Compass Selection for High-Latitude Operation of the Tethys AUV

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1 Summary

The purpose of this document is to examine the likely impact on AUV navigation accuracy from the use of low-power MEMS-based magnetic compasses at high latitudes. Specifically we seek to determine whether the Tethys AUV, equipped with one of several potential MEMS-based magnetic compasses can satisfy a navigation specification of 0.5% distance traveled while operating in Alaskan waters. The order of magnitude higher power consumption of north-seeking laser gyros (FOG and RLG) makes these more accurate technologies unsuited to use on the Tethys long range AUV.

On the basis of the analysis presented here, Tethys will be not able to meet the desired navigation performance using any of the commercially available MEMS AHRS surveyed. A navigation performance of between 2% and 5% distance traveled is likely feasible. I found almost no quantitative basis by which to differentiate between the MEMS AHRS surveyed. Based on prior success of similar units in the Beaufort Sea [?], relatively well documented test conditions, very low power consumption, and an apparently unique continuous "in-field" hard/soft calibration algorithm, I recommend equipping Tethys with a Sparton AHRS-M2. The specifications for the Sparton unit are not significantly different from all similarly priced models investigated with the exception of power consumption.

The next sections of this document provide some relevant background on the geomagnetic field and MEMS AHRS. In the latter I discuss the error sources typical of MEMS AHRS and their parameterization, with the objective of facilitating interpretation of manufacturers' datasheets. The following section presents a first order analysis of compass error, its sources, and how geomagnetic inclination affects each. I include a figure showing anticipated compass performance at various locations around Alaska. The next section presents a first order analysis of total dead-reckoned navigation performance, from which I derive a percent-distance-traveled navigation error metric expressed as a function of velocity noise and heading error. I use this metric along with specifications from AHRS vendors to quantify expected navigation performance of the Tethys AUV around Alaska. Some notes on the compiled specifications for the AHRS surveyed appear next. I conclude with more detailed recommendations.

2 Background

2.1 Geomagnetic Orientation

Magnetic compasses rely on the relative strength of the north and east components of the geomagnetic field to determine the direction toward the magnetic pole. At high latitudes the inclination of Earth's magnetic field increases toward 90° at the magnetic poles. Magnetic heading accuracy declines for a real sensor because the strength of these horizontal components falls off relative to internal and external magnetic noise sources.

NOAA uses the convention X, Y, Z for the north, east and vertical (positive down) components of the geomagnetic field, with H used to denote the total horizontal component. The derived quantities of inclination and declination are denoted I and D. NOAA's World Magnetic Model (WMM) provides predictions of each component and derived quantity; the latest, WMM2015[1], is valid for the interval between

[1] http://ngdc.noaa.gov/geomag/WMM/

2015 and 2020. WMM maps of inclination, horizontal field strength, and vertical field strength appear at the end of this report. The inclination over Alaska varies between 70° and 82°. The inclination near Woods Hole is 66°.

The WMM resolves the geomagnetic field to 3000 km wavelengths. This captures the dominant magnetic field produced by flows in the Earth's liquid outer core. Magnetized rocks in the crust dominate variations in the geomagnetic field at smaller wavelengths. Ionospheric and magnetospheric electric currents further alter the geomagnetic field and introduce short-term temporal variability. The error in each component of the geomagnetic field relative to the WMM is somewhat less than 200 nT RMS and latitude-dependent [?]. This value is similar in magnitude to bias in the magnetometers found in MEMS AHRS and exceeds the magnitude of random noise at 1 Hz in these units by an order of magnitude. Geomagnetic anomaly may therefore be significant source of navigation error.

Some MEMS AHRS automatically compensate for local declination using an internally stored version of the WMM. These units require initialization with the geodetic location to use this feature.

2.2 MEMS AHRS

Attitude Heading Reference Systems (AHRS) consist of an internal Inertial Measurement Unit (IMU) coupled with estimation algorithms and often with additional non-inertial sensors. IMUs measure inertial attitude or rotation rates using gyros or rate-gyros and inertial accelerations using accelerometers. Several vendors manufacture AHRS based on Micro-Electro-Mechanical (MEMS) rate-gyros and accelerometers. The advantages of MEMS AHRS over other technologies are primarily size and cost.[2] Currently the drift of MEMS rate-gyros limits achievable accuracy; however, the technology continues to rapidly improve and high-end MEMS rate-gyros may attain drift rates similar to low-end laser rate gyros within a decade [].

All of the MEMS AHRS surveyed in this report include a magnetometer to provide absolute orientation and to help stabilize gyro drift. Most magnetometers used in MEMS AHRS consist of three magneto-resistive sensors arrayed on orthogonal axes. PNI Corp. sells a gyro-less compass based on a proprietary magneto-inductive sensor similar in operation to a flux gate magnetometer []. Flux gate magnetometers offer higher accuracy than magneto-resistive units but are harder to miniaturize on account of requiring two coils of wire per axis.[3]

AHRS are used to measure both static and dynamic orientation. Applications requiring strictly static orientation, or platforms that maneuver slowly, require only accelerometers to measure static tilt and a vector magnetometer to determine the direction of the horizontal geomagnetic field. For example, Seagliders operating in the Beaufort Sea during the 2014 MIZ experiment used Sparton SP3004D compasses for attitude determination [?]. For dynamic applications both the magnetometer and accelerometers can be used to stabilize gyro drift because both measure a vector quantity with a fixed orientation relative to the earth (gravity and the geomagnetic field). Estimation becomes highly coupled for a dynamic platform and manufacturers have proprietary algorithms for this purpose. Qualitatively heading estimates from MEMS AHRS consist of integrated gyro output stabilized over long time scales to agree with the magnetic compass. This is typically accomplished using a complimentary filter or Kalman filter.

The accelerometers, rate-gyros, and magnetometers inside an AHRS are all subject to various sources of error. Woodman [?] provides a good overview for MEMS accelerometers and rate-gyros and Renaudin [?] for magneto-resistive magnetometers. Manufacturers typically provide performance specifications for their products in terms of a few parameters characterizing noise, bias, and non-linearity for the internal accelerometers, gyros and magnetometers. A compilation of available MEMS AHRS and their performance specifications appears in the spreadsheet that accompanies this report. To aid interpretation of that data and manufacturer datasheets in general Table 1 summarizes these specifications and what they mean.

