TECHNICAL NOTE

HARD & SOFT IRON CALIBRATION

Accounting for Magnetic Disturbances

VECTORNAV

1 INTRODUCTION

A magnetometer is used to measure the strength and direction of the local magnetic field surrounding a system. This magnetic field measurement can then be compared to models of Earth's magnetic field to determine the heading of a system with respect to magnetic North. While seemingly straightforward, using a magnetometer to accurately estimate heading can prove to be quite challenging as Earth's magnetic field is relatively weak and there often exist a number of different magnetic disturbances that can impact magnetometer measurements.

Magnetic disturbances can be time-varying or time-invariant, and can be categorized as internal or external. External disturbances are from the surrounding environment and internal disturbances are fixed with respect to the sensor (i.e. internal disturbances do not change regardless of the orientation and/or location of the system).

Internal, time-invariant magnetic disturbances can be categorized as either hard-iron or soft-iron disturbances both of which can be accounted for by a hard and soft iron (HSI) calibration. Hard-iron disturbances are created by objects that produce a magnetic field (i.e. speakers, magnets, electrical current, etc.) and cause a permanent bias in the local magnetic field. On the other hand, soft-iron disturbances are commonly caused by ferrous metals, such as iron, which distort and stretch the local magnetic field.

In a perfectly clean magnetic environment, if the sensor was spun about all three axes, the magnetic measurements form a sphere centered at the origin with a radius equal to the magnitude of Earth's magnetic field. Hard-iron distortions present in the surrounding magnetic field shift the center of the sphere away from the origin, but will not affect the overall shape of the sphere. Soft-iron distortions distort and warp the sphere into that of an ellipsoid. Figure 1 shows example HSI calibration measurements in a magnetically clean environment (black) and with hard- and soft-iron distortions (red). A hard and soft iron (HSI) calibration is a method used to map this biased and distorted ellipsoid back into a sphere centered at the origin.

In practice, because the true magnetometer measurements are not known, an HSI calibration instead uses the local magnetic vector, $\boldsymbol{m}_E$, as truth. The magnetometer measurements are modeled in Eq. 1 below where $\boldsymbol{m}_e(t)$ and $\boldsymbol{m}_i(t)$ are the external and internal time-varying magnetic disturbances, respectively.

$$\tilde{\boldsymbol{m}} = S_I^{-1}(\boldsymbol{m}_E + \boldsymbol{m}_e(t)) + \boldsymbol{b}_{HI} + \boldsymbol{m}_i(t) \tag{1}$$

