



9DoF Calibration Application

User Manual Rev 2.10a

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1. Introduction

This document is an accompaniment to the *Shimmer 9DoF Calibration* application. Its purpose is to instruct the user, step-by-step, on how to use the application. It is recommended that the user also views the video tutorial available for viewing on YouTube¹ or on our [website](#).

The *Shimmer 9DoF Calibration* application provides an automated procedure for calculating the calibration parameters for a tri-axial accelerometer, gyroscope and magnetometer. The calibration parameters can be stored to the Shimmer memory or a file location and recalled by other applications allowing for automated calibration of the sensor data.

The accelerometer and gyroscope calibration techniques used in this application are based on that described in the Journal Publication:

Ferraris F, Grimaldi U, and Parvis M. "Procedure for effortless in-field calibration of three-axis rate gyros and accelerometers" Sens. Mater. 1995; 7: 311-30.

The magnetometer calibration technique is based on that described in the Journal Publication:

J. Merayo et al. "Scalar calibration of vector magnetometers" Meas. Sci. Technol. 2000; 11: 120-132.

The users of this application should have a basic understanding of how the sensor technologies work and is recommended that they familiarise themselves with the theory behind kinematic sensor calibration, refer to the appendices for background information.

2. Pre-Requisites

- A *Shimmer2/2r/3* device programmed with the appropriate firmware as shown in the table below.

Hardware	Minimum Firmware Version
<i>Shimmer2/2r</i>	<i>BtStream</i> v1.2.0 or later
<i>Shimmer3</i>	<i>LogAndStream</i> v0.6.0 or later (recommended) <i>BtStream</i> v0.7.0 or later (supported)

Note: Use the firmware image that corresponds to the type of Shimmer you are using (*Shimmer2* or *Shimmer2r* or *Shimmer3*).

- The Shimmer needs to be paired with the PC (over Bluetooth using the Windows stack). For more information on pairing a Shimmer device with a Windows PC, see the *Shimmer User Manual* or corresponding tutorial video on YouTube².

¹ <https://www.youtube.com/watch?v=aI2WDecTtfs>

² <https://www.youtube.com/watch?v=C2UdTdfiQ1g>

If using the *Shimmer3* platform, you should use a calibration stand to ensure accurate calibration. Due to the rounded design of the *Shimmer3* enclosure, calibration should not be carried out without the calibration stand, as this will significantly affect the accuracy.



Figure 2-1 Shimmer3 Calibration Stand

To use the *Shimmer3 Calibration Stand*, simply remove the strap clips from the *Shimmer3* and insert the device into the stand using the clip slots, as shown in Figure 2-1. Ensure that the plastic clip inserts on the stand are securely inserted into the *Shimmer3* clip slots and that that user button is facing upwards, as illustrated.

- A CLR (Common Language Runtime) – 2.0 compatible version of the .NET framework installed on the target PC. It is recommended to install .NET framework v3.5 but other CLR – 2.0 compatible versions of the .NET framework should also work.

3. Installation

1. Run *setup.exe* and follow the instructions.

4. Shimmer Data Formats

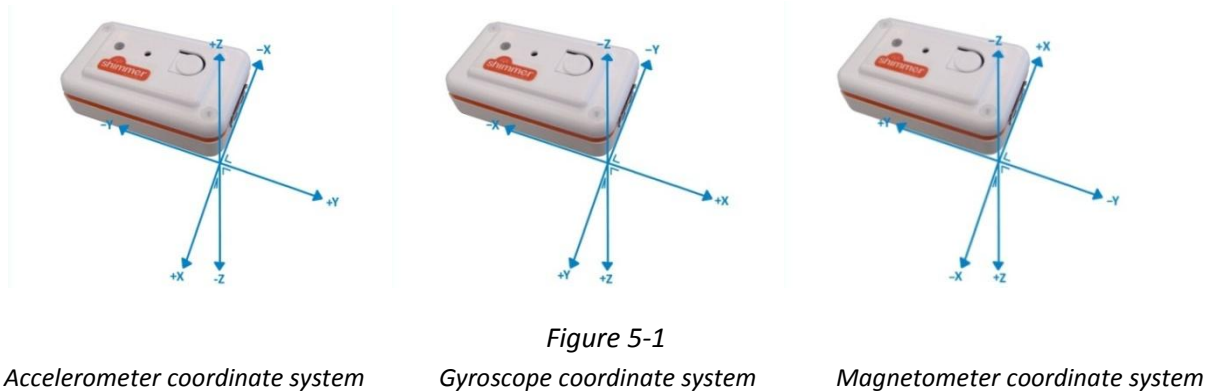
When acquiring data from a Shimmer the data is output from the Shimmer in raw ADC values. In order to convert the raw ADC values to standard units (e.g. m/s^2 , *degrees/s* etc) and thus obtain calibrated data, calibration parameters must be applied to the raw ADC values.

The *Shimmer 9DoF Calibration Application* allows for the calculation of the calibration parameters for a tri-axial accelerometer, gyroscope and magnetometer. Once calculated, the calibration parameters can be stored to the Shimmer memory and recalled by other applications allowing for automated calibration of the sensor data. Most of the Shimmer Instrument drivers (LabVIEW, and MATLAB) and Shimmer APIs (Android and C#) and applications such as *ShimmerCapture* and *Multi Shimmer Sync for Windows* provide this auto-calibration feature and thus provide data in both raw ADC format and calibrated format.

Note, if calibration parameters have not been saved to the Shimmer memory then the default offset, sensitivity and alignment values from the sensor data sheet will be used by the instrument drivers to calibrate the sensor data. To improve the accuracy of your measurements when using the inertial sensors (accelerometer, gyroscope or magnetometer) it is recommended that you use the *Shimmer 9DoF Calibration Application* to calculate and store the calibration parameters to Shimmer memory.

5. Shimmer Coordinate System

The mainboard of the Shimmer and *9DoF IMU daughterboard* (for *Shimmer2/2r*) should be contained within the Shimmer casing. The mechanical design of the *9DoF IMU daughterboard* is such that the direction of the raw X, Y and Z axis of the accelerometer, gyroscope and magnetometer are not the same. Figure 5-1 illustrates the hardware co-ordinate system for each of the three sensors on the *Shimmer2/2r* with a *9DoF IMU daughterboard*. The accelerometer has a right handed coordinate system, whilst the gyroscope and magnetometer both have left handed coordinate systems.



The equivalent co-ordinate system for the *Shimmer3* is illustrated in Figure 5-2 or Figure 5-3 depending on which revision of the *Shimmer3* you're using.

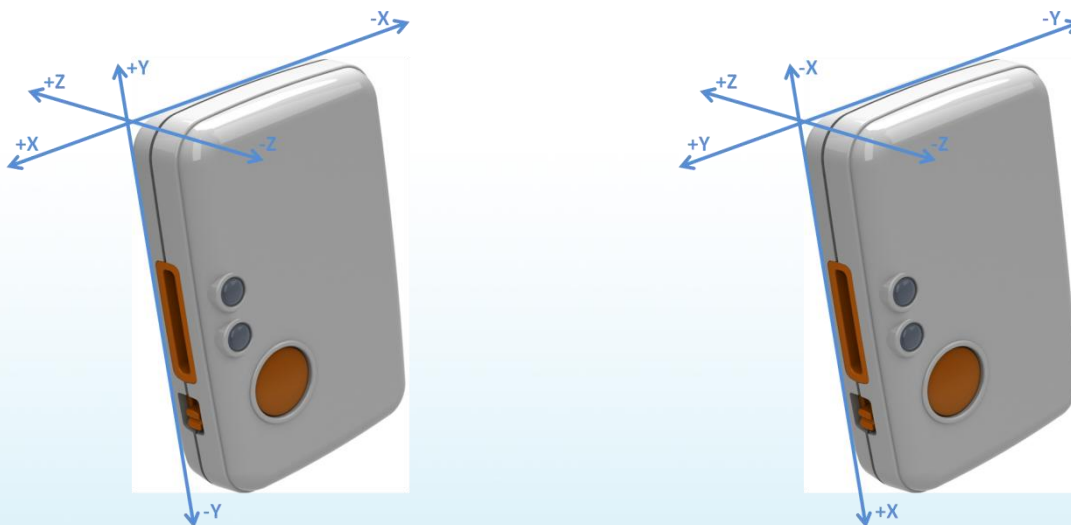


Figure 5-2 Co-ordinate systems for *Shimmer3*: LSM303DLHC chip wide range accelerometer and magnetometer (left); MPU9150 chip gyroscope and KXR5-2042 chip low noise accelerometer (right)

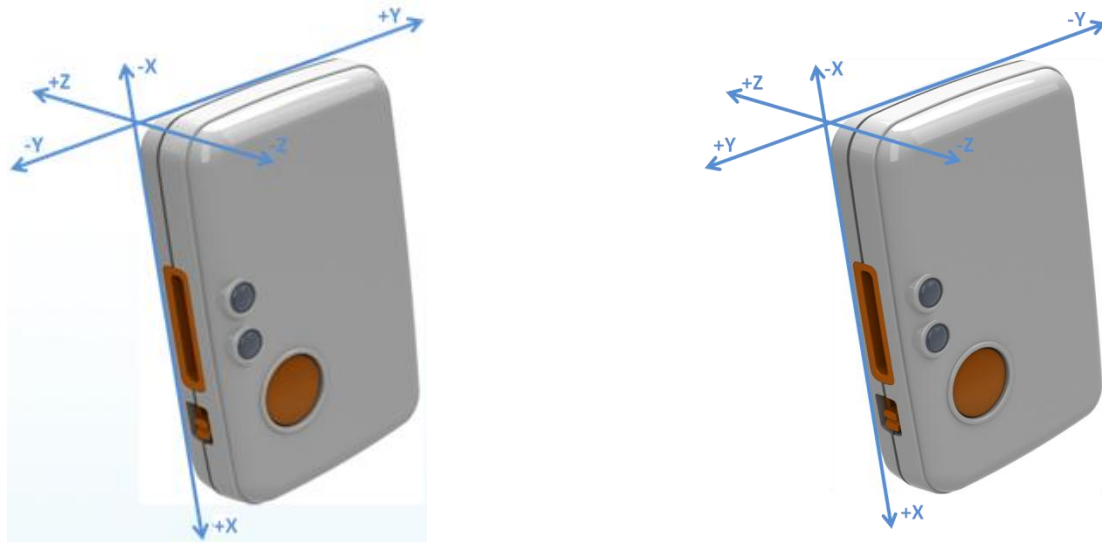


Figure 5-3 Co-ordinate systems for Shimmer3: LSM303AHTR chip wide range accelerometer and magnetometer (left); MPU9250 chip gyroscope and KXTC9-2050 chip low noise accelerometer (right)

You can identify which IMU chipset you're Shimmer3 has using the tables provided below.