The quality of MEMS AHRS is typically distinguished by the quality of their rate-gyros, noise density and in-run bias stability in particular. These determine how accurately an AHRS can track the dynamic attitude of its host platform. However, dynamic attitude depends primarily on integrating rate-gyro output because host platform maneuvers compromise resolution of the gravity vector from accelerometer output on short time-scales.

[2] A broad perspective on the range of IMU/AHRS/INS technologies, their performance, size and costs appears here: http://www.vectornav.com/support/library/imu-and-ins

[3] Ti flux-gate on a chip. Not clear if anyone is using this.

Specification	Acc.	Gyro	Mag.	Interpretation
Alignment Error	0.05°	0.05°	0.05°	RMS angle between the axes of the sensor. Produces a a directional error of similar magnitude in the sensed vector.
Linearity	0.1%	0.05	0.1%	Linearity (after calibration) over the full scale of a sensor. Expressed as % full-scale (%FS).
Scale-factor variation	0.05%	0.05%	0.2% ?	Variation in the slope of the approximately linear calibrated relationship between the output and input resulting from environmental influences, particularly temperature variation. Few reported values for magnetometers.
In-run Bias (In)Stability	40 mg	10 °/h	150 nT ?	The standard deviation of the underlying random walk used to model short-term variation in bias (100s of seconds for MEMS devices). Bias becomes apparent at averaging intervals sufficiently large to attenuate additive thermo-mechanical white noise. The figure quoted represents effectively the lowest possible remaining bias after bias estimation and compensation using complementary external data sources. Often listed as "bias stability," though usage is inconsistent and this sometimes refers to turn-on bias or long-term variation in static bias. Only one reported value for a magnetometer.
Turn-on Bias	1 mg ?	0.2 °/s	200 nT ?	Variation in initial bias between power cycles. Large variation between manufacturers for accelerometers and possibly inconsistent use. Few values provided for magnetometers.
Noise Density	100 μg/$\sqrt{\text{Hz}}$	0.01 °/$\sqrt{\text{Hz}}$	20 nT/$\sqrt{\text{Hz}}$	The standard deviation of the random noise that underlies short-term random walk of the integrated signal. Manufacturers sometimes quote an angular random walk (ARW) for rate-gyros (°/$\sqrt{\text{hr}}$) and velocity random walk (VRW) for accelerometers (m/s). ARW and VRW represent the growth in standard deviation of the integrated signal from each instrument (attitude and position respectively) over the specified interval. ARW and VRW can be derived from noise density and vice versa. See equations (7) and (8) in [?].

Table 1: Typical performance specifications for the components of MEMS AHRS.

3 Compass performance

How will operation at high latitudes affect AHRS performance? On what basis should one MEMS AHRS manufacturer be preferred over another—do the lower-level specifications specific to their magnetometers provide a means to do so? To answer these questions I derive an approximation for compass error as a function of the errors inherent to all MEMS compasses and show how these vary with the vertical (Z) and horizontal (H) strength of the geomagnetic field.

Magnetic compasses are subject to various sources of error: random noise, random bias, calibration error, tilt error, and unmodeled variation in the geomagnetic field. Random noise is unavoidable but generally small. Random bias consists of slow variation in sensor parameters both while active (mostly temperature effects) and from power cycling (turn-on bias). Calibration compensates for imperfections in manufacture and magnetic disturbances dependent on installation (hard and soft iron). Residual calibration error manifests itself as a heading-dependent but time-invariant bias. Tilt determination happens external to a magnetometer but is required to convert the field intensity measured along each axis into heading. Tilt error turns out to have a dominant effect on MEMS AHRS heading accuracy.

Most magnetometers found in MEMS AHRS consist of three magneto-resistive elements arranged on orthogonal axes. To determine heading the intensity of each axis is rotated into a level frame and the magnitude of the horizontal components compared:

$$\hat{\psi} = \operatorname{atan2}(\hat{h}_2, \hat{h}_1) \,, \tag{1}$$

where $\hat{\psi}$ denotes a heading estimate and $\hat{h}_{1,2}$ denote the horizontal elements of the total measured magnetic field after calibration $\hat{\mathbf{h}}$. The raw uncalibrated measured magnetic field is related to the actual magnetic field $\mathbf{h}$ by []:

$$R_e^v \, \mathbf{h_r} = SM\left(H_{si} R_e^v \mathbf{h} + \mathbf{h_{hi}}\right) + \mathbf{h_b} + \mathbf{h}_\epsilon \,, \tag{2}$$

where R_e^v denotes the rotation from the earth to body frames, S and M denote scaling and sensor axis alignment matrices respectively, H_{si} and $\mathbf{h_{hi}}$ describe the distortion caused by soft and hard iron respectively, $\mathbf{h_b}$ denotes offset biases and $\mathbf{h}_\epsilon$ denotes random noise. After simplification equation (2) consists of a 3×3 scaling and orientation matrix A, a lumped bias term $\mathbf{b}$, and random noise:

$$\mathbf{h_r} = A R_e^v \mathbf{h} + \mathbf{b} + \mathbf{h}_\epsilon \,, \tag{3}$$

The objective of compass calibration is to compute a scaling matrix $\hat{A}$ and bias $\hat{b}$ that are used to compensate the raw measurement for the distortions in (2):

$$\begin{aligned} R_e^v \, \hat{\mathbf{h}} &= \hat{A}^{-1}\mathbf{h_r} - \hat{\mathbf{b}} & (4) \\ &= \hat{A}^{-1} A R_e^v \mathbf{h} + \hat{A}^{-1}\mathbf{b} - \hat{\mathbf{b}} + \mathbf{h}_\epsilon \,. & (5) \end{aligned}$$

A good calibration yields $\hat{A}^{-1}A \approx I_3$ and $\hat{\mathbf{b}} \approx \hat{A}^{-1}\mathbf{b}$.