Magnetometer Calibration Data Example

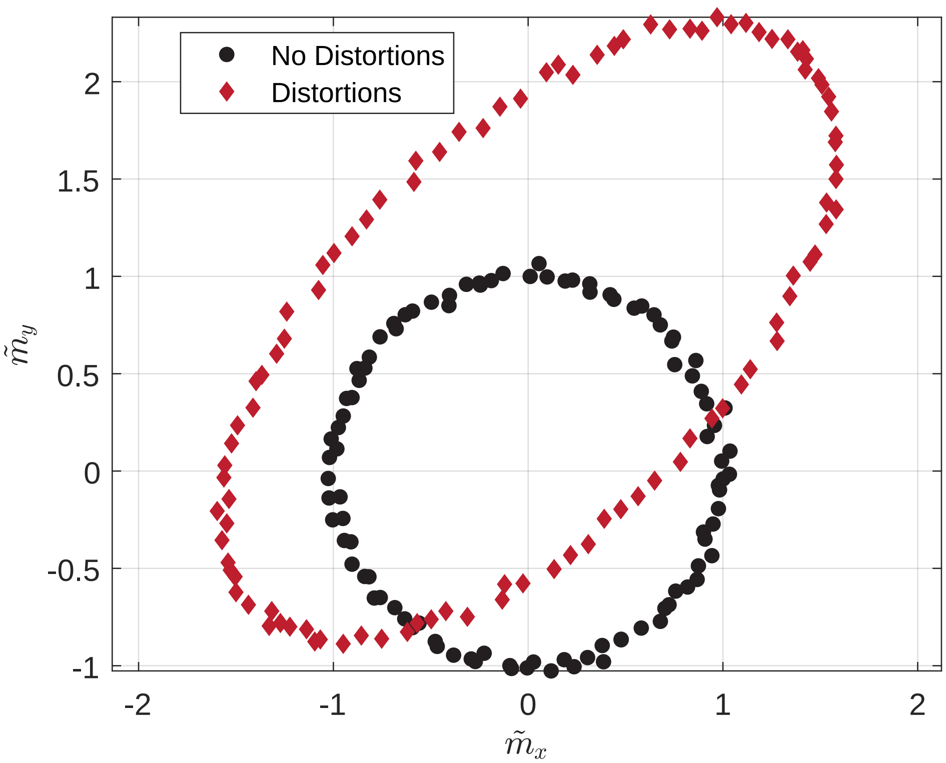

FIGURE 1

To map the ellipsoid back into a sphere, an HSI calibration must correct the local magnetometer measurements, $\tilde{\boldsymbol{m}}$, to the corrected magnetometer measurements, $\tilde{\boldsymbol{m}}_c$, by removing the hard iron distortions, $\boldsymbol{b}_{HI}$, and soft iron distortions, S_I, using a calibration model of the form:

$$\boldsymbol{m}_c = S_I(\tilde{\boldsymbol{m}} - \boldsymbol{b}_{HI}) \tag{2a}$$

$$\begin{bmatrix} \tilde{m}_{c_x} \\ \tilde{m}_{c_y} \\ \tilde{m}_{c_z} \end{bmatrix} = \begin{bmatrix} S_{00} & S_{01} & S_{02} \\ S_{10} & S_{11} & S_{12} \\ S_{20} & S_{21} & s_{22} \end{bmatrix} \begin{bmatrix} \tilde{m}_x - b_{H_x} \\ \tilde{m}_y - b_{H_y} \\ \tilde{m}_z - b_{H_z} \end{bmatrix} \tag{2b}$$

Notice in the magnetometer sensor model above in Equation 2a, $\boldsymbol{m}_e(t)$ and $\boldsymbol{m}_i(t)$ are assumed to be zero. Consequently, if any time-varying magnetic disturbance are present during an HSI calibration, either internally or externally, the accuracy of the calibration will degrade.

Because every individual system has a unique magnetic signature, it is recommended that an HSI calibration be performed on a system-by-system basis. An HSI calibration should be performed on all VectorNav AHRS/IMU products needing an accurate heading solution. Additionally, it is typically recommended that an HSI calibration be performed on VectorNav's single-antenna GNSS/INS products for robustness, particularly if the system will experience static and/or low-dynamic conditions. An HSI calibration is not usually required for VectorNav's dual-antenna GNSS/INS products if the GNSS compass is active, but it should be performed for robustness if GNSS outages are expected. More information on magnetometers and magnetic disturbances can be found in the Inertial Navigation Primer.

2 CALIBRATION SETUP

Prior to performing an HSI calibration, it is important to consider the environmental setup, motion requirements, and configuration of the sensor.

2.1 Environmental Setup

In order for an HSI calibration to estimate the hard and soft iron compensation parameters using Equation 2a, it must be assumed there are no external magnetic fields present other than Earth's. Accordingly, when performing an HSI calibration, the calibration **must** take place in an environment as close to magnetically clean as possible. Objects such as keys, cell phones, laptops, office furniture, watches, etc. will violate this assumption and can cause degradation in the calibration depending on their proximity to the sensor. Other objects in the environment such as cars or rebar in reinforced concrete can also cause issues during calibration even if several feet away.

The sensor, as well as the platform it is attached to, should be in its standard, operational state during calibration meaning that any onboard electronics, motors, etc. are powered on. This ensures that any magnetic-field generating currents that will be present during operation can be accounted for.

If any equipment that could potentially cause a magnetic disturbance is added or removed to the platform the sensor is rigidly attached to after calibration, the calibration will not be able to account for the subsequent changes. A common example of this would be swapping out batteries, adding a new payload, or altering any electronics equipment in a system. It is recommended that a new HSI calibration be performed any time changes are made to the platform that could affect its magnetic signature.