Hardware	Old IMUs	New IMUs
Low Noise Accelerometer	KXRB5-2042	KXTC9-2050
Wide Range Accelerometer	LSM303DLHC	LSM303AHTR
Gyroscope	MPU9150	MPU9250
Magnetometer	LSM303DLHC	LSM303AHTR

Table 1 IMU chips on Shimmer3

Hardware	Boards with old IMUs	Boards with new IMUs
Shimmer3 ExG Unified	<= SR47-2-0	>= SR47-3-0
Shimmer3 GSR+ Unified	<= SR48-2-0	>= SR48-3-0
Shimmer3 Bridge Amplifier Unified	<=SR49-1-0	>= SR49-2-0
Shimmer3 IMU	<= SR31-5-0	>= SR31-6-0
Shimmer3 Proto3 Deluxe/Mini/anything else etc.	N/A	== SRx-x-171 (where x is any number)
Shimmer3 Proto3 Deluxe	<= SR38-2-0	>= SR38-3-0
Shimmer3 Proto3 Mini	<= SR36-2-0	>= SR36-3-0

Table 2 Board revisions with old and new IMUs on Shimmer3



Figure 5-4 Shimmer3 board revision number can be found on the sticker on the back of the unit

In order to compensate for the differing coordinate systems, the calibration procedure presented here includes the calculation of an alignment matrix which can be used to align differing coordinate systems to a common system. The alignment matrix also allows the user to choose which ever direction they wish as the X, Y and Z orthogonal axes. For more information on the alignment matrix please refer to Appendix I of this document.

For the purposes of this User Manual and the associated tutorial video we use the coordinate system convention as illustrated Figure 5-5 below. For simplicity, it is recommended that users who are not familiar with the concept of alignment matrices should also use this system.

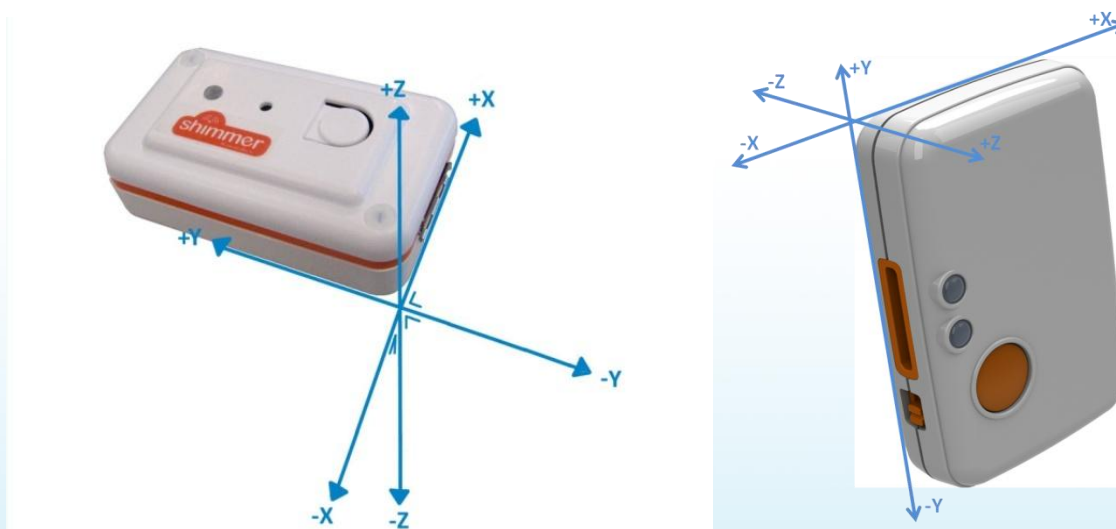


Figure 5-5 X-Y-Z coordinate system used in this manual: Shimmer2r (left); Shimmer3 (right)

Note: It may be a good idea to label your Shimmer casing with the axes you have defined so that you can easily recall which axis is which.

In the case that you decide to use your own coordinate axis convention then the process of calibrating the accelerometer and gyroscope will automatically calculate the alignment matrix for each sensor. The alignment matrix for the magnetometer can be determined based on the accelerometer alignment matrix, refer to section 7.6 for an example.

6. Familiarisation with the User Interface

Run *Shimmer 9DoF Calibration Application.exe*. Figure 6-1 depicts the GUI application on start-up.

6.1.1. Upper Panel

The upper panel contains;

- Four multi-colour control buttons which are used to *connect/disconnect* the Shimmer Bluetooth connection and to *start/stop streaming* data from the Shimmer.
- *Shimmer BT ID*: Used to select a valid Shimmer to be calibrated. This is a drop down menu which is automatically populated with the list of Shimmers available on the host PC. To locate your Shimmer BT ID, look at the sticker on the back of the Shimmer. If your device is not listed press the REFRESH button and search for the BT ID again.
- *Shimmer Com Port*: Used as an alternative method to select a valid Shimmer to calibrate. This is a drop down menu which is automatically populated with the list of COM ports that the PC has assigned to devices. To locate the COM port that your Shimmer has been assigned to, see the Appendices section.
- Shimmer Status indicators:
 - An *Application State* text box which display the current state of the Shimmer (e.g. Shimmer Disconnected, Shimmer Connected, Shimmer Streaming etc.).
 - A colour box indicating the state of the Shimmer.
 - Grey – Disconnected
 - Green – Connected
 - Flashing Green – Streaming
 - A *Shimmer Version* text box which displays the hardware revision of the Shimmer platform is connected to the application. The text box displays *Unknown* when the Shimmer is in a *disconnected* state.
- Five black buttons which are used to save/load calibrations parameters to/from a chosen file location or Shimmer memory. When using these buttons **the calibration parameters for all three 9DoF sensors** are saved/loaded, this differs from the use of the dark blue save/load buttons in the lower panel which are used to save/load the calibration parameters for an individual sensor.



Figure 6-1 Shimmer 9DoF Calibration GUI on start-up

6.1.2. Lower Panel

The lower panel contains a number of different selectable tabs. Each sensor (accelerometer, gyroscope and magnetometer) has a separate tab. The tab for a specific sensor contains:

- A display containing the calibration parameters in the application for the specific sensor.
- A display containing the calibration parameters stored in the Shimmer memory for the specific sensor. This display is inactive if there is no Shimmer connected.
- Four dark blue buttons which can be used to save/load **only the calibration parameters for that specific sensor** to/from a chosen file location or Shimmer memory.
- A varying number of grey buttons which are the controls for the calibration of that specific sensor.

The *Data Analysis* tab contains features to view both calibrated and raw data values streaming from the Shimmer.

7. Using the Application

7.1. Connect to and Stream Data from the Shimmer

- Using the drop down menu labelled *Shimmer BT ID* or the *Shimmer Com Port* drop down menu, select the Shimmer you wish to calibrate.
- Connect to the Shimmer by clicking on the blue *Connect* button. During the process of establishing the connection, the *Application State* text box will display *Shimmer Connecting*.
- On successful connection with the Shimmer, the *Application State* text box should change to *Shimmer Connected* and the colour box will turn green to indicate that the Shimmer is connected. A number of other buttons and features (e.g. Load ACCEL from Shimmer etc.) will also be enabled.

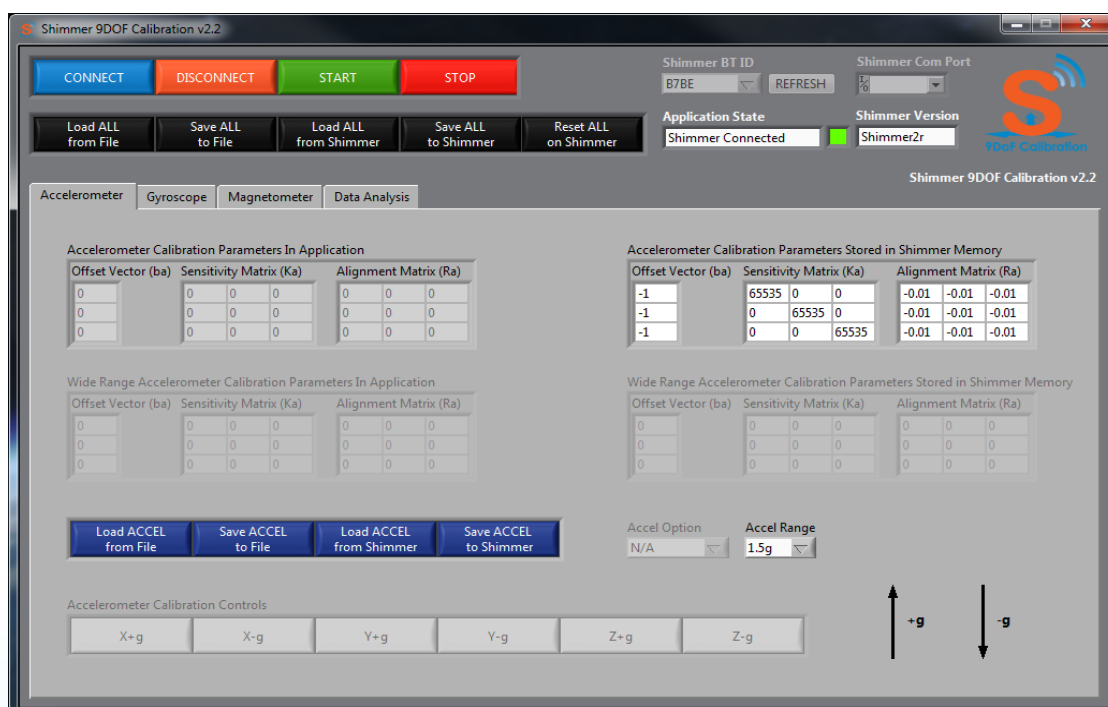


Figure 7-1 Shimmer accelerometer calibration GUI – Connected

- On a successful connection the accelerometer, gyroscope and magnetometer calibration parameters currently stored on the Shimmer are loaded into the application and will appear in the display labelled *(Sensor Name) Calibration Parameters Stored in Shimmer Memory* on each sensor tab. Figure 7-1 shows the GUI once a successful connection is made with the Shimmer with the appropriate values displayed.
- If the connection fails, *Shimmer Disconnected* will be displayed in the *Application State* text box. To attempt to connect again, click *Connect*. If connection fails again go to the troubleshoot section in the Appendices.
- Once connected press the green *Start* button to start streaming data from the Shimmer. The *Application State* may briefly display *Starting to Stream* before changing to *Shimmer Streaming* which indicates that it is streaming data. The colour box will flash green.