The calibration process itself consists of fitting an ellipsoid to measurements of the magnetic field vector in the frame of the magnetometer. After calibration the compensated magnetic field vector will lie on a sphere centered at the origin. The absolute orientation of the magnetometer is not used during the fitting procedure however the magnetometer's orientation must be varied to the extent possible in order to adequately sample the ellipsoid and attain a good fit.

Even supposing a good calibration some residual calibration error will remain from random noise in the measurements used to perform the calibration, temporal variability (drift) in the calibration parameters, and unmodeled effects.[4] Assuming residual calibration error results solely from drift, the compensated field will include a small constant bias term in addition to random noise:

$$\hat{R}_e^v \, \tilde{\mathbf{h}} = \tilde{A} R_e^v \mathbf{h} + \tilde{\mathbf{b}} + \mathbf{h}_\epsilon \,, \tag{6}$$

where the elements of $\tilde{A}$ and $\tilde{\mathbf{b}}$ are small. The rotation on the left hand side of (6) is an estimate and an additional source of error in heading estimates.

[4] The scaling matrix A in (3) need not be symmetric because M need not be symmetric. @@@ Published calibration routines find a symmetric A. Not sure if this is significant but M will be very close to orthogonal so it probably doesn't matter much.

Equation (5) can be used to estimate the variation in magnitude of each error source versus geomagnetic inclination. We assume a good calibration such that remaining errors are small to permit the use of small angle approximations. In particular the heading estimate for true heading near zero $\hat{\psi}$ becomes

$$\tilde{\psi} = \hat{\psi} \approx \tan\hat{\psi} = \frac{\hat{h_2}}{\hat{h_1}} \; . \tag{7}$$

Without loss of generality we further assume the sensor is level and oriented such that one axis points toward local magnetic north. The measured magnetic field is a distortion of these conditions and will yield a heading estimate that points somewhat away from local magnetic north. Under these conditions and ignoring second order terms (3) simplifies to

$$\tilde{\psi} = \tilde{a}_{21} + \frac{Z}{H}\tilde{a}_{23} + \frac{1}{H}\tilde{b}_2 + \frac{Z}{H}\tilde{\phi} + \frac{1}{H}\epsilon_2 \; , \tag{8}$$

where the $\tilde{a}_{ij}$ and $\tilde{b_i}$ denote elements of $\tilde{A}$ and $\tilde{\mathbf{b}}$ in (6). The specific elements of $\tilde{A}$ and $\tilde{\mathbf{b}}$ that appear here are an artifact of the particular nominal orientation chosen and not inherently significant. For the assumed orientation the roll error ϕ impacts heading; for other orientations the pitch would play a similar roll.

To determine geographic heading the local declination must be added to the magnetic heading computed by (7). The WMM provides an estimate of local declination D but is also subject to error. The error over Alaska is between 0.2° and 1.2° on the length scale of the WMM although localized areas of 3° to 4° below this scale are common worldwide []. Error in declination is either constant in a given location or a consequence of unpredictable magnetic storms. It may be worthwhile to consider the use of a higher resolution geomagnetic model (e.g. NOAA's EMM). For trajectories that return to their start location a constant declination error would serve only to rotate the entire trajectory. I exclude declination error in the analyses that follow.

Equation (8) offers some insights into the impact of geomagnetic inclination. The first three terms consist of residual calibration error and random bias. The latter two of these grow with increasing inclination. The fourth term in (8) shows the dominant impact of tilt error on heading accuracy. The geomagnetic inclination is at least 50° over all of the continental United States and exceeds 80° on Alaska's Northern Slope. In this area tilt error bleeds into heading error at a ratio of 1:1 and by a ratio as high as 6:1 on the Northern Slope. Random noise is also amplified at higher inclinations because the intensity of the horizontal field declines resulting in a lower signal-to-noise ratio.

To proceed we need magnitudes for each of the terms in (8). Unfortunately we have no basis from which to assign statistics to the residual calibration error terms. Assuming the model (2) is structurally accurate, the calibration residual should tend toward magnetometer noise for a sufficiently large number of samples. Comparing the expected noise with the calibration residual is one possible means of assessing calibration quality but I will assume this criterion has been met. Structural error in the model (insufficient degrees of freedom) would yield a residual somewhat above the noise floor but the impact of this kind of error on heading is difficult to model and likely small considering the maturity of magnetometer calibration. A likely dominant source of residual calibration error is drift in the parameters over time. Data from temporally separated calibrations would enable quantification of this source of error but I do not have any such data available. For the remainder of this analysis I assign a value of zero to these terms.

Most manufacturers provide noise statistics for their magnetometers and one also provided in-run bias instability. A noise density of 200 μG/$\sqrt{\text{Hz}}$ is typical. At a sample rate of 10 Hz this gives $\sigma_\epsilon \approx 60$ nT. Only SBG Systems lists an in-run bias instability: 150 nT for its Ellipse A model. Renaudin [] includes experimental results for a low-end (consumer-grade) magnetometer. They find an in-run bias instability of 4 nT. In-run bias instability represents a minimum error contribution from time-varying bias that would apply if it were possible to estimate and remove the bias at the shortest possible timescale, i.e. when bias becomes distinguishable from noise. Unlike thermo-mechanical noise bias cannot be removed by averaging but it can be estimated by comparison with complementary data sources. For a single measurement in isolation the error induced from bias can be modeled as having a standard deviation equal to the in-run bias instability. This assumes any variation in the bias above this value has been estimated and removed. I will ignore magnetometer in-run bias instability for lack of data and because worst case it appears to be similar in value to thermo-mechanical noise.

