

PNI White Paper

Local Magnetic Distortion Effects on 3-Axis Compassing

SUMMARY

Digital 3-axis compasses from three different manufacturers were tested for heading error when a battery (having magnetic distortion properties) was placed in close proximity to the compass. After installing the battery, a compass underwent the manufacturer's recommended magnetic calibration procedure. Heading error was then measured at various pitch and roll angles as the compass was rotated 360° in heading. The effectiveness of the manufacturer's magnetic distortion compensation algorithms was established by this test. Test results indicate a significant difference in the effectiveness of these algorithms, as the total range in heading variation for the worst case compass was $\pm 6^\circ$ (at only 20° of pitch), while it was about $\pm 1^\circ$ (at 50° of pitch or roll) for the PNI compass.

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This white paper first examines sources of localized magnetic distortions, their effects on compass measurements, and how to correct for these distortions to get accurate compass readings. Next, the paper discusses tests performed at PNI to measure the effectiveness of magnetic distortion correction algorithms on 3-axis compasses from three different companies. Results from these tests are presented and reviewed.

OVERVIEW OF MAGNETIC DISTORTION

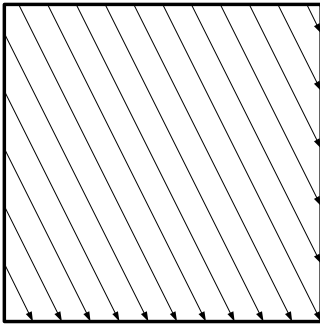


Figure 1: Earth's Undistorted Magnetic Field

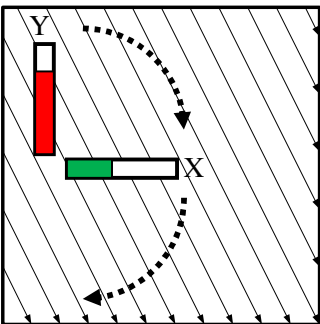


Figure 2: 2-axis Compass in Undistorted Magnetic Field

Earth's undistorted magnetic field in a local region will be of constant magnitude and direction, as represented in Figure 1. However, the local magnetic field often is altered by two types of magnetic distortion: hard iron distortion and soft iron distortion. In this section we will review how a basic 2-axis compass works and these two types of magnetic distortion.

Before discussing hard and soft iron distortion, consider a compass comprised of 2 magnetic sensors (X and Y) which are mounted orthogonally to each other and in a horizontal plane (i.e. a 2-axis compass). Each sensor measures the strength (either positive or negative) of the magnetic field which is parallel to its orientation. This is depicted in Figure 2, where the compass is superimposed over the magnetic field. The length of the bar represents the strength of the magnetic field and the color (red or green) represents whether the field is positive or negative. If these orthogonal sensors are now rotated through 360° in the horizontal plane, the resulting plot of each sensor's output is shown in Figure 3. For this plot, the X sensor's reading is shown along the plot's x axis and the Y sensor's reading along the y axis. (The units on this plot are mGauss: Earth's magnetic field strength is nominally 0.5 Gauss, although this is dependent on where the measurement is taken.) In an undistorted field, the resulting plot is a circle, as indicated.

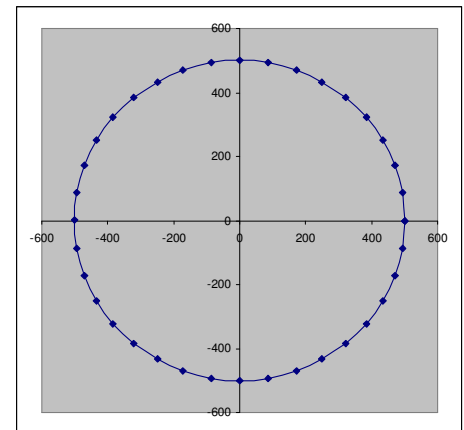


Figure 3: Local Magnetic Field - Undistorted Field

Hard Iron Distortion

Hard iron distortions occur when magnetic dipoles exist on the platform in which the sensors are mounted. For example, a magnetic sensor mounted in the mirror of a car will be affected by magnetic dipoles throughout the car, such as audio speakers, the engine, fan motors, DC currents carried in wires, batteries, etc. These magnetic dipoles add a constant magnetic vector to Earth's magnetic field relative to the X and Y sensors. This results in a shift of the local magnetic field, as shown in Figure 4.