Note: The *Data Analysis* tab in the lower panel can be used to review data when streaming.

7.2. Accelerometer Option

If using the *Shimmer3 platform*, the user has the option to select which accelerometer to calibrate using the *Accelerometer Option* control. The available options are the Analog/Low Noise accelerometer or the Digital/Wide Range accelerometer. The default option is the Low Noise accelerometer. This option can only be changed when the Shimmer is in a *Connected* state.

Note: The *Accelerometer Option* control is not available for *Shimmer2/2r* as this platform has only one accelerometer.

7.3. Accelerometer Range

Important: Before the starting the calibration procedure, the user has the option to change the accelerometer range on the Shimmer. Use *Accelerometer Range* to select the desired range. The available range are listed in Table 3 below.

Note: The accelerometer range can only be changed when the Shimmer is in the *Connected* state.

Hardware Version	Accelerometer Range	Accelerometer Enabled
Shimmer2	1.5g, 2g, 4g, 6g	N/A
Shimmer2r	1.5g, 6g	N/A
Shimmer3	2g	Analog/Low noise
Shimmer3	2g, 4g, 8g, 16g	Digital/Wide Range

Table 3 Accelerometer Ranges

Note: Due to the use of a different accelerometer chip in the *Shimmer2r*, the $\pm 2g$ and $\pm 4g$ ranges are not available on that Shimmer. If the *Accelerometer Range* input is set to $\pm 2g$ or $\pm 4g$ when using the Shimmer 2r then the setting will default to $\pm 1.5g$ even though the *Accelerometer Range* control may show otherwise.

Note: Calibration parameters, when stored on the Shimmer, are only valid for one specific range. It is advised that the range chosen to calibrate the accelerometer is the range that will be used for subsequent applications involving the same Shimmer. If you wish to use the Shimmer configured with a different accelerometer range in subsequent applications then it is necessary to repeat the calibration procedure using the desired range.

7.4. Calibrating the Accelerometer

Important: A change from previous versions of the application is that the direction of the gravity vector is now taken to point upwards.

- Connect to the Shimmer of choice and start data streaming.
- Find a flat horizontal surface.

Note: For greatest accuracy you should use a spirit level to ensure the surface is horizontal.

Decide on a coordinate system convention for your Shimmer (see the section 0 on the Shimmer Coordinate System for more info)

- **Step 1 of 6** – Place the Shimmer on the surface such that the positive **X-axis is pointing in the direction of the gravity vector (vertically up)**. With the Shimmer held static press the **X+g** button (which should turn green) on the GUI. Hold the Shimmer in this position; perfectly still, until the **X+g** button turns off automatically. See Figure 7-2.

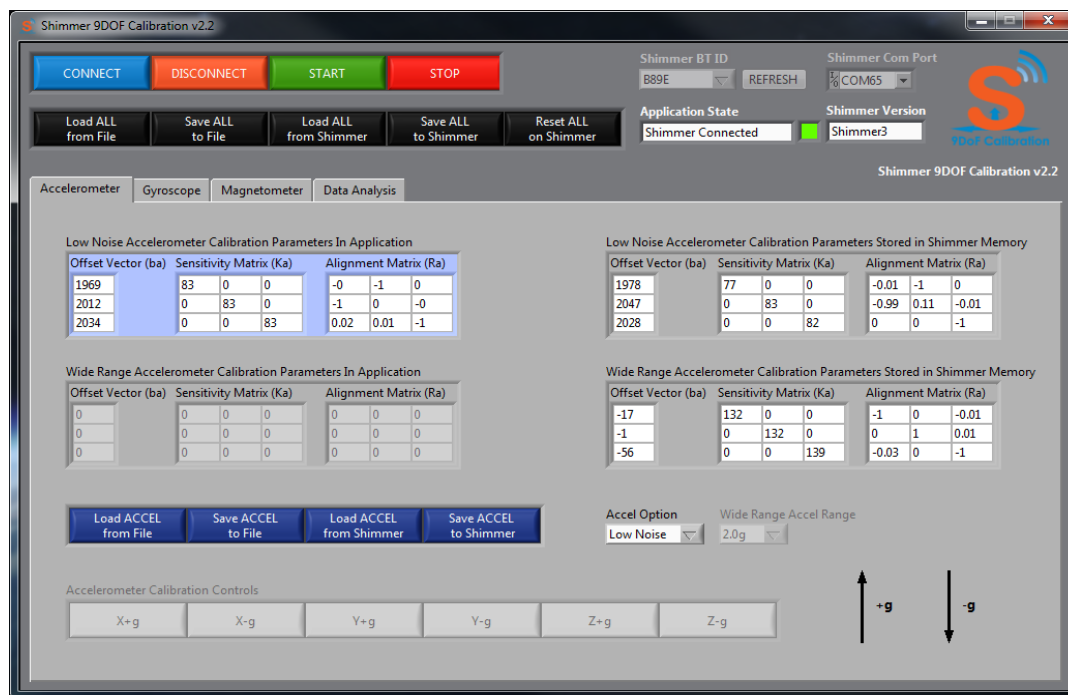


Figure 7-2 GUI during Step 1 of 6 in the accelerometer calibration

- **Step 2 of 6** – Place the Shimmer on the surface such that the positive **X-axis is pointing away from the direction of the gravity vector (vertically down)**. With the Shimmer held static press the **X-g** button (which should turn green) on the GUI. Hold the Shimmer in this position, perfectly still, until the **X-g** button turns off automatically.
- **Step 3 of 6** – Place the Shimmer on the surface such that the positive **Y-axis is pointing in the direction of the gravity vector (vertically up)**. With the Shimmer held static press the **Y+g** button (which should turn green) on the GUI. Hold the Shimmer in this position, perfectly still, until the **Y+g** button turns off automatically.
- **Step 4 of 6** – Place the Shimmer on the surface such that the positive **Y-axis is pointing away from the direction of the gravity vector (vertically down)**. With the Shimmer held static press the **Y-g** button (which should turn green) on the GUI. Hold the Shimmer in this position, perfectly still, until the **Y-g** button turns off automatically.
- **Step 5 of 6** – Place the Shimmer on the surface such that the positive **Z-axis is pointing in the direction of the gravity vector (vertically up)**. With the Shimmer held static press the **Z+g** button (which should turn green) on the GUI. Hold the Shimmer in this position, perfectly still, until the **Z+g** button turns off automatically.

- **Step 6 of 6** – Place the Shimmer on the surface such that the positive **Z-axis is pointing away from the direction of the gravity vector (vertically down)**. With the Shimmer held static press the Z-g button (which should turn green) on the GUI. Hold the Shimmer in this position, perfectly still, until the Z-g button turns off automatically.

Note: It is OK to perform steps 1 to 6 in any order and it is also OK to repeat one or more of the steps at any stage during the calibration.

- Once all six recordings have been made, the accelerometer offset vector (b_a), the sensitivity matrix (K_a) and axis alignment matrix (R_a) parameters in the *Accelerometer Calibration Parameters in the Application* display will contain with the relevant values for the accelerometer that has just been calibrated as in Figure 7-3.

Note: If these parameters do not display valid data or contain “NAN”, an error may have been made in the calibration process and it is advised to repeat the accelerometer calibration procedure.

Note: For more information on the significance of each of these parameters please refer to the Appendices section of this document.

Low Noise Accelerometer Calibration Parameters In Application								
Offset Vector (b_a)			Sensitivity Matrix (K_a)			Alignment Matrix (R_a)		
1969			83	0	0	-0	-1	0
2012			0	83	0	-1	0	-0
2034			0	0	83	0.02	0.01	-1

Figure 7-3 Parameters populated after accelerometer calibration

Note: When the *(Sensor) Calibration Parameters in Application* display is blue as in Figure 7-3, it means that the *(Sensor) Calibration Parameters in Application* differ from the *(Sensor) Calibration Parameters Stored in Shimmer Memory*. When the *(Sensor) Calibration Parameters in Application* is saved to the Shimmer, the display will return to its original state to indicate that calibration parameters in the application are the same as the ones on the Shimmer.

7.5. Calibrating the Gyroscope

For *Shimmer3* the user has the option to change the gyroscope. To change the gyroscope range select the desired range from *Gyroscope Range* on the *Gyroscope* tab. The gyroscope range can only be modified when the Shimmer is in the *Connected* state.

- If the Shimmer of choice is not *Connected* or *Streaming*, connect to the Shimmer and start streaming data.
- Use the same coordinate system convention for gyroscope calibration as you did for accelerometer calibration (see section 0).
- **Step 1 of 4** – Place the Shimmer on a perfectly motionless surface and press the white *Stationary* button. The button will become green. Don't move the Shimmer until the *Stationary* button turns off automatically.

- **Step 2 of 4** – Place the Shimmer on a suitable surface, the surface does not have to be perfectly horizontal. Press the *Rotate X* button to begin step 2. Once the *Rotate X* button becomes green, rotate the Shimmer **360 degrees (1 full rotation) in a clockwise direction around the x-axis** (the positive direction of the x-axis should be pointing into the imaginary clock). When you have completed the Shimmer rotation around the x-axis press the *Rotate X* button again to end step 2.
- **Step 3 of 4** – Press the *Rotate Y* button to begin step 3. Once the *Rotate Y* button becomes green, rotate the Shimmer **360 degrees (1 full rotation) in a clockwise direction around the y-axis** (the positive direction of the y-axis should be pointing into the imagined clock). When you have completed the Shimmer rotation around the y-axis press the *Rotate Y* button again to end step 3.
- **Step 4 of 4** – Press the *Rotate Z* button to begin step 4. Once the *Rotate Z* button becomes green, rotate the Shimmer **360 degrees (1 full rotation) in a clockwise direction around the z-axis** (the positive direction of the z-axis should be pointing into the imagined clock). When you have completed the Shimmer rotation around the z-axis press the *Rotate Z* button again to end step 4.