Thermo-mechanical magnetometer noise contributes a heading error of about 0.1° at 10 Hz for $Z/H = 0/30000$ (ideal conditions). The sampling rate of 10 Hz is typical for AUV applications and produces a

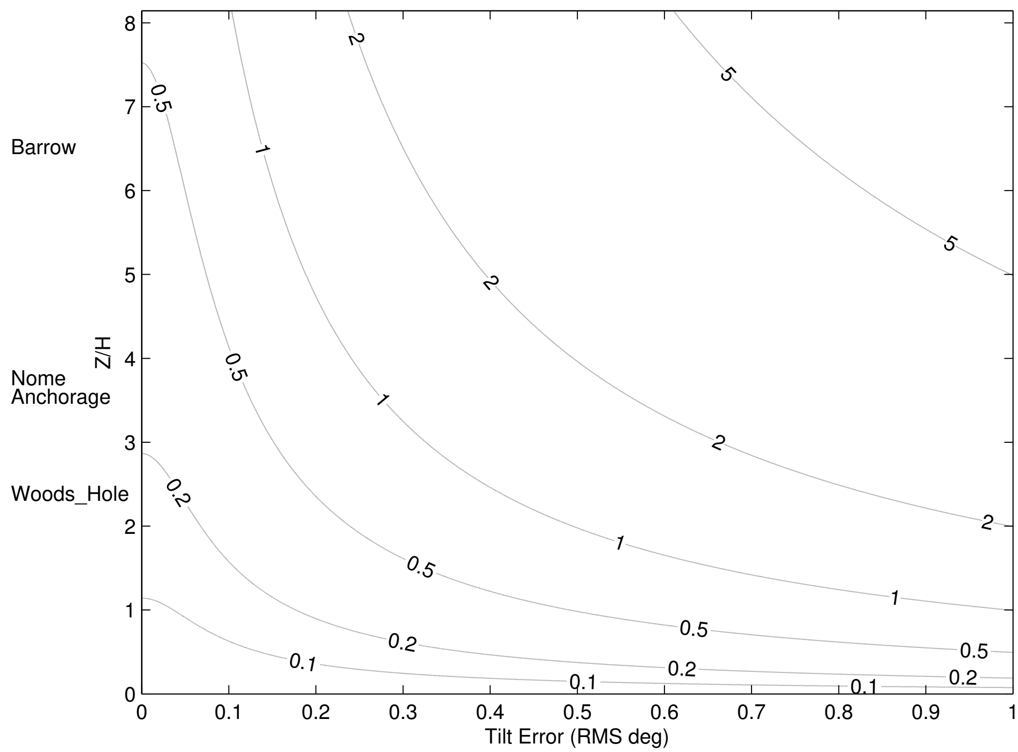

Figure 1: Heading error (RMS, 10 Hz) contoured versus tilt error and the ratio of the vertical and horizontal components of the geomagnetic field. Woods Hole and several locations around Alaska are marked on the vertical axis. This plot can be used to evaluate different AHRS based on their tilt (pitch/roll) error specification, assuming uniform calibration quality.

heading error about a factor of two better than the most optimistic manufacturer specifications for static heading performance. [5]

Referring to manufacturers' specifications, the magnitude of claimed static tilt (pitch and roll) error is at least as large as the error from random noise at 10 Hz. In the presence of an inclined magnetic field tilt error contributes directly to heading error. Static pitch and roll are determined by finding the direction of the gravity vector using accelerometers. I applied a similar analysis to manufacturers' accelerometer specifications in order to predict pitch and roll error. The results indicated error was dominated by sensor axis alignment; however, my analysis predicted tilt errors an order of magnitude smaller than those claimed by manufacturers. All subsequent analyses use the manufacturers' own specifications for tilt error to predict heading error.

Figure 1 summarizes the impact of geomagnetic field inclination on heading accuracy. The impact of both thermo-mechanical noise and tilt error are included. The effect of thermo-mechanical noise alone appears along the vertical axis.

[5]Only Sparton lists the conditions under which their specifications were generated. They use a horizontal field of 30000 nT with no vertical component. These are ideal conditions. No manufacturer explicitly lists the sampling rate for which their specifications apply.

4 Navigation Performance

Tethys will dead reckon for long periods of time between GPS fixes. It will use a DVL to measure its velocity over ground and a MEMS AHRS to determine its attitude. Dead-reckoned position is computed according to

$$\hat{\mathbf{x}} = \int R_v^e \, \mathbf{u} \, dt \; . \tag{9}$$

Both $\mathbf{u}$ (body-frame velocity) and R_e^v are subject to measurement error that corrupts the position estimate. Ignoring the vertical coordinate, and supposing the AUV travels due north at a velocity U, and that measurement errors in horizontal velocity and heading are small, and ignoring second order terms gives

$$\hat{\mathbf{x}} = \int \begin{bmatrix} u + u_\epsilon \\ U\tilde{\psi} + v_\epsilon \end{bmatrix} dt \tag{10}$$

where u_ϵ and v_ϵ are white velocity noise with standard deviation σ_u. I model the heading error $\tilde{\psi}$ as composed of a constant bias plus a random noise component:

$$\tilde{\psi} = \psi_b + \psi_\epsilon \; , \tag{11}$$

with standard deviations σ_b and σ_ψ respectively. Under these assumptions the position estimate will execute a two dimensional random walk. Heading error results in greater across-track than along-track error:

$$\sigma_x^2(t) = \sigma_u^2 t \delta t \tag{12}$$

$$\sigma_y^2(t) = U^2 \sigma_b^2 t^2 + U^2 \sigma_\psi^2 t \delta t + \sigma_u^2 \delta t \tag{13}$$

where x and y denote along-track and across-track respectively and δt denotes the interval between samples in a discrete implementation of (9). These equations do not include the effect of pitch and roll error on horizontal velocity nor of scaling errors in velocity nor of inter-sensor misalignment. These are first-order error sources that should be revisited in a future iteration of this report. The bias term in (12) is scaled by t^2 whereas all other terms are scaled by t and attenuated by more rapid sampling.[6] Heading bias will likely dominate navigation performance. Heading bias results both from imperfect calibration and tilt bias. Recall the impact of tilt error on heading error is amplified at high inclinations.