2.2 Sensor Configuration

An HSI calibration can only account for time-invariant magnetic disturbances that are rigidly attached to the sensor. To perform a valid HSI calibration, the sensor must be rigidly mounted in its final, operational location on the user's platform. A non-rigid attachment between the sensor and the platform will lead to degradation in the calibration. Additionally, any time-varying magnetic disturbances on the platform cannot be accounted for and should be mounted as far away from the sensor as possible.

3 OFFLINE CALIBRATION

Performing an HSI calibration using the offline calibration tools will provide the most reliable and robust method of calibrating the magnetometer.

3.1 Algorithm & Figures of Merit

As discussed previously, an HSI calibration maps the magnetometer measurements from an ellipsoid back into a sphere. The offline calibration tools accomplish this transformation using two distinct optimization fits, an ellipsoid data fit and an alignment data fit.

During calibration, the offline calibration tools use a selective algorithm in determining how much data to collect. This selection algorithm stores a measurement when the heading changes by a specific amount. Additional validation checks are also performed during a 2D calibration to ensure the sensor is rotated on a flat plane.

Upon completion, the offline calibration tools will report various figures of merit to provide feedback to the user on the quality of the calibration solution. These figures of merit include fit coverage metrics, which provide feedback on whether a sufficient amount of data has been collected, as well as the mean, maximum, and standard deviations of the residuals of each of the data fits, which indicate how magnetically clean the surrounding environment is during calibration. Each metric has a score (eg. Great, Good, Fair, Poor) and a corresponding value—the lower the value the better the calibration.

3.2 Motion Requirements

An HSI calibration can be implemented with two different types of motion—a 2D calibration or a 3D calibration depending on the range of movement feasible during calibration. Typically, a 2D calibration is sufficient if the platform will stay between 5° to 10° of level in both pitch and roll. Outside of that range, a full 3D calibration is strongly recommended. While each calibration has distinct motion requirements, neither calibration has a requirement on the speed in which the sensor is rotated.

A 2D calibration requires that the sensor be rotated 360° about the axis parallel to gravity. The sensor should be rotated on a flat surface with less than 10° of tilt. Unfortunately, given this requirement, a 2D calibration will not viable in dynamic conditions such as a high seas environment. During a 2D calibration, the sensor does not necessarily need to travel in a full circle— simply spinning the sensor in place is sufficient.

When performing a full 3D calibration, the sensor needs to be rotated about all axes to cover as much as possible a sphere of measurement. To achieve this, the following steps are recommended:

1. Align the sensor x-axis to the North-South vector and rotate a full 360°
2. Repeat Step 1 for the y- and z-axes, aligning each to the North-South vector and rotating the sensor a full 360°
3. Align the sensor x-axis to the East-West vector and rotate a full 360°
4. Repeat Steps 1-3 for the y- and z-axes, aligning each to the East-West vector and rotating the sensor a full 360°

If this type of motion is not feasible, contact VectorNav support for feedback on other viable motion profiles.

3.3 Hard/Soft Iron Estimator Tool

An offline HSI calibration can be performed on a sensor using the Hard/Soft Iron Estimator tool in the VectorNav Control Center software, which can be downloaded free of charge on VectorNav's website. This tool collects data from a connected VectorNav sensor and computes the associated magnetic correction values, allowing the user the ability to perform either a 2D or 3D calibration. Prior to calibration, the user must obtain the sensor's current latitude and longitude and input this position into the calibration tool. This position information is used to obtain Earth's local magnetic field vector where the calibration is being performed, which is needed in Equation 2a. This position does not need to be particularly precise, nor does the sensor need to be re-calibrated if the platform is moved to a new location. To perform an HSI calibration through the Hard/Soft Iron Estimator tool:

1. Download the Control Center software from VectorNav's website if it is not already installed on the user's Windows computer.
2. Open a new instance of Control Center and connect to the sensor by selecting the corresponding COM port and baudrate.