Note: It is OK to perform steps 1 to 4 in any order and it is also OK to repeat one or more of the steps at any stage during the calibration.

Also, the rotation does not need to be perfectly smooth. **The most important thing is that the Shimmer rotates 360 degrees about the axis of interest and thus finishes with the exact same orientation as it had at the start of the rotation.**

The rotation of the Shimmer about the axis of interest can actually be performed around any axis parallel to the axis of interest (i.e. don't be too concerned about aligning the centre of the Shimmer with the axis of rotation).

Linear movements of the Shimmer should not affect the calibration. With that in mind it should be OK to move the shimmer vertically or horizontally during the rotation if required.

A slight deviation/wobble from the axis of interest is acceptable as long as the Shimmer finishes at the same orientation as it started.

If you rotate beyond the starting position it is ok as long as you rotate it back.

What we recommend is to use an object with a flat surface at a fixed angle to the surface of the table (see the Figure 7-4 below) and proceed to rotate about the relevant axis. The surfaces of the table and object will allow you to know when the Shimmer is rotated a full 360 degrees, back to its starting position.



Figure 7-4 Use of flat surfaces for gyroscope calibration

- Once all four recordings have been made, the gyroscope offset vector (bg), the sensitivity matrix (Kg) and axis alignment matrix (Rg) parameters in the *Gyroscope Calibration Parameters in the Application* display will contain with the relevant values for the gyroscope that has just been calibrated as in Figure 7-5.

Note: If these parameters do not display valid data or contain “NAN”, an error may have been made in the calibration process and it is advised to repeat the gyroscope calibration procedure.

Note: For more information on the significance of each of these parameters please refer to the Appendices section of this document.

Gyroscope Calibration Parameters In Application								
Offset Vector (bg)			Sensitivity Matrix (Kg)			Alignment Matrix (Rg)		
1859			2.77	0	0	-0	-1	0.04
1847			0	2.77	0	-1	0.01	-0.03
1862			0	0	2.75	-0.03	0	-1

Figure 7-5 Parameters populated after gyroscope calibration

Note: When the *(Sensor) Calibration Parameters in Application* display is blue as in Figure 7-5, it means that the *(Sensor) Calibration Parameters in Application* differ from the *(Sensor) Calibration Parameters Stored in Shimmer Memory*. When the *(Sensor) Calibration Parameters in Application* is saved to the Shimmer, the display will return to its original state to indicate that calibration parameters in the application are the same as the ones on the Shimmer.

7.6. Calibrating the Magnetometer

Before the calibration procedure, the user has the option to change the magnetometer’s range for *Shimmer2r* and *Shimmer3*. Use *Magnetometer Range* to select the desired range. The *Magnetometer Range* is located on the *Magnetometer* tab. Note that the range can only be changed when the Shimmer is in the *Connected* state.

- With the Shimmer already streaming data, find a suitable location within range of the Bluetooth radio to perform the calibration. The location should have a relatively uniform

magnetic field with low levels of interference (e.g. at least a meter above the ground and away from power cables and large metal objects).

- Press the *Rotate XYZ* button to begin the procedure, the button should turn green. Using your hand rotate the Shimmer about itself through a series of different orientations. There are an infinite amount of different orientations so it is not possible to position the Shimmer in each orientation however try to cover a wide spectrum of different orientations. For optimal results you should try to rotate your Shimmer to trace as much of a full sphere as is feasible. Figure 7-6 illustrates what the plots look like when a full sphere is traced. Once satisfied, press the *Rotate XYZ* button to end the procedure.

Note: The user does not have to be concerned about rotating about a single axis at a time; the Shimmer can be rotated randomly in any direction at any time. Also it is OK if the Shimmer is moved up or down or left or right. **The most important thing is to stay within a general area that has a uniform magnetic field.**

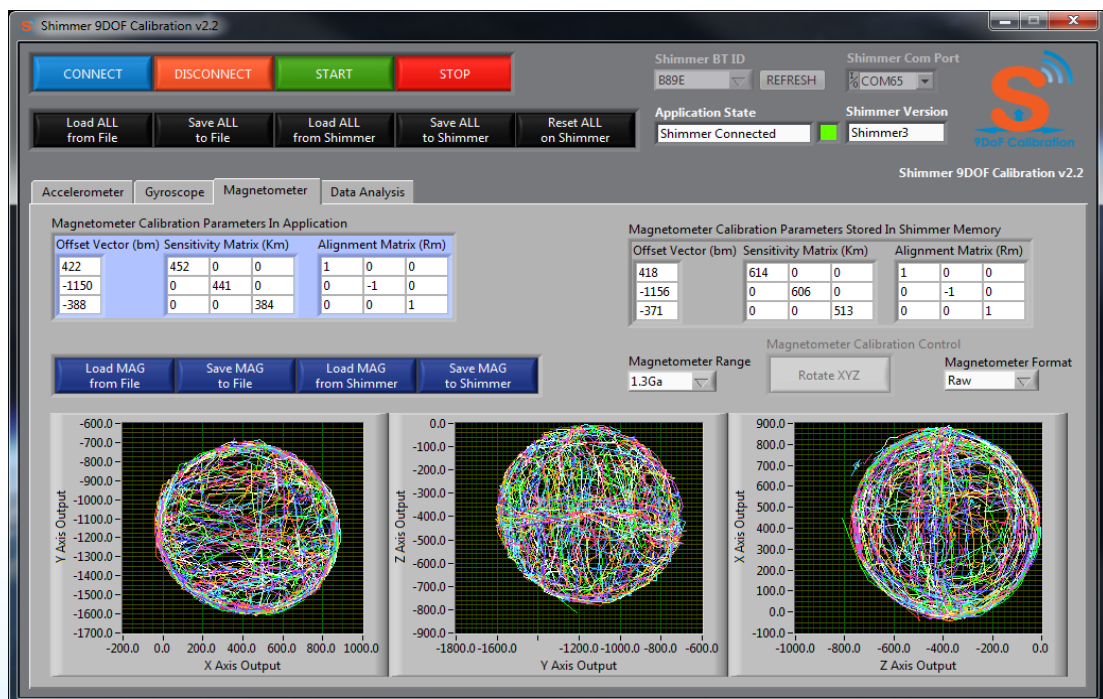


Figure 7-6 Calibrating the magnetometer

- The magnetometer offset vector (bm), the sensitivity matrix (Km) and axis alignment matrix (Rm) parameters in *Magnetometer Calibration Parameters In Application* display contains the relevant values for the magnetometer that has just been calibrated, see Figure 7-7.
- To verify the accuracy of the magnetometer calibration, change the *Magnetometer Format* to *Calibrated*. The application uses the *Magnetometer Calibration Parameters In Application* to calibrate the data displayed when the *Magnetometer Format* is set to *Raw*. The three graphs should now display three near perfect unit circles centred at (0,0,0), as shown in Figure 7-8. If the circles are off centre or somewhat oddly shaped you may want to repeat the magnetometer calibration procedure. Alternatively, if unsatisfied with the results of the automated magnetometer calibration, the user can derive the magnetometer calibration parameters themselves. See the appendices section for more details.
- The Data Analysis tab also contains a method to check the accuracy of the magnetometer calibration. The *Magnetometer Calibration Accuracy* indicator displays the accuracy of the magnetometer calibration procedure. The value equates to the sum of the square of the errors of the calibrated signal during the period of rotation and so a value closer to 0 indicates a higher level of accuracy.

Magnetometer Calibration Parameters In Application								
Offset Vector (bm)			Sensitivity Matrix (Km)			Alignment Matrix (Rm)		
-58			457	0	0	1	0	0
-210			0	437	0	0	1	0
-10			0	0	440	0	0	-1

Figure 7-7 Parameters populated after magnetometer calibration

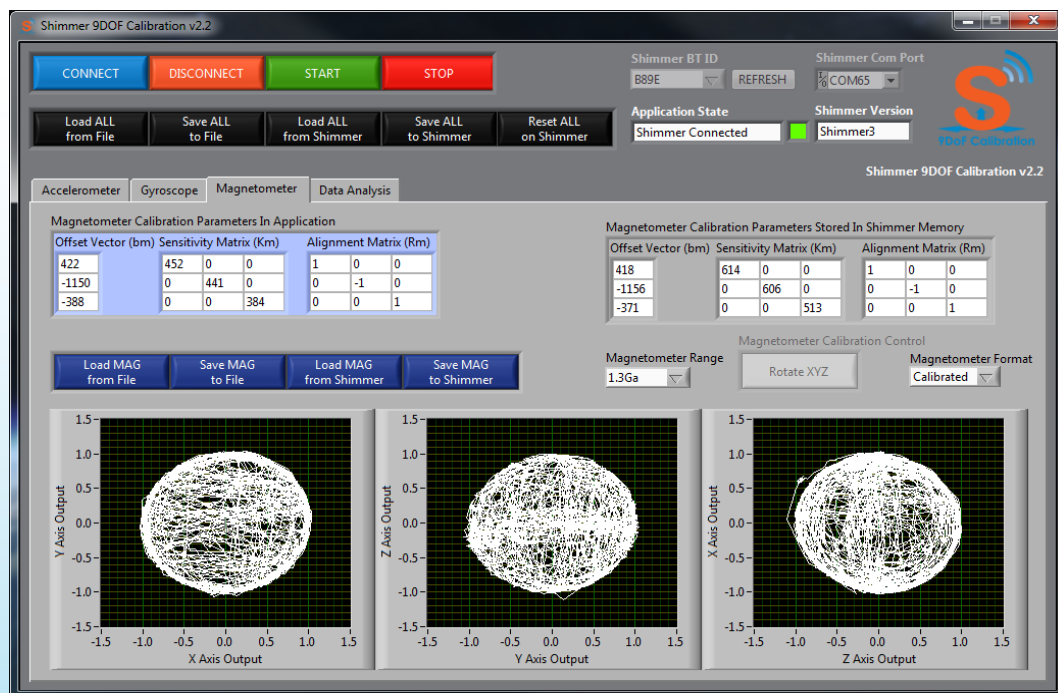


Figure 7-8 Verifying the accuracy of the magnetometer calibration

Note: When the *(Sensor) Calibration Parameters in Application* display is blue as in Figure 7-7, it means that the *(Sensor) Calibration Parameters in Application* differs from the *(Sensor) Calibration Parameters Stored in Shimmer Memory*. When the *(Sensor) Calibration Parameters in Application* is saved to the Shimmer, the display will return to its original state to indicate that calibration parameters in the application are the same as the ones on the Shimmer.