Percent distance traveled (%DT) is a typical metric for specifying dead-reckoned navigation performance. However there is no consistent standard for how the uncertainty in position after some distance is defined. Common choices are 50% Circular Error Probable (CEP) and multiples of the standard deviation in the position estimate. I will use the latter, specifically

$$\%\text{DT} = 2\frac{\sigma_y(t_L)}{L} \times 100 \; , \tag{14}$$

where the time required to travel a distance L is $t_L = \frac{L}{U}$. The factor 2 yields a 95% confidence interval. Equation (14) is conservative because it considers only across-track error (the actual 95% uncertainty is elliptical and the along-track axis is shorter). Substituting into (12) and simplifying yields

$$\%\text{DT} = 2\sqrt{\sigma_b^2 + \sigma_\psi^2 \tfrac{U}{L}\delta t + \sigma_u^2 \tfrac{1}{UL}\delta t} \times 100 \; . \tag{15}$$

Equation (15) is weakly dependent on the actual distance traveled—as a performance metric %DT improves with increasing distance. This is consistent with the behavior of a random walk. After sufficient distance these terms add a negligible contribution and %DT becomes a suitable metric for comparing systems.

Figure 2 shows %DT versus the same axes as Fig. 3. I have regarded tilt error as a constant bias to generate this plot. Bias as opposed to random noise dominates navigation performance. Achieving 0.5 %DT in Alaskan waters is likely not achievable with a magnetic compass based on manufacturer specifications for tilt, regardless of compass calibration quality. Two %DT may be achievable and 5 %DT almost certainly.

TODO: Threshold for DVL performance assuming a perfect compass.

TODO: No bottom lock will make currents the dominant source of error. Not considered here.

TODO: Reciprocal tracklines.

[6] This is the effect of discrete integration. The σ in (12) describe the underlying continuous-time white noise process, not sample standard deviations. Their values can be determined from plots of Allan Variance.

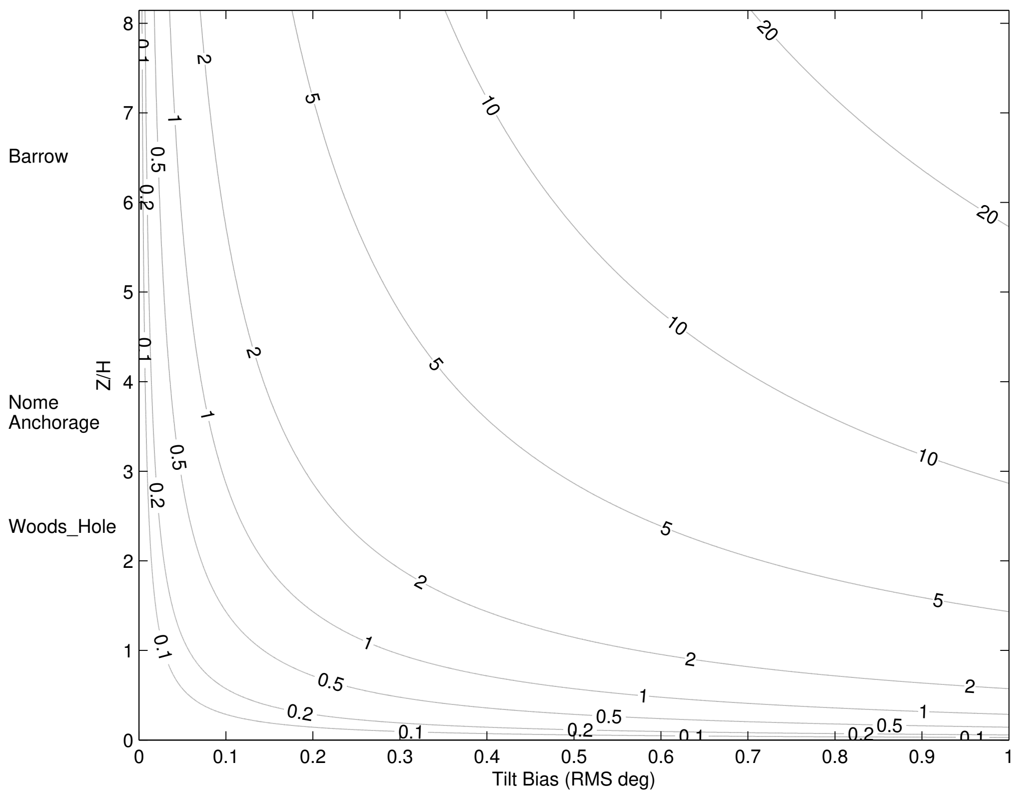

Figure 2: Navigation performance (%DT), 95% confidence, contoured versus tilt bias and the ratio of the vertical (Z) and horizontal components (H) of the geomagnetic field. This ratio for Woods Hole and several locations around Alaska are marked on the vertical axis.

5 Compiled Specifications

I surveyed a range of readily available MEMS AHRS. All are small (~50 mm square), low power (~100 mW) and claim similar performance. Prices range from under \$1000 about \$1500 with one outlier at \$3535 (Xsens MTi-100). Manufacturer specifications in terms of overall static pitch and roll performance vary relatively little in comparison to static heading which varies between a likely optimistic 0.2° and 1° for similarly priced systems. Component-level specifications for accelerometer, gyroscope and magnetometer performance are similar across all units with the greatest variation appearing in noise density, although reported values still agree to within an order of magnitude. Surprisingly there is no obvious correlation between component performance, overall attitude performance, and price.

I had hoped to be able to differentiate manufacturers' offerings according to their component-level performance by determining which parameters are most relevant for estimating quasi-static heading at high latitudes. I identified the importance of tilt error, and especially tilt bias, which suggests that accelerometer accuracy should be important (gyro performance dominates for high-speed maneuvers). However the tilt error estimates I attained this way were almost entirely due to axis alignment error, a figure uniformly reported as $+/-0.05^\circ$ by those manufacturers that listed it, and at least a factor of 5 too low. The noise densities and in-run biases reported by manufacturers had negligible impact. In fact the second-best static pitch roll accuracy claimed by a manufacturer is for a unit that also has the worst accelerometer performance (Sparton AHRS-M2). Magnetometer performance specifications proved similarly uninformative for two reasons. There was little variation between units and tilt error proved a dominant source of heading error at high inclinations when compared to noise sources intrinsic to magnetometers. Residual calibration error also results in a bias, though it was not possible to quantitatively explore that effect here. It is possible that differences between the calibration routines built into the sensors would differentiate one unit from another.