To compensate for hard iron distortion it is necessary to subtract X and Y offset values from the sensor readings once these values are established. It is relatively straightforward to determine and apply these offset values.

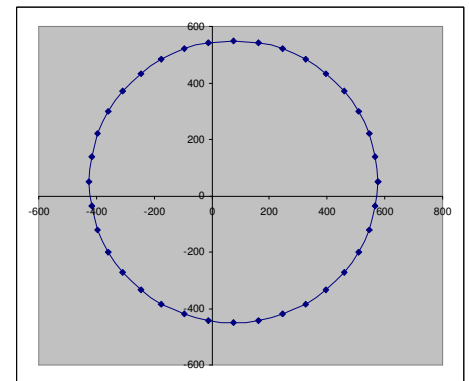


Figure 4: Local Magnetic Field with Hard Iron Distortion

Soft Iron Distortion

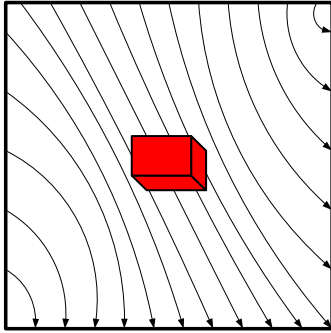


Figure 5: Soft Iron Local Field

Soft iron distortion is caused by magnetically permeable objects on the compass platform that attract and distort the local field, as depicted in Figure 5. Materials such as nickel, iron, and other magnetic materials are the main cause of soft iron distortion.

The local magnetic field plot now is an ellipse, as shown in Figure 6. In this case the soft-iron effects can be compensated for by scaling the X and Y sensor outputs as a function of the rotation angle. Determining these scaling factors and properly applying them, however, is

considerably more complicated than determining and applying the X and Y offset values for hard iron compensation.

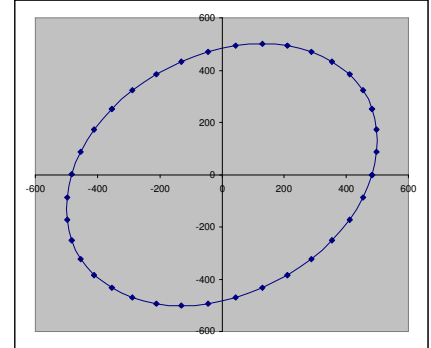


Figure 6: Local Magnetic Field with Soft Iron Distortion

Combining Hard and Soft Iron Distortions

In most applications both hard iron and soft iron distortions are present and need to be compensated for. The resultant local magnetic field plots as an ellipse that is offset from the center, as depicted in Figure 7.

It should be noted that the local magnitude field can be significantly stronger than Earth's local undistorted field. Consequently, the operating range of the sensor needs to be large enough to allow all of the local distortions to be accommodated and calibrated out. These local distortions can be calibrated out as long as they are spatially fixed with reference to the sensors. Distortion from buildings and other sources that are not moved with the sensors cannot be compensated.

