Other triplets of addresses starting with 16 x *N*, with *N* = 0 to 15, are available. A calibration sheet is provided with each instrument that carries the magnetometer.

Logic

The MicroMag3 produces a 16-bit datum upon request. The value of this datum is a linear function of the field strength along the axis of the sensor. Each axis must be requested separately. The response time of the MicroMag3 depends on the requested averaging period. We always request the maximum averaging period of 4096 because this maximizes the resolution of the magnetometer. The maximum response time is specified at 60 ms, but this value depends on the strength of the magnetic field.

The magnetometer interface board (P032), requests data from the MicroMag3 at the maximum operating speed of the MicroMag3. As soon as the datum from one axis is received, a request is issued for the next axis, and this process continues as long as power is supplied to the board. Thus, a single triplet of readings (one from each axis) can take as long as 180 ms and the effective sampling rate is 5.6 Hz, or greater, depending on field strength. The manufacturer does not specify how the response time varies with field strength, but it appears from actual data collected at 32 samples per second, that there are usually 4 consecutive identical values. This implies that the response time is about 130 ms which is a little shorter than the specified maximum of 180 ms. This is the case for all three components.

The interface board operates in free-running mode and continually updates its three internal registers with the latest values from the Micromag3. The user accesses these values by transmitting the address for one of the axes (32, or 33, or 34) on the instrument bus. The board responds with the latest current value for the chosen channel.

In practice, the user adds the addresses 32-34 to the address matrix in the setup file on the master computer that runs the data acquisition software. The master computer is either the ship-board data acquisition computer for a tethered instrument (running ODAS4RT) or the PC-104 computer in an internally recording instrument (running ODAS4IR). In addition, if the magnetometer channels and their calibration coefficients are identified in the setup file, then the ODAS4RT software will provide a real-time display of the compass orientation of the profiler. Details are given below.

Magnetometer Calibration

The magnetometers are calibrated at the Rockland Scientific International facility after they are installed in the VMP. The principle of the calibration is the same as that used for accelerometer calibration (described in AN-001).

The three axes of a vertical profiler are defined as follows, with the profiler nose pointed down.

- The *z*-axis is the axial center-line of the instrument and is normally vertical and is positive upwards.
- The *x*-axis is at right angles to the *z*-axis and is directed through the pressure port and is positive away from the instrument.
- The *y*-axis is at right angles to both the *z*- and the *x*-axis and is positive away from the instrument, such that when the *x*-axis points east, then the *y*-axis points north.

This convention is the same as used with the accelerometers. It also is the convention usually applied by physical oceanographers. However, ocean engineers frequently choose a *z*-axis that is directed down instead of up.

The magnetometer is calibrated by placing it on a rotating table so that the *z*-axis is vertical and the nose is pointed down, which is the normal orientation while profiling. The *x*-axis is then set to point to the magnetic north pole. Readings (averaged over 1 second) are taken in this position. Additional readings are then taken after rotating the instrument around its *z*-axis by 90, 180, 270 and at 360º. The last reading provides a check on the first reading. The instrument is then flipped so that the nose is up and the *z*-axis is vertical. An additional reading is taken in this position. A sample calibration report is shown in Appendix A.

Appendix A shows that the readings from the magnetometer aligned with the *z*-axis is much larger than readings from the two horizontal magnetometers. The calibrations are conducted in Victoria, Canada where the vertical magnetic field is about 2.5 times stronger than the horizontal component. The sensitivity to the local horizontal field of the *x*-axis magnetometer is obtained by subtracting the readings taken when this axis is North and South. This difference represents a change of twice the horizontal field. So, the difference divided by 2 is the sensitivity to the local horizontal field. The offset of the magnetometer is half of the sum of the readings. It is ideally zero and should not depend on the field strength.

The actual field strength is determined from values published by the National Geophysical Data Center operated by NOAA. The readings are updated daily and are accessed through

www.ngdc.noaa.gov/seg/geomag/jsp/struts/calcPointIGRF

The “sensitivity” is then normalized by the value of the horizontal field to get the actual sensitivity per unit field strength. The sign of the sensitivity is set so that it is positive when the axis points to the magnetic North Pole. The readings taken at orientations of 90 and 180º are used to derive the actual sensitivity of the magnetometer aligned with the *y*-axis.

The nose up and down readings provide the sensitivity of the magnetometer aligned with the *z*-axis. However, for this axis we use the published value of the vertical component of the local magnetic field.

The equations for converting the raw (integer number) magnetometer readings into physical units of micro-tesla are given in the right column of the last table in the calibration report (see Appendix A). Notice that, after they are converted to physical units, the M_x and M_y values are at their maximum when the *x*-axis and the *y*-axis point to magnetic North, respectively. When the nose is down, the M_z readings are negative which is the correct sign because the local magnetic field is directed downward into the earth in Victoria.