A few differences are worth noting. Both the Sparton and Vectornav units can be configured to internally compensate for local declination using the WMM. The Sparton AHRS-M2 has what appears to be a unique adaptive in-field hard and soft iron compensation algorithm. Sparton was the only manufacturer that listed the conditions under which their AHRS were calibrated. Sparton and PNI units list a maximum geomagnetic inclination angle of 80° and 85°, respectively. These figures likely represent an inclination at which performance degrades below some threshold, presumably for the reasons explored here, and not a hard limit. The PNI Seatrax in addition lists a maximum platform tilt angle of 65° (all other units are full 360°).

6 Conclusions and Recommendations

A navigation performance of 0.5% distance traveled is likely not achievable in Alaskan waters. Tilt error, rather than magnetometer performance is the limiting factor. Attaining 0.5%DT in the Beaufort sea would require a tilt bias of well below 0.1°. Attaining 2%DT is likely possible and 5%DT almost certainly possible.

There proved little basis on which to differentiate the various AHRS offerings available from manufacturers today. The Lord Microstrain 3DM-GX5-25, Sparton AHRS-M2, and Xsens MTi-30 all purport to offer similar performance at a similar price. Units both significantly cheaper and significantly more expensive either listed relatively worse performance or indicated similar component-level performance except for their rate-gyros. The Xsens MTi-100 and SBG Systems Ellipse-A both have somewhat better rate-gyros than other units. Better dynamic performance might be expected from these units but the present low-speed application doesn't justify the substantially higher power consumption. Based on prior success of similar units in the Beaufort Sea [?], relatively well documented test conditions, very low power consumption, and an apparently unique continuous "in-field" hard/soft calibration algorithm, I recommend equipping Tethys with a Sparton AHRS-M2.

In-field calibration of the AHRS magnetometer will be necessary. As usual this will prove challenging because of the unsuitability of the shipboard environment and maneuvering limitations of the vehicle for in situ calibration. I showed how the effect of a poor calibration is amplified at high geomagnetic inclinations relative to low inclinations. Tethys poses an additional challenge because it includes a moving mass for pitch control that will affect at least the hard iron bias. Claus [?] provides a method to compute calibration coefficients parameterized by the position of a glider's moving mass. The adaptive in-field calibration routine of the Sparton AHRS-M2 may suffice.

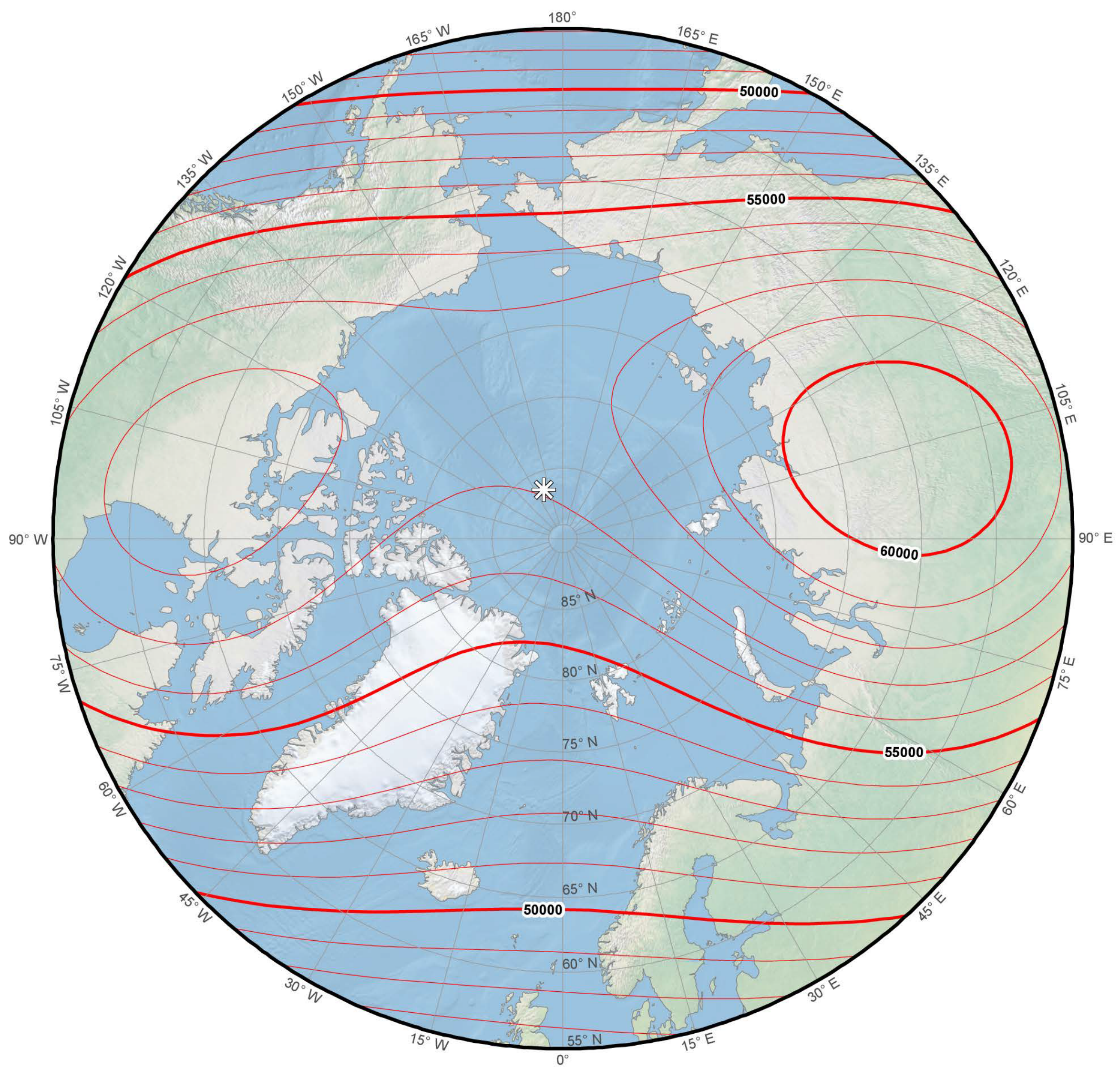

Figure 3: Main field vertical intensity (Z). Reproduced from [?].