3. Under the Configuration tab, click on the Hard/Soft Iron Estimator icon: 

4. The calibration wizard window in Figure 2 should now appear, which provides different information for the user:
   - Settings: Configuration options allowing the users to select the type of calibration—2D or 3D, the user defined location, and algorithm control which starts or stops the algorithm.
   - Algorithm Statistics: Shows the figures of merit in real time.
   - Graph: During calibration, the user can observe both the uncalibrated (red) and calibrated (green) measurements as they are processed. These measurements can be viewed in 3D space as well as in a particular 2D plane using the Point Cloud Viewer buttons. Monitoring this window during calibration provides the user real-time, visual feedback on the quality of the calibration and cleanliness of the magnetic environment.
5. Select the HSI mode.
6. Input the current latitude and longitude of the sensor.
7. Start the algorithm and collect data.
8. Stop collecting data once the algorithm statistics have converged and/or they are acceptable.
9. Click *Write Hard/Soft Iron To Device* to write the values to the Magnetometer Calibration register (Register 23) on the sensor.

The sensor will now apply the magnetometer compensations from the offline HSI calibration process. Note this will only write these estimated parameters to the volatile memory of the sensor. A Write Settings command should be issued to the sensor in order for these values to persist through a reset or power cycle of the sensor.

HSI Wizard

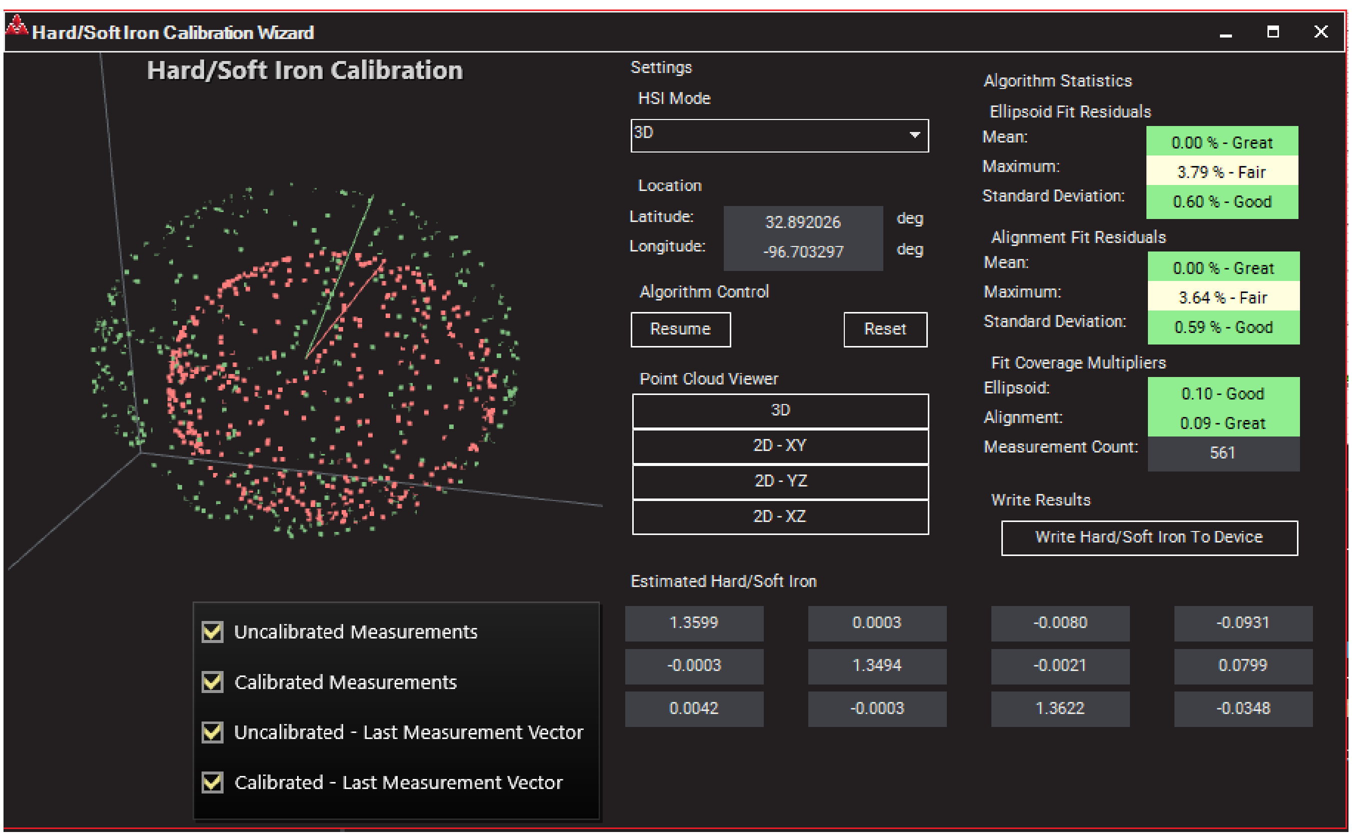

FIGURE 2

3.4 Embedded HSI Library

In many applications, connecting the sensor to a laptop or computer to run the offline calibration through VectorNav's Control Center software may not be feasible. For these cases, VectorNav offers an embedded version of the Hard/-Soft Iron Estimator offline calibration tool that can be directly implemented into a customer's onboard computer or processor. This embedded C-library uses the same calibration algorithms and figures of merit as the tool in Control Center, while allowing the user additional flexibility in performing a calibration on their system. The embedded HSI library requires a royalty-free software license agreement be in place before access can be granted. Please contact VectorNav for more information on using the embedded HSI library in your application.

4 REAL-TIME CALIBRATION

While the offline calibration tools will provide the most accurate and robust way of performing an HSI calibration, each VectorNav product is also equipped with a real-time calibration tool that can be used in instances where an offline calibration is not feasible. Typically, the real-time calibration tool is only utilized in applications in which the size of the system or onboard processing restrictions cause an offline calibration to be challenging. A real-time HSI calibration is typically better than not performing a calibration at all. The following sections describe two use cases of the real-time calibration algorithm.