Note: It is important to observe that the alignment matrix for the magnetometer is not automatically calculated in the calibration procedure. It can however be determined based on the accelerometer alignment matrix.

For Shimmer3, the Magnetometer alignment matrix should be identical to that of the wide range accelerometer.

For Shimmer2r, the magnetometer and accelerometer are rotated relative to each other on the board. See Figure 7-9 below for an example.

Alignment Matrix (Ra)			Alignment Matrix (Rm)		
-1	0	0	1	0	0
0	-1	0	0	1	0
0	0	1	0	0	-1

Figure 7-9 Example of suitably matched alignment matrices for the accelerometer and magnetometer for Shimmer2r

Note: In the event of a data overflow on a magnetometer axis - as would be the case if the local magnetic field strength exceeds the configured magnetometer range - the corresponding axis channel will read as a value of -4096 in 2's complement form. To overcome this, simply increase the magnetometer range.

7.7. Saving and Loading Calibration Parameters

7.7.1. Save the Calibration Parameters to the Shimmer Memory

- To save calibration parameters to the Shimmer memory the Shimmer must be in the *Connected* state.
- There is an option to save the calibration parameters for all three sensors or save the calibrations parameters for just one sensor.
 - To save the calibration parameters for a specific sensor select the tab of the sensor of interest in the lower panel. Press the dark blue *Save SENSOR NAME to Shimmer* button.
 - The *Application Status* display will display *Saving Parameters* while the parameters are saving.
 - To save the calibration parameters for all three sensors press the black *Save ALL to Shimmer* button in the upper panel.
- **Important:** If you reprogram the Shimmer with any firmware then the stored calibration parameters will be erased from the Shimmer memory. For this reason it is useful to save a

copy of the calibration parameters to a file. The calibration parameters can then be loaded back into the application and stored to the Shimmer memory.

7.7.2. Save the Calibration Parameters to a File

- To save calibrations parameters to a file the Shimmer must be in the *Disconnected* or *Connected* state.
- The calibration parameters are stored in a *.ini* file format which can be viewed in most standard text file editors.
- There is an option to save the calibration parameters for all three sensors or save the calibrations parameters for just one sensor.
 - To save the calibration parameters for a specific sensor select the tab of the sensor of interest in the lower panel. Press the dark blue *Save SENSOR NAME to File* button. Select a suitable filename and file location and name a press *Save*.

Note: When saving accelerometer calibration parameters to file a separate set of parameters can be stored for each setting of the *Accelerometer Range*, *Gyroscope Range* (if using *Shimmer3*) and *Magnetometer Range* (*Shimmer2r* and *Shimmer3*) control.

- To save the calibration parameters for all three sensors press the black *Save ALL to File* button in the upper panel. Select a suitable file location and name a press *Save*.

Note: If your Shimmer has an SD card it is a good idea to save a copy of the file to the SD card so it is easily retrieved should the Shimmer memory be overwritten.

7.7.3. Load the Calibration Parameters from the Shimmer Memory

- To load calibrations parameters from the Shimmer memory the Shimmer must be in the *Connected* state.
- There is an option to load the calibration parameters for all three sensors or load the calibrations parameters for just one sensor.
 - To load the calibration parameters for a specific sensor select the tab of the sensor of interest in the lower panel. Press the dark blue *Load SENSOR NAME from Shimmer* button.
 - To load the calibration parameters for all three sensors press the black *Load ALL from Shimmer* button in the upper panel.

7.7.4. Load the Calibration Parameters from a File

- To load calibrations parameters from an existing file the Shimmer must be in the *Disconnected* or *Connected* state.
- There is an option to load the calibration parameters for all three sensors or load the calibrations parameters for just one sensor.
 - To load the calibration parameters for a specific sensor select the tab of the sensor of interest in the lower panel. Press the dark blue *Load SENSOR NAME from File* button. Select a *.ini* file from a suitable location and press load.

Note: When loading calibration parameters from a file a separate set of parameters can be loaded for each setting of the *Accelerometer Range*, *Gyroscope Range* and *Magnetometer Range* control.

- To load the calibration parameters for all three sensors press the black *Load ALL from Shimmer* button in the upper panel. Select a *ini* file from a suitable location and press *Load*.
- **Note:** The file *Documents\Shimmer\Shimmer 9DoF Calibration v2.x\Application Settings\ShimmerX_default.ini* contains a set of default calibration parameters that can be loaded and stored to the Shimmer. These parameters can be used for basic testing however for optimal accuracy the user should calculate the parameters specific to the Shimmer being used and store them in the Shimmer memory.

7.7.5. Reset the Calibration Parameters on Shimmer Memory

- Pressing the *Reset ALL on Shimmer* button restores the default calibration parameters (as obtained from the sensors data sheet) for all three 9DoF sensors.
- To reset the calibration parameters on Shimmer memory, the Shimmer must be in the *Connected* state.

7.8. Calibration Accuracy

It should be noted that the accuracy of calibration required varies depending on the application of the sensor. Due to the fact the Shimmer is a measurement system and, like all measurement systems it contains a certain amount of noise, the user should not expect to achieve perfect calibration. The user should however try to achieve a level of calibration that meets the needs of their application.

The Data Analysis tab on the lower panel can be used to evaluate the implementation of the calibration parameters (see Figure 7-10).



Figure 7-10 Evaluating the accelerometer calibration parameters using the Data Analysis tab

The user can use the *Select Sensor* control to select which sensor data, accelerometer or gyroscope they wish to view. To view the magnetometer sensor data, select the *Magnetometer* tab. The calibrated data is determined using the parameters currently stored in the Shimmer memory so any new calibration parameters calculated using this application will need to be stored to the Shimmer memory in advance of evaluating them here.

Note: An asterisk after the **Units** (e.g. m/s^2*) indicates that no calibration parameters were stored on the Shimmer and the default offset and sensitivity values from the sensor data sheet have been used to calibrate the sensor data.

7.8.1. Evaluating the Calibration Parameters

The unit of the calibrated accelerometer is meters per square second (m/s^2). A perfectly calibrated accelerometer that is stationary with one axis pointed vertically upwards will measure $9.81m/s^2$ on that axis and $0m/s^2$ on the other two. Due to noise on the accelerometer signal you may observe that the signal actually fluctuates above and below $9.81m/s^2$. The influence of this noise can be reduced using filtering techniques in post processing.

The unit of the calibrated gyroscope is degrees per second (deg/s). A gyroscope with its offset calibrated perfectly will measure $0 deg/s$ on all axes when stationary. It should be noted that the gyroscope offset can vary with temperature (refer to the sensor datasheet for more details). A reliable turntable can be used to verify the accuracy of the sensitivity calibration. The alignment calibration can be verified through a series of rotations of the Shimmer by hand.

The unit of the calibrated magnetometer is local. One local unit is equivalent to the magnetic field strength at the location where the calibration procedure is performed. Since the magnetic field strength varies from location to location the local unit is not standardised. This method of calibration

is sufficient for applications which need to determine the direction of the magnetic field vector or detect relative changes in magnetic field strength.

A perfectly calibrated magnetometer with one axis pointed towards the magnetic field vector (at the location in which it was calibrated) will measure 1 on that axis and 0 on the other two. Due to noise on the magnetometer signal you may observe that the signal actually fluctuates above and below 1. The influence of the noise can be reduced using filtering techniques in post processing.

When graphing the calibrated output of the magnetometer, the graphs should each display a unit circle centred at (0,0) when the magnetometer is rotated about all of its axes. See Figure 7-11 for an illustration of a well calibrated magnetometer.

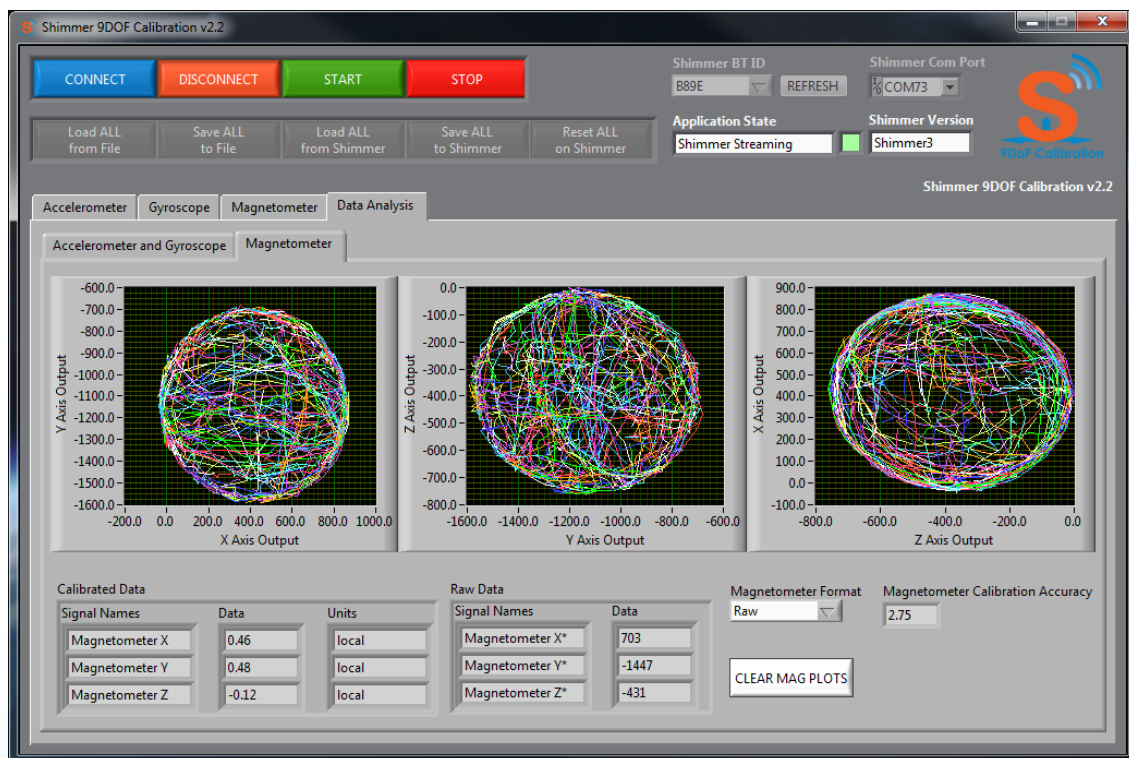


Figure 7-11 Evaluating the magnetometer calibration parameters using the Data Analysis tab

Note: The magnetic field vector is not parallel to the surface of the earth; it is at an angle to the surface known as magnetic inclination or magnetic dip. The magnitude of the angle varies at different locations around the planet. It can be measured by observing the angle of the Shimmer when the measured magnetic field value is at its maximum.