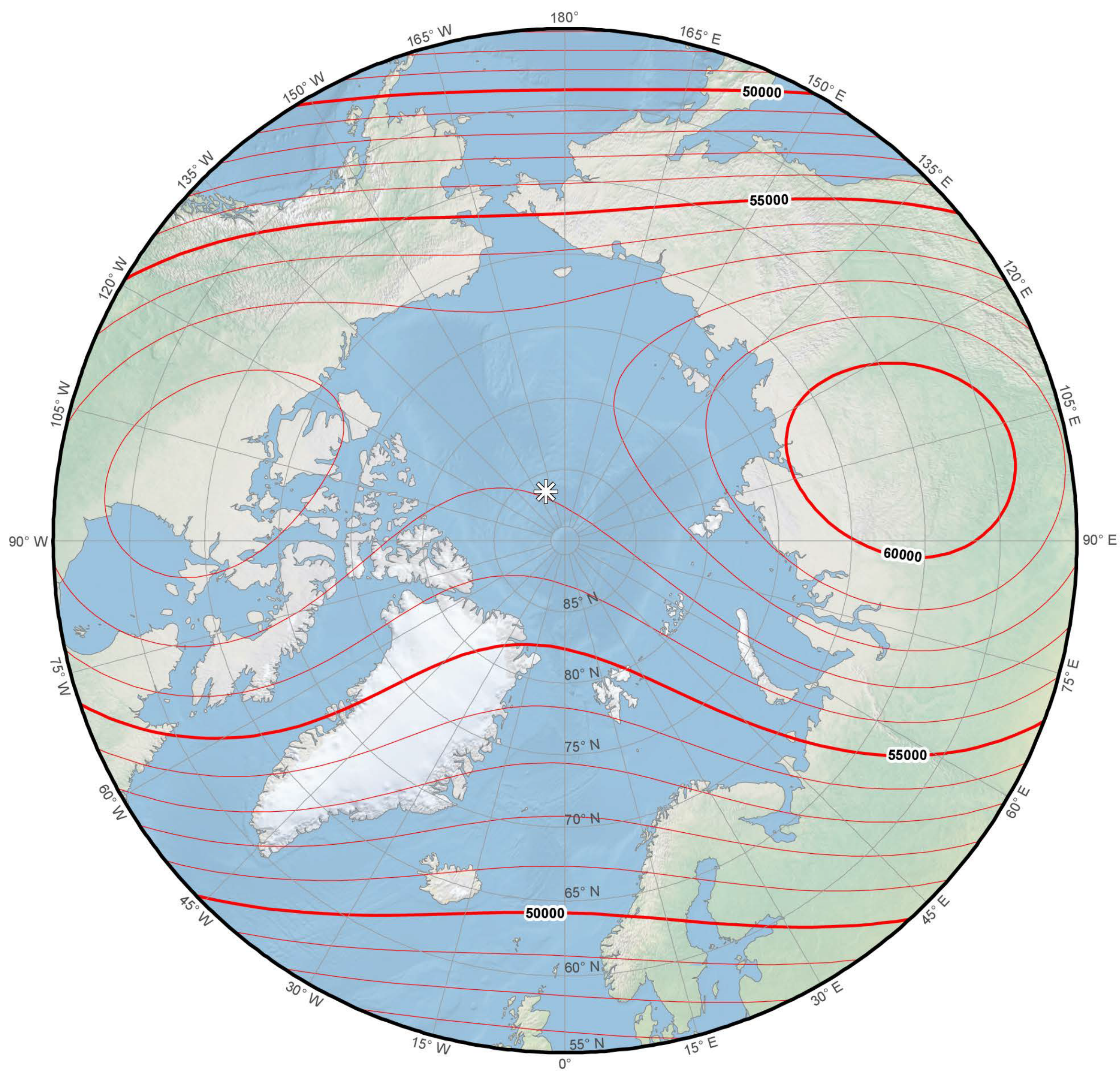

Figure 4: Main field horizontal intensity (H). Reproduced from [?].