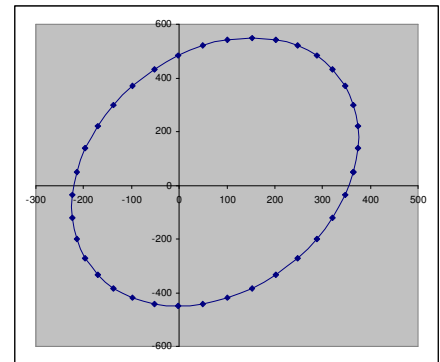


Figure 7: Local Magnetic Field with Hard and Soft Iron Distortion

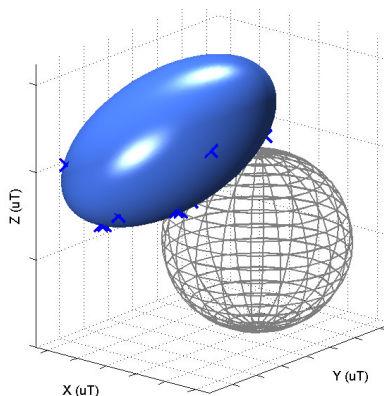


Figure 8: Hard and Soft Iron Distortion in 3D

In a 3-axis system wherein the compass can be tilted, the hard and soft iron distortions would be represented by the graph in Figure 8. The blue ellipsoid represents the actual measured local magnetic field while the grey wireframe sphere represents how the compass should report the local magnetic field (undistorted field) after the calibration algorithms are applied.

The overall accuracy of a compass in the real world is dependent on a number of factors, including the ability of the compass to correct for hard and soft iron distortions. The next section applies a local magnetic distortion near 3 different compasses, then examines the effectiveness of the various compass algorithms to correct for this distortion.

3-AXIS DIGITAL COMPASS TESTING

Devices under Test

PNI performed comparison testing of three (3) digital compass modules: Honeywell's HMR3500 (TruePoint), Ocean Server's OS5000, and PNI's TCM3. All are 3-axis, tilt-compensated modules that claim hard and soft iron magnetic distortion compensation.

Test Setup

A compass module was mounted onto a distortion free plate which was used as the test platform. Added to this test platform was a single AA battery, as shown in Figure 9. The distortion source (battery) and placement were chosen as a rather severe, but not atypical, real world condition.

The test platform (compass module plus battery) was then field calibrated per the manufacturer's calibration procedure. A few notes on these different procedures:

- The OS5000 requires separate hard iron calibration and soft iron calibration.
 - The hard iron procedure requires taking calibration samples while rotating the compass 360° in a horizontal plane, then rolling the platform 90° onto its side and again rotating the compass 360° while taking calibration samples.
 - To perform the soft iron calibration it was necessary to know the direction of magnetic north, south, east, and west.
- The HMR3500 combines hard and soft iron calibration into a single procedure and requires taking 16 data points as the compass is rotated 360° in a horizontal plane.
- The TCM3 similarly combines hard and soft iron calibration into a single procedure. Twelve (12) data points were taken as the compass was rotated 360° in heading, while the pitch and roll were varied $\pm 45^\circ$.

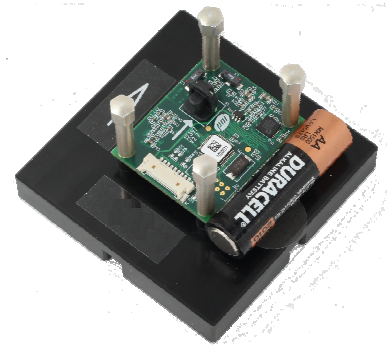


Figure 9: Test Platform (Compass Module plus Battery)

After a calibration was performed, data was collected using PNI's precision turntable, which was located in a magnetically clean environment. Data was collected for headings of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. These headings were measured with the test platform having 0°, 10°, 20°, 30°, 40°, and finally 50° pitch. (Pitch is analogous to the angle of an airplane from back to front. When the plane is going up, it has a positive pitch and when it is going down it has a negative pitch.) Then the test platform was measured when having a roll of 0°, 10°, 20°, 30°, 40°, and 50°. (Roll is analogous to an airplane banking left or right. Banking left would be a negative roll and banking right would be a positive roll.)

Test Results

Ocean Server OS5000 heading error at various pitch angles is plotted in Figure 10. Data was not taken for pitch angles greater than 20° because the errors were substantial at 20°. Roll data was not taken for the OS5000 due to equipment availability issues. Based on data from the Honeywell and PNI tests, we would expect the roll data to be similar to the pitch data.