The actual values of the sensitivity are very similar for the three components and they are very close to the nominal specification given by the manufacturer of the MicroMag3.

Compass Conventions

Heading or direction is a frequent source of confusion and ambiguity. Mariners and navigators like zero degrees to be North and values to increase in a clockwise direction looking down. That is, east is 90º. Mathematicians, on the other hand, like angles to increase in the anti-clockwise direction and take 0º to be East. Moreover, when direction is encoded as a complex number, the real component is positive pointing East and the imaginary component is positive pointing North. We leave it up to the user to decide which convention to apply. There is sufficient information in the calibration report to use either convention. The real-time heading readout provided ODAS4RT uses the mathematical convention.

Setup File

The data acquisition is controlled by parameters specified in the setup file. An example of the three lines in the setup file that identify the magnetometer channels and their calibration coefficients is shown in the table below.

channel:	32,Mz,-32,62.02,0,0,0,0,0,0,0
channel:	33,My,40,65.65,0,0,0,0,0,0,0
channel:	34,Mx,121,63.86,0,0,0,0,0,0,0

In this example, the magnetometer axes are assigned to their default addresses. The eight numeric values on the right hand side are the calibration coefficients for the magnetometer. The first is the offset, which is the number that is subtracted from the readings to remove the offset. The second value is the sensitivity, which is the number by which the offset-corrected values are divided to convert the readings to magnetic field strength in units of micro-tesla. The remaining coefficients are ignored but are required for consistent parsing of the calibration coefficients by the data acquisition software. A tab-character can be used to separate the colon (:) from the address. However, only a comma (,) can be used to separate the component and its calibration coefficients.

An example of the address matrix that sets the order of sampling and the addresses of the channels that get sampled is shown in the table below. Note that the magnetometer channels are associated with the slow channels listed in the first column. For more information on the setup file, refer to the ODAS4-RT Software User Guide or the ODAS4-IR User Manual.

matrix:	0	1	2	3	5	7	8	9
matrix:	4	1	2	3	5	7	8	9
matrix:	6	1	2	3	5	7	8	9
matrix:	16	1	2	3	5	7	8	9
matrix:	17	1	2	3	5	7	8	9
matrix:	18	1	2	3	5	7	8	9
matrix:	19	1	2	3	5	7	8	9
matrix:	10	1	2	3	5	7	8	9
matrix:	11	1	2	3	5	7	8	9
matrix:	4	1	2	3	5	7	8	9
matrix:	6	1	2	3	5	7	8	9
matrix:	32	1	2	3	5	7	8	9
matrix:	33	1	2	3	5	7	8	9
matrix:	34	1	2	3	5	7	8	9
matrix:	0	1	2	3	5	7	8	9
matrix:	0	1	2	3	5	7	8	9

Tilt Corrections

The magnetometer readings are very sensitive to the tilt and roll of the instrument when the vertical component of the geo-magnetic field is much larger than the horizontal component. The pitch and roll information from the accelerometers can be used to project the magnetometer reading back into the horizontal plane.

For example, at high latitudes in the Northern Hemisphere, the vertical component of the geo-magnetic field is several times larger than the horizontal components and it is directed downwards. If the pitch and roll angles are both small, and if the instrument *x*-axis pitches up above the local horizontal plane, then the *x*-axis magnetometer will sense the vertical and the horizontal components of the geo-magnetic filed. The readings of M_x, in physical units, will decrease because of the negative vertical component of the geo-magnetic field while the reading of M_z will decrease only slightly. Readings taken in a pitched coordinate system can be rotated back into the horizontal plane by the transformation

$$\hat{M}_x + j\hat{M}_z = (M_x + jM_z)\exp(-j\phi) = \\ M_x\cos(\phi) + M_z\sin(\phi) + j(M_z)\cos(\phi) - M_x\sin(\phi) \tag{1}$$

where the carets (^) indicate the true horizontal and vertical values of the magnetic field. That is, the true magnetic field in the horizontal direction is given by

$$\hat{M}_x = M_x\cos(\phi) + M_z\sin(\phi) \\ \hat{M}_x = M_x + \frac{M_z A_x}{g} \tag{2}$$

where the pitch angle is derived from the accelerometer readings using

$$\phi = \sin^{-1}\left(\frac{A_x}{g}\right). \tag{3}$$

Similarly, if the *y*-axis rolls and points upwards above the horizontal plane, then the roll-corrected *y*-component of the magnetic field is

$$\hat{M}_y = M_y\cos(\theta) + M_z\sin(\theta) \\ \hat{M}_y = M_y + \frac{M_z A_y}{g} \tag{4}$$