8. Using the Calibration Parameters feature in other Applications

It should be noted that the method used for the calibration of the 9DoF sensor data is not performed on the Shimmer itself. Instead the Shimmer calibration parameters are loaded from the Shimmer memory into the host side application and the calibration of the data is performed there. This signal calibration method is integrated into the *ShimmerSensing LabVIEW Instrument Driver* by default and can be easily integrated into other application development environments and third party applications.

Appendices

Appendix I – Default Factory Calibration Parameters

Shimmer 2/2r

Accelerometer						
Offset	Sensitivity (+/- 1.5g)			Alignment		
2048	101	0	0	-1	0	0
2048	0	101	0	0	-1	0
2048	0	0	101	0	0	1
	Sensitivity (+/- 2g)					
	76	0	0			
	0	76	0			
	0	0	76			
	Sensitivity (+/- 4g)					
	38	0	0			
	0	38	0			
	0	0	38			
	Sensitivity (+/- 6g)					
	25	0	0			
	0	25	0			
	0	0	25			

Table 4 Shimmer2/2r Accelerometer Calibration Parameters

Gyroscope						
Offset	Sensitivity (+/- 500 dps)			Alignment		
1843	2.73	0	0	0	-1	0
1843	0	2.73	0	-1	0	0
1843	0	0	2.73	0	0	-1

Table 5 Shimmer2/2r Gyroscope Calibration Parameters

Old Magnetometer HMC5843						
Offset	Sensitivity (+/- 0.7 Ga)			Alignment		
0	1620	0	0	1	0	0
0	0	1620	0	0	1	0
0	0	0	1620	0	0	-1
Sensitivity (+/- 1.0 Ga)						
	1300	0	0			
	0	1300	0			
	0	0	1300			
Sensitivity (+/- 1.5 Ga)						
	970	0	0			
	0	970	0			
	0	0	970			
Sensitivity (+/- 2.0 Ga)						
	780	0	0			
	0	780	0			
	0	0	780			
Sensitivity (+/- 3.2 Ga)						
	530	0	0			
	0	530	0			
	0	0	530			
Sensitivity (+/- 3.8 Ga)						
	460	0	0			
	0	460	0			
	0	0	460			
Sensitivity (+/- 4.5 Ga)						
	390	0	0			
	0	390	0			
	0	0	390			

Table 6 Shimmer2/2r Magnetometer (HMC5843) Calibration Parameters

New Magnetometer HMC5883L					
Offset	Sensitivity (+/- 0.88 Ga)			Alignment	
0	1370	0	0	1	0
0	0	1370	0	0	1
0	0	0	1370	0	0
Sensitivity (+/- 1.3 Ga)					
	1090	0	0		
	0	1090	0		
	0	0	1090		
Sensitivity (+/- 1.9 Ga)					
	820	0	0		
	0	820	0		
	0	0	820		
Sensitivity (+/- 2.5 Ga)					
	660	0	0		
	0	660	0		
	0	0	660		
Sensitivity (+/- 4.0 Ga)					
	440	0	0		
	0	440	0		
	0	0	440		
Sensitivity (+/- 4.7 Ga)					
	390	0	0		
	0	390	0		
	0	0	390		
Sensitivity (+/- 5.6 Ga)					
	330	0	0		
	0	330	0		
	0	0	330		
Sensitivity (+/- 8.1 Ga)					
	230	0	0		
	0	230	0		
	0	0	230		

Table 7 Shimmer2/2r Magnetometer (HMC5883L) Calibration Parameters

Shimmer3

Low Noise Accelerometer - Kionix KXRB5-2042

Offset	Sensitivity (+/- 2.0 g)			Alignment		
2047	83	0	0	0	-1	0
2047	0	83	0	-1	0	0
2047	0	0	83	0	0	-1

Table 8 Shimmer3 Low Noise Accelerometer (Kionix KXRB5-2042) Calibration Parameters

Low Noise Accelerometer - Kionix KXTC9-2050

Offset	Sensitivity (+/- 2.0 g)			Alignment		
2253	92	0	0	0	-1	0
2253	0	92	0	-1	0	0
2253	0	0	92	0	0	-1

Table 9 Shimmer3 Low Noise Accelerometer (Kionix KXTC9-2050) Calibration Parameters

Wide Range Accelerometer - LSM303DLHC

Offset	Sensitivity (+/- 2.0 g)			Alignment		
0	1631	0	0	-1	0	0
0	0	1631	0	0	1	0
0	0	0	1631	0	0	-1
Sensitivity (+/- 4.0 g)						
815	0	0				
0	815	0				
0	0	815				
Sensitivity (+/- 8.0 g)						
408	0	0				
0	408	0				
0	0	408				
Sensitivity (+/- 16.0 g)						
135	0	0				
0	135	0				
0	0	135				

Table 10 Shimmer3 Wide Range Accelerometer (LSM303DLHC) Calibration Parameters

Wide Range Accelerometer - LSM303AHTR						
Offset	Sensitivity (+/- 2.0 g)			Alignment		
0	1671	0	0	0	-1	0
0	0	1671	0	1	0	0
0	0	0	1671	0	0	-1
Sensitivity (+/- 4.0 g)						
	836	0	0			
	0	836	0			
	0	0	836			
Sensitivity (+/- 8.0 g)						
	418	0	0			
	0	418	0			
	0	0	418			
Sensitivity (+/- 16.0 g)						
	209	0	0			
	0	209	0			
	0	0	209			

Table 11 Shimmer3 Wide Range Accelerometer (LSM303AHTR) Calibration Parameters

Gyroscope - MPU9150 and MPU9250						
Offset	Sensitivity (+/- 250 dps)			Alignment		
0	131	0	0	0	-1	0
0	0	131	0	-1	0	0
0	0	0	131	0	0	-1
Sensitivity (+/- 500 dps)						
	65.5	0	0			
	0	65.5	0			
	0	0	65.5			
Sensitivity (+/- 1000 dps)						
	32.8	0	0			
	0	32.8	0			
	0	0	32.8			
Sensitivity (+/- 2000 dps)						
	16.4	0	0			
	0	16.4	0			
	0	0	16.4			

Table 12 Shimmer3 Gyroscope Calibration Parameters

Magnetometer - LSM303DLHC						
Offset	Sensitivity (+/- 1.3 gauss)			Alignment		
0	1100	0	0	-1	0	0
0	0	1100	0	0	1	0
0	0	0	980	0	0	-1
Sensitivity (+/- 1.9 gauss)						
	855	0	0			
	0	855	0			
	0	0	760			
Sensitivity (+/- 2.5 gauss)						
	670	0	0			
	0	670	0			
	0	0	600			
Sensitivity (+/- 4.0 gauss)						
	450	0	0			
	0	450	0			
	0	0	400			
Sensitivity (+/- 4.7 gauss)						
	400	0	0			
	0	400	0			
	0	0	355			
Sensitivity (+/- 5.6 gauss)						
	330	0	0			
	0	330	0			
	0	0	295			
Sensitivity (+/- 8.1 gauss)						
	230	0	0			
	0	230	0			
	0	0	205			

Table 13 Shimmer3 Magnetometer (LSM303DLHC) Calibration Parameters

Magnetometer - LSM303AHTR						
Offset	Sensitivity (+/- 49.152 gauss)			Alignment		
0	667	0	0	0	-1	0
0	0	667	0	1	0	0
0	0	0	667	0	0	-1

Table 14 Shimmer3 Magnetometer (LSM303AHTR) Calibration Parameters

Appendix II – Alignment Matrix, Sensitivity Matrix and Offset Vector

The calibration of the tri-axial inertial sensor signal is achieved through the implementation of the formula

$$c = R^{-1} \cdot K^{-1} \cdot (u - b)$$

where

c = 3x1 calibrated signal vector

R = 3x3 alignment matrix

K = 3x3 sensitivity matrix

u = 3x1 uncalibrated signal vector

b = 3x1 offset vector

Alignment Matrix

The alignment matrix R can serve 4 functions in the calibration of a tri-axial inertial sensor.

1. It can be used to allow the user to define to which axes they wish to assign the name x-axis, y-axis and z-axis.
2. It can be used by the user to define which direction they wish to be considered the positive direction of the measuring axis.
3. It can be used to correct for Shimmer design discrepancies whereby the XYZ outputs of each sensor do not agree. For example in the Shimmer the accelerometer x-axis is aligned with the gyroscope y-axis and vice versa.
4. It can be used to correct for any misalignment of axes within each sensor, i.e. the fact that all three axes are not perfectly orthogonal.

Default Alignment Matrix

The alignment matrix below is a default alignment matrix and has no effect on the calibrated signals of the sensor. This alignment matrix should be used if the user is satisfied with the coordinate system and is convinced that the sensor axes are suitably orthogonal.