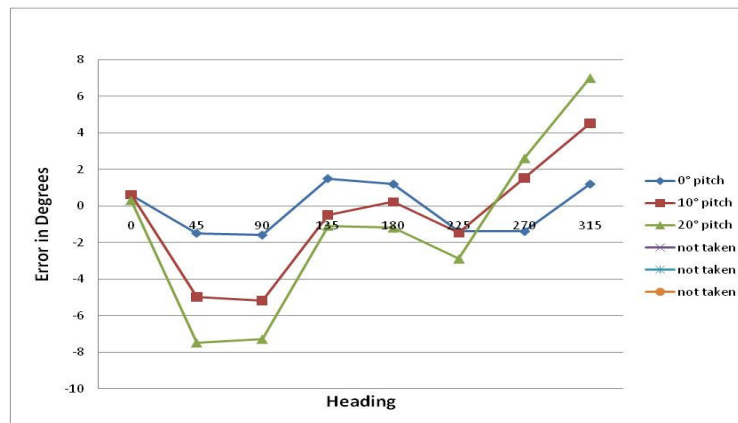


Figure 10: Ocean Server OS5000 Heading Error at Various Pitch Angles

As previously noted, the OS5000's soft iron calibration technique requires the user to indicate when the compass is facing North, East, South, and West during calibration. Consequently, we should have seen zero error at 0° pitch when the headings were 0°, 90°, 180°, and 270°. It is not clear why this was not the case.

Honeywell HMR3500 heading error at various pitch angles is shown in Figure 11. Note the scale is different from the OS5000 plot because the error range was significantly less for the HMR3500. As depicted, the errors become quite large when the compass module is not operating on a horizontal plane.

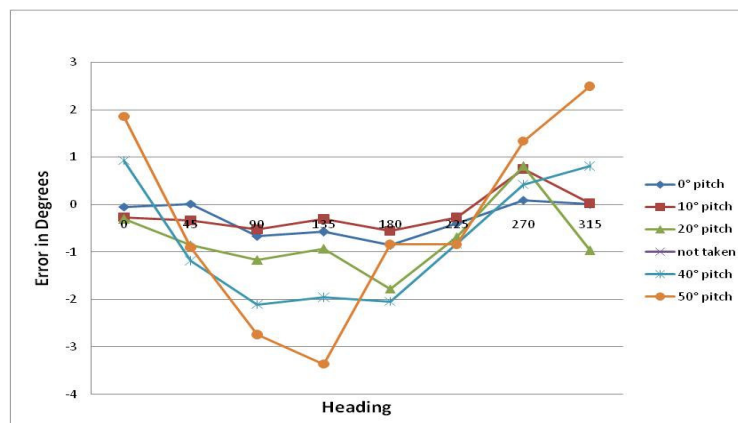


Figure 11: Honeywell HMR3500 Heading Error at Various Pitch Angles

Figure 12 depicts the data taken for the HMR3500 at various roll angles. The readings for 0° pitch and 0° roll are the same because they both represent the horizontal plane. As with the previous measurements, the further the module is from the horizontal plane, the greater the error.

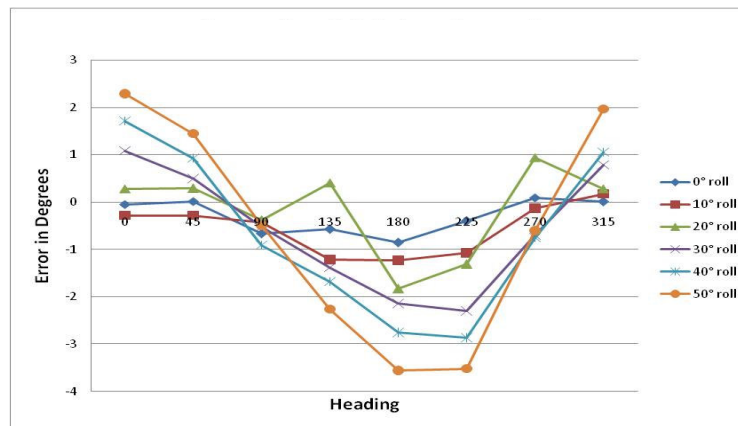


Figure 12: Honeywell HMR3500 Heading Error at Various Roll Angles

PNI TCM3 heading error at various pitch angles is depicted in Figure 13. The scale for the graph was kept the same as for the HMR3500. Total heading error is around $\pm 1^\circ$, even with the pitch at 50°.