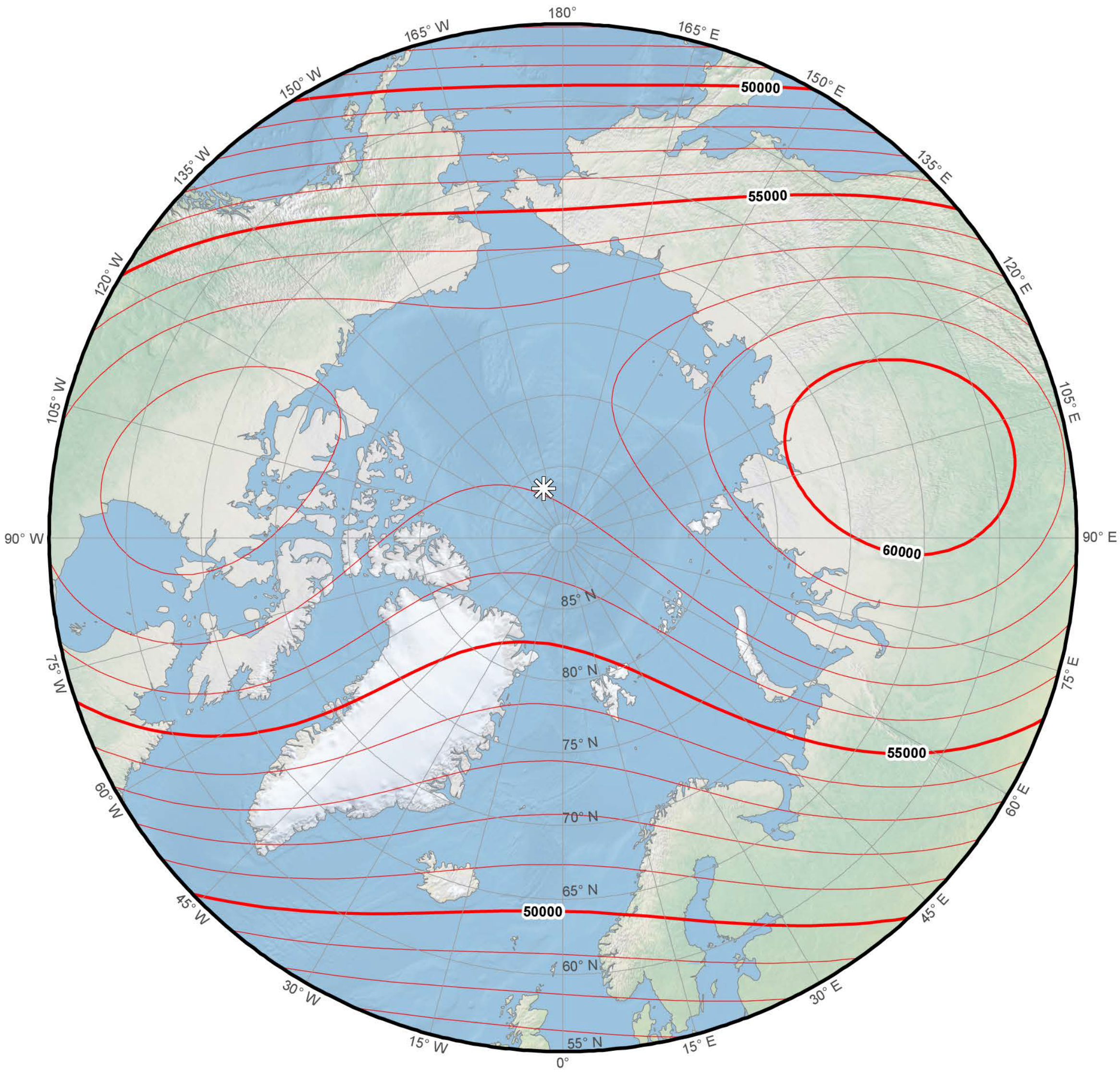

Figure 5: Main field total intensity (F). Reproduced from [**?**].

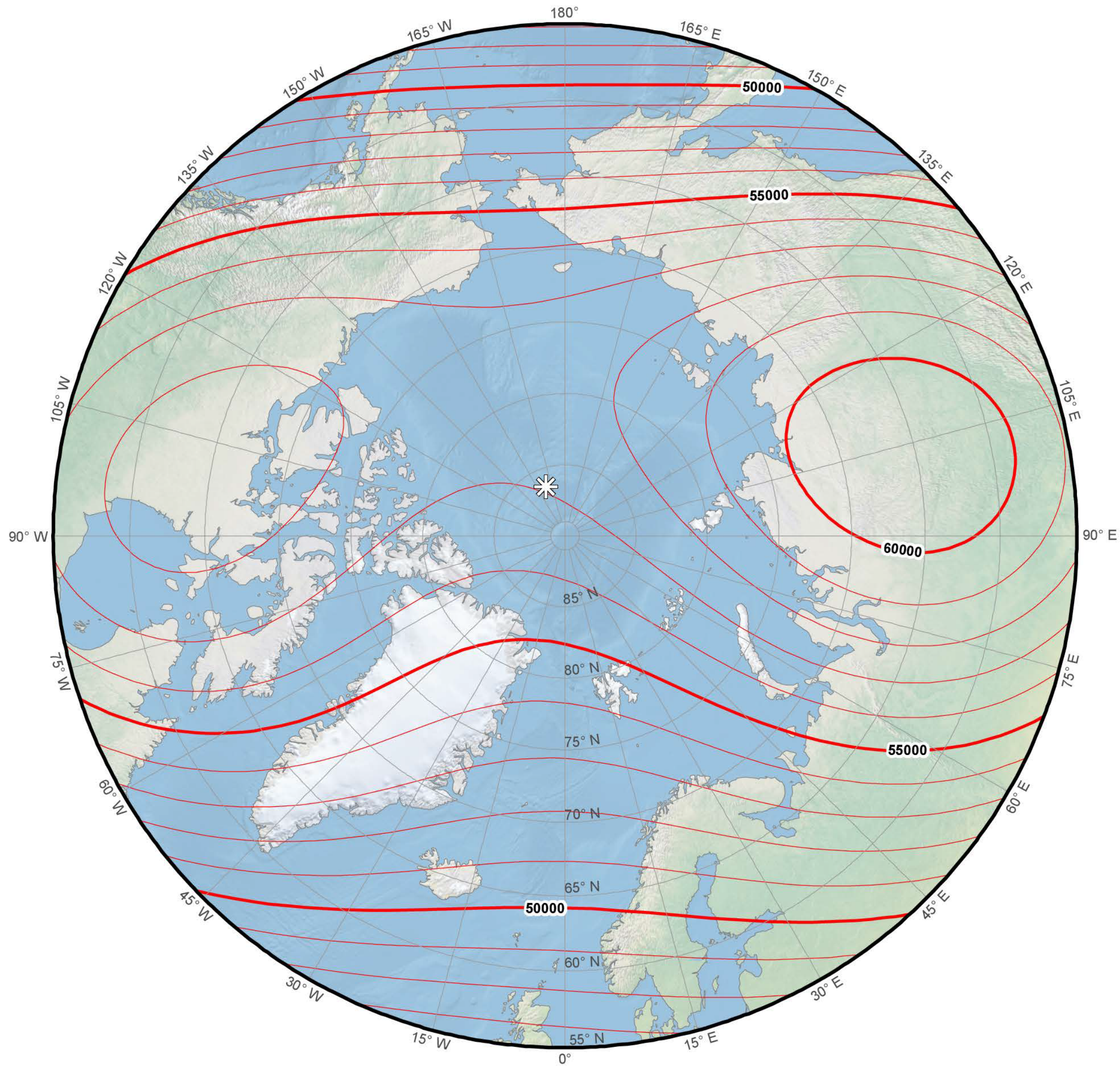

Figure 6: Main field inclination (I). Reproduced from [?].

References