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Changing the Names of Axes

Changing the names of the axes can be achieved by changing the position of the value 1 in the relevant column of the matrix. For example the alignment matrix below has the effect of making the uncalibrated x-axis (x^* -axis) the calibrated y-axis and makes the uncalibrated y-axis (y^* -axis) the

calibrated x-axis. The row order represents the uncalibrated axes order (x*-axis, y*-axis, z*-axis) and the column order represents the calibrated axes order (x-axis, y-axis, z-axis).

$$R = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Changing the Direction of Axes

Changing the direction which is considered to be positive can be achieved by changing the sign of the value 1 in the relevant column of the matrix. For example the alignment matrix below has the effect of reversing the directions of both the x-axis and the z-axis from their uncalibrated directions.

$$R = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

Correcting for Non-Orthogonal Axes

Correcting for misalignment of the axes is not straightforward as it requires the use of a verified calibration procedure. The alignment matrix below corrects for very minor misalignment of axes.

$$R = \begin{bmatrix} 0.99 & 0.01 & 0.05 \\ 0.06 & 0.98 & 0.2 \\ 0.07 & 0.02 & 0.99 \end{bmatrix}$$

In general the sensors used on the Shimmer should have axes which are sufficiently orthogonal and for most applications it isn't necessary to calculate for the misalignment. The accelerometer calibration procedure integrated into the application outlined in this document automatically calculates an alignment matrix which corrects for non-orthogonal accelerometer axes. The gyroscope calibration procedure outlined in Appendix II describes how to calculate an alignment matrix which corrects for non-orthogonal gyroscope axes.

Sensitivity Matrix

The sensitivity matrix **K** defines the sensitivity of each axes of the tri-axial sensor. Although the matrix is a 3 by 3 matrix, only 3 of the values are of relevance and the other six values are equal to zero. In fact the sensitivity matrix is essentially a 3 by 1 sensitivity vector which is expanded and padded with zeros for the purposes of convenient matrix multiplication. An example sensitivity matrix **K** is shown below along with its corresponding sensitivity vector **k**.

$$K = \begin{bmatrix} 10 & 0 & 0 \\ 0 & 10 & 0 \\ 0 & 0 & 10 \end{bmatrix} \quad k = \begin{bmatrix} 10 \\ 10 \\ 10 \end{bmatrix}$$

Offset Vector

The offset vector **b** defines the zero offset for each axes of the tri-axial sensor. It is a simple 3 by 1 vector and example of which is shown below.

2250
 $b =$ 2340
1890

Appendix III – Accelerometer and Gyroscope Calibration Procedure

This appendix describes the gyroscope and accelerometer calibration procedure proposed for the calibration of the 6DoF IMU's. It is based on the work done by Ferraris et al. in *“Procedure for Effortless In-Field Calibration of Three Axis Rate Gyros and Accelerometers”* [1]. The calibration procedure outlined here has been implemented into the *Shimmer 9DoF Calibration Application*.

Sensor Models

Gyroscope Model

- The uni-axial rate gyro output y_g , as a function of the angular velocity component ω directed along the sensor sensitivity axis is modelled as

$$y_g = k_g \omega + b_g \quad \text{Equation 1}$$

Where

k_g is the rate gyro scale factor

b_g is the rate gyro offset (the gyroscope offset drifts with time so should be considered as a linear function of time, $b_g(t) = b_{g0} + b_{g1}(t)$)

Note: Ferraris' paper includes an extra component $d_{g,a}$ in the gyroscope model. This is the effect of the linear acceleration on the rate gyro. Most modern day MEMS gyroscope sensors are designed such that the effect of linear acceleration on the measured signal is negligible and so this component may be ignored for the purpose of this application.

Accelerometer Model

- The uni-axial accelerometer output y_a , as a function of the acceleration component a directed along the sensor sensitivity axis is

$$y_a = k_a a + b_a \quad \text{Equation 2}$$

where

k_a is the accelerometer scale factor

b_a is the accelerometer offset

Three-Axis Model

- Ideal three axis rate gyros and accelerometers are composed of three mutually orthogonal sensors.
- Misalignment may occur due to sensors not being exactly mutually orthogonal and also the fact that the actual sensitivity axis of each sensor may not match exactly the assumed sensitivity axis.
- The presence of misalignment makes it necessary to characterise the actual orientation of the sensitivity axis of each sensor with respect to the assumed orientation of the sensitivity axis. This is done in four steps
 1. Define the assumed sensitivity axis Σ_A as, $\Sigma_A = (x, y, z)$
 2. Define the actual sensor sensitivity axis as Σ_S as, $\Sigma_S = (x', y', z')$,
 3. Set the actual sensor sensitivity axis Σ_S such that each axis is approximately parallel to an axis of the assumed sensitivity axis Σ_A .
 4. Express the orientation of the actual sensitivity axis Σ_S with respect to the assumed sensitivity axis Σ_A , in the form of a 3 by 3 orientation matrix

$$R_g = \begin{bmatrix} r_{g,x'x} & r_{g,x'y} & r_{g,x'z} \\ r_{g,y'x} & r_{g,y'y} & r_{g,y'z} \\ r_{g,z'x} & r_{g,z'y} & r_{g,z'z} \end{bmatrix} \quad \text{for the gyroscope}$$

$$R_a = \begin{bmatrix} r_{a,x'x} & r_{a,x'y} & r_{a,x'z} \\ r_{a,y'x} & r_{a,y'y} & r_{a,y'z} \\ r_{a,z'x} & r_{a,z'y} & r_{a,z'z} \end{bmatrix} \quad \text{for the accelerometer}$$

- The 3x1 vector outputs of the two sensor triplets, y_g and y_a corresponding to the angular velocity vector ω and the acceleration vector a both expressed with respect to the assumed sensitivity axis Σ_A , are given by

$$\hat{y}_g = K_g \cdot R_g \cdot \hat{\omega} + \hat{b}_g \quad \text{Equation 3a}$$

$$\hat{y}_a = K_a \cdot R_a \cdot \hat{a} + \hat{b}_a \quad \text{Equation 3b}$$

Where

$$\hat{y}_g = \begin{bmatrix} y_{gx} \\ y_{gy} \\ y_{gz} \end{bmatrix} \quad \text{is the tri-axial gyroscope output vector}$$

$$\hat{\omega} = \begin{bmatrix} \omega_{x'} \\ \omega_{y'} \\ \omega_{z'} \end{bmatrix}$$

is the angular velocity vector of the sensor unit

$$\hat{b}_g = \begin{bmatrix} b_{gx'} \\ b_{gy'} \\ b_{gz'} \end{bmatrix}$$

is the gyroscope offset vector

$$\hat{y}_a = \begin{bmatrix} y_{ax} \\ y_{ay} \\ y_{az} \end{bmatrix}$$

is the tri-axial accelerometer output vector

$$\hat{a} = \begin{bmatrix} a_{x'} \\ a_{y'} \\ a_{z'} \end{bmatrix}$$

is the acceleration vector of the sensor unit

$$\hat{b}_a = \begin{bmatrix} b_{ax'} \\ b_{ay'} \\ b_{az'} \end{bmatrix}$$

is the accelerometer offset vector

K_g, K_a are the diagonal matrices of the scale factors of the three sensors in each triplet

$$K_g = \begin{bmatrix} k_{g,x} & 0 & 0 \\ 0 & k_{g,y} & 0 \\ 0 & 0 & k_{g,z} \end{bmatrix}$$

for the gyroscope

$$K_a = \begin{bmatrix} k_{a,x} & 0 & 0 \\ 0 & k_{a,y} & 0 \\ 0 & 0 & k_{a,z} \end{bmatrix}$$

for the accelerometer

- Once the variables $R_g, R_a, K_g, K_a, \hat{b}_g$ and \hat{b}_a are known, equations 3a and 3b may be rearranged to obtain angular velocity and acceleration estimation from the outputs.

$$\hat{\omega} = R_g^{-1} \cdot K_g^{-1} \cdot (\hat{y}_g - \hat{b}_g) \quad \text{Equation 4a}$$

$$\hat{a} = R_a^{-1} \cdot K_a^{-1} \cdot (\hat{y}_a - \hat{b}_a) \quad \text{Equation 4b}$$

Calibration Algorithms

Gyroscope

Gyro Offset

- The gyroscope offset is calculated by measuring the sensor output under static conditions (i.e. when the angular velocity = 0)
- *Ferraris et al.* suggest that for precision the sensitive axis of the sensor should be directed roughly in the east west direction during this determination so that the influence of the earth's rotation, which is 0.004 deg/s becomes negligible. However since gyroscope offset varies with temperature and needs to be updated regularly during use (this is easily done) the east west alignment is not of benefit.

Gyro Scale Factors and Alignment Orientation Matrix

- Requires computation of three rotations of known angles directed along the three axes of the assumed sensitivity axis Σ_A , and of the integral of the rate gyro outputs
- Any angle of known value is suitable however a full revolution angle has several advantages in that it is easy to set and the relevant platform manipulation is very simple
- Nine gyroscope output measurements (3 sensitive axes for 3 rotations) are grouped into a square 3 by 3 matrix Y_g

$$Y_g = \begin{bmatrix} y_{g,x'x} & y_{g,x'y} & y_{g,x'z} \\ y_{g,y'x} & y_{g,y'y} & y_{g,y'z} \\ y_{g,z'x} & y_{g,z'y} & y_{g,z'z} \end{bmatrix}$$

where the elements $y_{g,cd}$ have the first subscript c ($c = x' \text{ or } y' \text{ or } z'$) which refers to the direction of the actual sensitive axis and the second subscript d ($d = x \text{ or } y \text{ or } z$) which refers to the assumed axis along which angular velocity is applied.