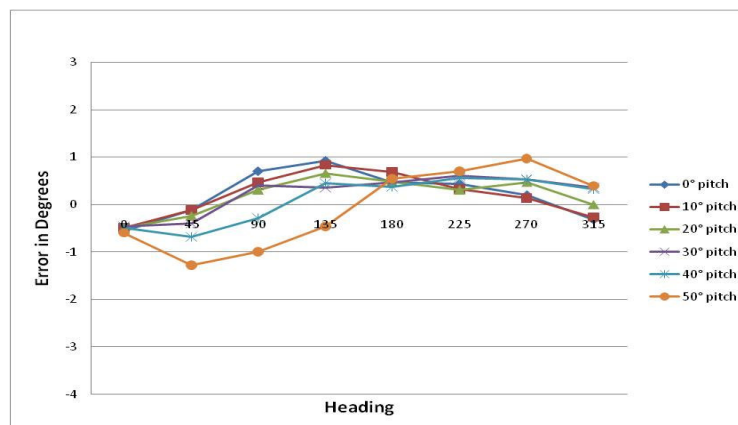


Figure 13: PNI TCM3 Heading Error at Various Pitch Angles

Figure 14 depicts data taken for PNI's TCM3 at various roll angles. Again, the total heading error is kept to around $\pm 1^\circ$ at 50° of roll.

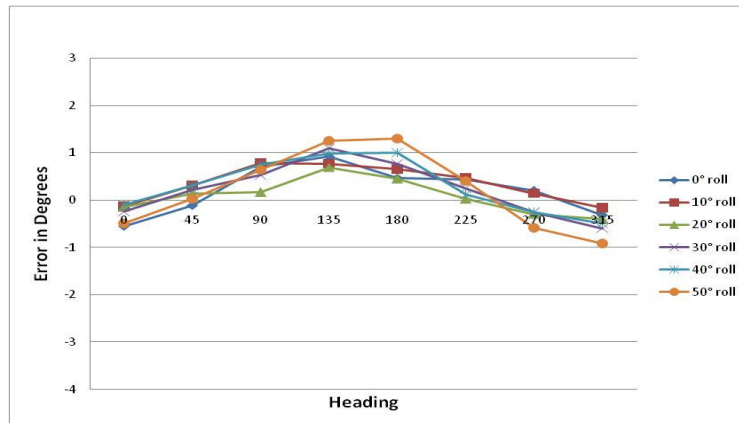


Figure 14: PNI TCM3 Heading Error at Various Roll Angles

DISCUSSION

The test results demonstrate PNI's calibration algorithms provide considerably better heading accuracy than the competition, and this is especially pronounced as the tilt angle of the compass increases. The TCM3 showed around $\pm 1^\circ$ of variation at 50° of pitch and roll, while the HMR3500 demonstrated around $\pm 3^\circ$ of error at 50° of pitch and roll, and the OS5000 provided $\pm 7^\circ$ of error at only 20° of pitch. One apparent reason for the difference in performance is the HMR3500 and OS5000 perform their soft iron calibration solely in a horizontal plane, while PNI recommends introducing 0° and $\pm 45^\circ$ of tilt during the calibration.

It should be noted that for certain applications it may be difficult to introduce $\pm 45^\circ$ of tilt during the calibration process. Looking at the 3 compasses that were tested, the HMR3500 does not require tilt at any time during the calibration process, so the results presented should be indicative of its performance if constrained to a level calibration process. However, the OS5000 requires the module to be rolled 90° during the hard iron calibration process, so it does not provide the benefit of a simplified calibration routine. The TCM3 does not require $\pm 45^\circ$ of tilt during the calibration process, and a calibration can be performed without any tilt, but with diminished performance. But, if the user cannot tilt the compass during calibration, PNI recommends using the TCM6 which incorporates several calibration modes including 2-D calibration ($< 5^\circ$ tilt), limited-tilt calibration ($> 5^\circ$ to $< 45^\circ$ tilt), and full range calibration ($\geq 45^\circ$ tilt).

For information on all of PNI's compassing modules, go to www.pnicorp.com.