4.1 Dedicated Calibration

In applications in which an offline HSI calibration is not feasible, the next best approach for calibrating the magnetometer would be to perform a dedicated HSI calibration through the real-time calibration tool. Similar to an offline calibration, a dedicated real-time HSI calibration should be performed in a clean magnetic environment.

The real-time HSI calibration is controlled through the Real-Time HSI Control register (Register 44), shown in Figure 3. The *Mode* field within this register controls the mode of operation for the real-time calibration, whether it is on, off, or should be reset. The *ApplyCompensation* field instructs the sensor whether the compensation parameters from the real-time calibration should be applied to the magnetometer measurements. The last field in this register, *ConvergeRate*, controls how quickly the real-time calibration converges on a new solution.

To begin the HSI calibration, the following steps must be performed prior to the calibration:

1. Clear any previous real-time calibration solutions by setting *Mode* to *Reset* in the Real-Time HSI Control register.
2. Set the *HeadingMode* field in the VPE Basic Control register (Register 35) to *Absolute* (leaving the *HeadingMode* in the *Relative* or *Indoor* modes can lead to a poor magnetometer calibration).

Real-Time HSI Control Register

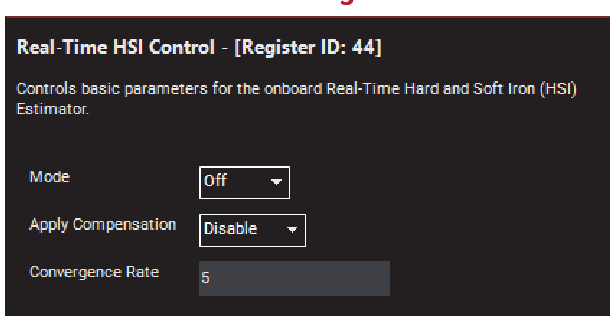

FIGURE 3

After the initial configuration, the following steps should be performed to start the calibration process:

3. In Register 44, *Mode* should be set to *Run*.
4. Move the sensor in a wide range of orientations while checking the real-time HSI calibration's convergence. The user will need to periodically poll the Real-Time HSI Results register (Register 47). When the estimated parameters have minimal changes between polling, the algorithm has converged.
5. Set *Mode* to *Off* and *ApplyCompensation* to *Enable* in Register 44 after the calibration has converged.

After the calibration is complete, a Write Settings command is necessary to store the calibration parameters to non-volatile memory.

The sensor will now apply the magnetometer compensations from the real-time HSI calibration process. These estimated hard and soft iron compensation parameters from the real-time calibration can be viewed in the Real-Time HSI Results register (Register 47). Note the real-time calibration only saves these estimated parameters to the volatile memory of the sensor. A Write Settings command should be issued to the sensor in order for these values to persist through a reset or power cycle of the sensor.