- Rearranging equation 3a

$$\hat{y}_g - \hat{b}_g = K_g \cdot R_g \cdot \hat{\omega} \quad \text{Equation 5}$$

The equivalent of equation 5 for the 3 x 3, 9 gyroscope output reading matrix is

$$Y_g - B_g = K_g \cdot R_g \cdot \Omega \quad \text{Equation 6}$$

Where

$$\Omega = \begin{bmatrix} \omega_{x'x} & \omega_{x'y} & \omega_{x'z} \\ \omega_{y'x} & \omega_{y'y} & \omega_{y'z} \\ \omega_{z'x} & \omega_{z'y} & \omega_{z'z} \end{bmatrix}$$

$$B_g = \begin{bmatrix} b_{gx'} & b_{gy'} & b_{gz'} \\ b_{gx'} & b_{gy'} & b_{gz'} \\ b_{gx'} & b_{gy'} & b_{gz'} \end{bmatrix}$$

- Integration of both sides over a period of time, where K_g and R_g are constant

$$\int (Y_g - B_g) dt = K_g \cdot R_g \cdot \int \Omega dt \quad \text{Equation 7}$$

$$W_g = K_g \cdot R_g \cdot \Theta \quad \text{Equation 8}$$

where

Θ is the known angle of rotation

W_g is the integrated gyro O/P minus offset

- Rearranging equation 8,

$$K_g \cdot R_g = W_g \cdot \Theta^{-1} \quad \text{Equation 9}$$

- The separation of K_g and R_g can be obtained by noting the rows of R_g are unit vectors, therefore

$$\begin{bmatrix} k_{g,x}^2 \\ k_{g,y}^2 \\ k_{g,z}^2 \end{bmatrix} = \text{diag} \left[(K_g \cdot R_g) \cdot (K_g \cdot R_g)^T \right] = \text{diag} \left[(W_g \cdot \Theta^{-1}) \cdot (W_g \cdot \Theta^{-1})^T \right] \quad \text{Equation 10}$$

and

$$R_g = K_g^{-1} \cdot W_g \cdot \Theta^{-1} \quad \text{Equation 11}$$

Accelerometer

Accelerometer Offset

- Recording of all three accelerometer outputs in all six possible platform positions (i.e. with gravity parallel and anti-parallel to each axis of Σ_A). The measurements are grouped into two triplets corresponding to the positive and negative directions of the three axes.

$$Y_{a+} = K_a \cdot R_a \cdot a^{+g} + B_a \quad \text{Equation 12}$$

$$Y_{a-} = K_a \cdot R_a \cdot a^{-g} + B_a \quad \text{Equation 13}$$

where

Y_{a+}, Y_{a-} are 3 by 3 matrices containing the accelerometer outputs where the elements $y_{a,cd}$ have the first subscript c ($c = x \text{ or } y \text{ or } z$) which refers to the direction of the sensitive axis and the second subscript d ($d = x \text{ or } y \text{ or } z$) which refers to the axis placed approximately vertical during the measurement.

$$Y_{a+} = \begin{bmatrix} y_{a,x'x}^{+g} & y_{a,x'y}^{+g} & y_{a,x'z}^{+g} \\ y_{a,y'x}^{+g} & y_{a,y'y}^{+g} & y_{a,y'z}^{+g} \\ y_{a,z'x}^{+g} & y_{a,z'y}^{+g} & y_{a,z'z}^{+g} \end{bmatrix}$$

$$Y_{a-} = \begin{bmatrix} y_{a,x'x}^{-g} & y_{a,x'y}^{-g} & y_{a,x'z}^{-g} \\ y_{a,y'x}^{-g} & y_{a,y'y}^{-g} & y_{a,y'z}^{-g} \\ y_{a,z'x}^{-g} & y_{a,z'y}^{-g} & y_{a,z'z}^{-g} \end{bmatrix}$$

B_a is a offset matrix which contains the offset estimation of each accelerometer (by rows) obtained in the different positions

$$B_a = \begin{bmatrix} b_{ax'} & b_{ay'} & b_{az'} \\ b_{ax''} & b_{ay''} & b_{az''} \\ b_{ax'''} & b_{ay'''} & b_{az'''} \end{bmatrix}$$

- The offset matrix may be calculated as the sum of equations 12 & 13,

$$Y_{aS} = Y_{a+} + Y_{a-} \quad \text{Equation 14}$$

$$B_a = \frac{Y_{aS}}{2} \quad \text{Equation 15}$$

Accelerometer Scale Factors and Alignment Orientation Matrix

- Using the same measurements from the accelerometer offset procedure, the difference between equations 12 & 13 is calculated as

$$Y_{aD} = Y_{a+} - Y_{a-} \quad \text{Equation 16}$$

$$K_a \cdot R_a = \frac{Y_{aD}}{2g} \quad \text{Equation 17}$$

- The separation of K_a and R_a can be obtained by noting the rows of R_a are unit vectors, therefore

$$\begin{bmatrix} k_{a,z}^2 \\ k_{a,y}^2 \\ k_{a,z}^2 \end{bmatrix} = \text{diag} \left[(K_a \cdot R_a) \cdot (K_a \cdot R_a)^T \right] = \frac{1}{4g^2} \text{diag} [Y_{aD} \cdot Y_{aD}^T] \quad \text{Equation 18}$$

and

$$R_a = K_a^{-1} \cdot \frac{Y_{aD}}{2g} \quad \text{Equation 19}$$

Appendix IV – Magnetometer Calibration

If the user is unsatisfied with the automated magnetometer calibration provided by the application, the magnetometer calibration parameters can be calculated manually by following the steps below;

1. Complete the magnetometer calibration procedure outlined in section 7.6 which should result in three magnetometer plots as shown in Figure 0-1.
2. Calculate the offset of each axis of the magnetometer by using the graphs shown in Figure 0-1 to find how much the centre of each of the real circles is shifted from the centre of the ideal circle (0,0) .

Example:

- I. Find the centre of the circle plotted in the first graph along the x-axis in Figure 0-1 using $(X_{\max} - X_{\min})/2$, the centre was found to lie at (-56, 208)
 - II. The offset of the x axis is -56 away from 0, so the offset is taken as -56.
 - III. Enter the offset value in the *Offset Vector (bm)* control.
 - IV. Repeat steps I, II and III to find the y-axis and z-axis offsets.
3. Calculate the sensitivity of each axis of the magnetometer by using the graphs shown in Figure 0-1 to find the diameter of the circle along each axis and dividing it by two.

Example:

- I. Find the diameter of the circle along the x-axis plotted in the first graph in Figure 0-1 using $(\text{Abs}(X_{\max} - X_{\min}))/2$, the diameter was found to be 918.
 - II. The sensitivity of the x axis is $918/2$, which is 459
 - III. Enter the sensitivity value in the *Sensitivity Matrix (Km)* control.
 - IV. Repeat steps I, II and III to find the y-axis and z-axis sensitivities.
4. You can verify your manually calculated magnetometer calibration parameters by changing the *Magnetometer Format* drop down menu to *Calibrated*. The three magnetometer plots should display three unit circles centred at (0,0).

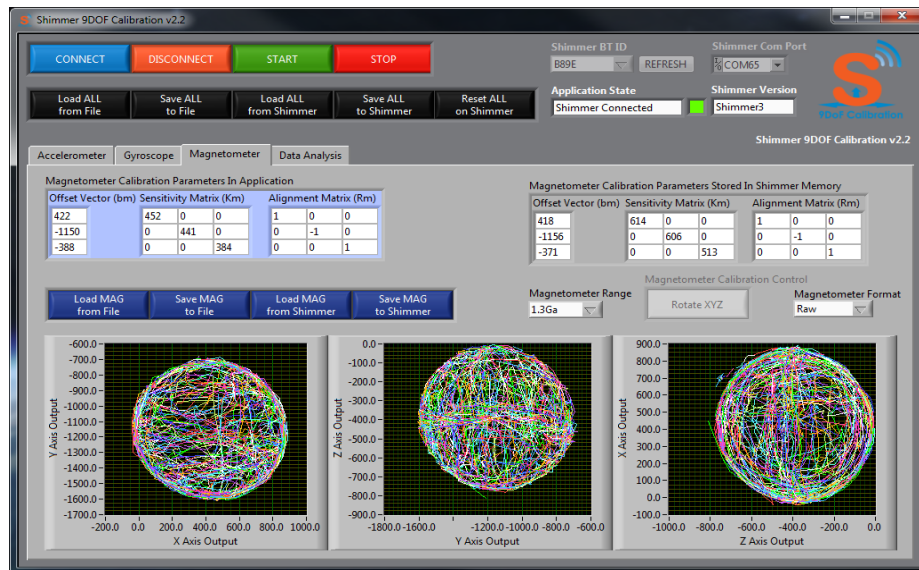


Figure 0-1 Manual magnetometer calibration

Appendix V – Troubleshoot

When I use the Shimmer BT ID down menu, my Shimmer isn't listed?

- Verify that the Shimmer has been paired with your Windows machine. Press the REFRESH button and search for the BT ID again. Alternatively you can use the *Shimmer Com Port* drop down menu to select your Shimmer device.

When I press the **Connect** Button, the Shimmer fails to connect?

- Verify Shimmer is within range of host side device and has a clear line of sight...
 - While the Shimmer BT radio has a range of 10m the range of your host side BT radio may vary and should be verified. Also Bluetooth communication doesn't necessarily require line of sight however for establishing the connection it is recommended.
- Verify that there are no issues with a low or problematic battery...
 - Place the Shimmer in a powered charging dock. If the cause of the connection issues is the Shimmer battery then placing the Shimmer in the dock should rectify the issue.
- Make multiple connection attempts...
 - Making multiple connection attempts may be required for the following reasons:
 - Paging Inquiry - When the Shimmer is not connected the paging inquiry window on the BT radio defaults to 320ms (out of 2.56s) so the Shimmer is only 'listening' for a connection 12.5% of the time.
 - FHS (frequency hopping synchronization) - When a BT slave successfully connects or pairs with a BT master they synchronize their frequency hopping pattern. If a master has not connected to a slave over a long period of time

then the frequency hopping pattern can get severely out of sync. Variations in clock drift across Shimmers means that some Shimmers will get out of sync more easily than others. Note that once a connection is made the frequency pattern of the master and slave are once again synchronised.

When I complete the calibration procedure no values or nonsensical values appear in the display [Sensor Name] Calibration Parameters In Application.

If the values are 0 or do not make any sense then there is a possibility that the calibration procedure was performed incorrectly. It is suggested that you repeat the calibration procedure once again while taking note of the following points.

- Ensure that the Shimmer you are calibrating is the Shimmer that is connected to the PC (the green LED will blink when the Shimmer is idle, the green LED will stay permanently on when the Shimmer is connected and the green LED will blink at a rate of 1Hz when the Shimmer is streaming).
- Once you have decided on your sensor coordinate axis ensure that you observe the correct orientations for each step of the calibration.
- Ensure that you hold the Shimmer static during the appropriate periods.
- Make sure to perform each step of the calibration.

References

- [1] Ferraris F, Grimaldi U, and Parvis M. Procedure for effortless in-field calibration of three-axis rate gyros and accelerometers. *Sens. Mater.* 1995; **7**: 311-30.
- [2] J.Merayo et al. Scalar calibration of vector magnetometers. *Meas. Sci. Technol.* 2000; **11**: 120-132.

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