where θ is the roll angle. These pitch and roll angles must be derived using the equations given with the accelerometer calibrations, which is a part of the ASTP calibration certificate issued with each instrument. The pitch and roll corrected horizontal magnetometer readings can then be used to determine the magnetic orientation of the instrument using standard procedures. For example, the magnetic bearing of the *x*-axis (in the convention used by navigators) is

$$\psi = -\frac{180}{\pi}\operatorname{atan2}\left(\hat{M}_y, \hat{M}_x\right), \qquad \text{or} \\ \psi = -\frac{180}{\pi}\operatorname{angle}\left(\hat{M}_x + j\hat{M}_y\right), \tag{5}$$

where atan2 is a standard two-argument arctangent function supported by all computer languages and angle is a Matlab function for finding the angle of a complex number with respect to the real axis. Equations (1) - (5) are only valid for small angles of pitch and roll. They are correct to second order if all of ϕ, θ, M_x/M_z and M_y/M_z are small compared to 1. They are correct to first order if the angles are small compared to 1.

Accelerometers report both the inertial acceleration and the component of gravity along their axes of the instrument. The inertial accelerations tend to have a high-frequency content usually caused by vehicular vibrations while the pitch and roll induced gravity signals tend to be at low frequencies. Thus, it is wise to low-pass filter the accelerometer data before using (1) - (5) for pitch and roll corrections of the magnetometer readings. In addition, the accelerometers are “fast” channels and are usually sampled at 512 Hz while the magneto-meter readings are “slow” channels and are usually sampled at 32 samples per second. One procedure to bring both the pitch and roll records on to the same sampling rate as the magnetometer measurements is to block-average the accelerometer readings by the ratio of sampling rates (512/32 = 8). Further filtering, applied identically to the magnetometer and the block-averaged accelerometer readings can then be used to derive pitch- and roll-corrected magnetometer readings and subsequently to derive the magnetic orientation of the instrument.

Appendix A

Magnetometer Calibration

Date: Model: PNI MicroMag3

SN: NA

Circuit Board: P032R00, SN=002

Tester: 4 90-degree rotations about vertical axis for M_x and M_y

Nose up and down for M_z

Operator: Dave Cronkrite

M_x Ch 34	M_y Ch 33	M_z Ch 32	**Comments** Position of pressure port wrt magnetic north.
-1091.8	184.2	-3246.7	N, Nose Down
238.4	1284.8	-3228.7	E, Nose Down
1332.9	-125.4	-3197.8	S, Nose Down
-8.2	-1205.8	-3209.3	W, Nose Down
-1092.3	179.4	-3247.0	N, Nose Down
3165.6	96.9	1122.5	Nose Up

Definition of axes on VMP: Let the central axis of the instrument be vertical and the nose pointed down (i.e. in normal profiling configuration). Then the *x*-direction points away from the instrument through the pressure port. When the *x*-direction points east, the *y*-direction is north. The *z*-direction points straight up (and away from the nose) along the central axis of the instrument.

Readings of the magnetometer are taken with the pressure port pointing to magnetic North, East, South and West. These reading provide the sensitivity of the M_x and M_y magnetometers. The sensitivity per unit magnetic field strength is the maximum reading minus the minimum reading divided by 2 and then divided by the local horizontal magnetic field strength. The offset of the magnetometer is the maximum reading plus the minimum reading divided by 2. The pair of readings taken when the pressure port is North and South give the M_x calibration while the other pair give the M_y calibration.

The vertical magnetometer is calibrated by flipping the instrument to bring its nose straight up. The difference between the maximum and minimum reading divided by 2 and divided by the vertical magnetic field strength calibrates the sensitivity of M_z. The sum of the maximum and the minimum divided by 2 gives the offset of M_z.

Local Field strength in Victoria, Canada, is M_V = -51.56µT, M_H = 18.98 µT.

Magnetometer	α offset [counts]	β sensitivity [counts]	Comments
M_x Max = 1333 Min = -1092 CH 34	121	1212	$M_x = 18.98 \frac{N_{Mx} - 121}{1212}$ $M_x = \frac{N_{Mx} - 121}{-63.86}$ [µT] maximum when pressure port points North.
M_y Max = 1285 Min = -1206 Ch 33	40	1246	$M_y = 18.98 \frac{N_{My} - 40}{1246}$ $M_y = +\frac{N_{My} - 40}{65.65}$ [µT] maximum when pressure port points East.
M_z Max = 3166 Min = -3230 Ch 32	-32	3198	$M_z = 51.56 \frac{N_{Mz} - (-32)}{3198}$ $M_z = +\frac{N_{Mx} - (-32)}{62.02}$ [µT]

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