4.2 Real-Time Operation

If performing even a dedicated HSI calibration is not viable using the real-time calibration tool, the user can enable the real-time calibration tool to run continuously during operation of the sensor. However, this approach should only be reserved for applications in which the calibration methods detailed previously cannot be accomplished. To enable the real-time calibration during continuous operation, the user should configure the *Mode* to *Run* and *ApplyCompensation* to *Enable* in the Real-Time HSI Control register (Register 44). In addition, the *HeadingMode* field in the VPE Basic Control register (Register 35) must be set to *Absolute* (leaving the *HeadingMode* in the *Relative* or *Indoor* modes can lead to a poor magnetometer calibration).

When the real-time HSI calibration tool is left continuously running, the calibration is susceptible to errors in the HSI compensation parameters caused by external magnetic disturbances in the operating environment. Errors in the estimated compensation parameters will consequently lead to degradation of the estimated heading angle. Accordingly, it is strongly recommended that a dedicated HSI calibration be performed if at all possible rather than leaving the real-time calibration continuously running during operation.

5 TROUBLESHOOTING

If any issues are encountered during the calibration of the sensor, additional troubleshooting may be required. Below are the most commonly encountered issues when performing an HSI calibration. If the issue persists after reviewing these troubleshooting tips, please reach out to the VectorNav support team for additional assistance.

5.1 Bad Figures of Merit

After performing an offline calibration through either the Hard/Soft Iron Estimator in Control Center or the embedded library, it is recommended to review the figures of merit. Poor or fair scores reported in the coverage metrics indicate there was not enough motion performed for a valid calibration. Poor or fair scores in the residual metrics suggest:

- Calibration procedure was not performed in a magnetically clean environment
- System is exceeding $\pm 10°$ pitch/roll during calibration (for a 2D calibration)
- System has time-varying magnetic fields affecting the calibration

In general, these are indications that the calibration has not been performed in a clean magnetic environment and/or there are time-varying magnetic disturbances on the system. Depending on the severity, the location of the calibration should be changed. Figure 1 is a good example of how the end calibration should look (black circle). Any deviations from the circle/sphere will yield less accurate calibration parameters.

5.2 Drifting Heading

VectorNav sensors should provide a drift-free attitude solution. If the sensor's heading is drifting after an HSI calibration has been performed, it is recommended to check for the following:

- A bad HSI calibration was applied: Ensure during the calibration that the procedure is performed in a magnetically clean environment with minimal time-varying magnetic disturbances in proximity to the sensor and the system in its operational state.
- The HSI calibration may not have been successfully written to the device: After an HSI calibration is performed, a Write Settings command must be issued to the sensor to save the calibration parameters to the non-volatile memory and have them persist through a power cycle or reset of the device.
- The *Mode* field in Register 44 is set to *Run*: If an application requires that the *Mode* be on because neither an offline calibration nor a dedicated real-time calibration are feasible, ensure the *Absolute* mode is configured in the *HeadingMode* field of the VPE Basic Control register (Register 35). The real-time HSI calibration feature

is incompatible with any VPE Heading Mode other than the *Absolute* mode. In all other circumstances, if a calibration procedure is not being run, then the *Mode* field in Register 44 must be turned off to ensure proper function of the sensor.

- Strong electromagnetic interference: There are some situations where the magnetic disturbances around the sensor are severe enough that even with an HSI calibration the heading will not be stable. A good example is if the sensor is in close proximity to electric motors. Electric motors produce time-varying magnetic disturbances which an HSI calibration cannot account for. Ensure that the HSI calibration was performed with the system powered on and running in its nominal state. In general, move the sensor as far away from the magnetic disturbance as possible to minimize its effect.
- The system has been changed from the calibration setup: An HSI calibration can only account for time-invariant disturbances at the time of calibration. If any equipment that could potentially change the magnetic signature of the system is added to or removed from the system after calibration, the compensation parameters will not be able to account for the subsequent changes. A common example of this is swapping out batteries on a system. It is recommended that a new calibration be performed when changes are made to a system that could affect its magnetic signature.

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Version 26-002-R0