

# Technical Reference Guide

## Physical Pendulum Lab

### Purpose of the Guide

This guide has been written to aid the EduForce Module (“module”) user in understanding each tab of the workbook specifically for the Pendulum Lab. The user should also be familiar with the Module and EduForce Dashboard (“Dashboard”) User’s Guides. This guide is divided into sections relative to each tab of the workbook.

### Pendulum Experiment Explained

The purpose of the Physical Pendulum lab is to demonstrate that the period of a pendulum is only dependent on the Moment of Inertia around the pivot point and the distance from the pivot to the body’s center of mass.

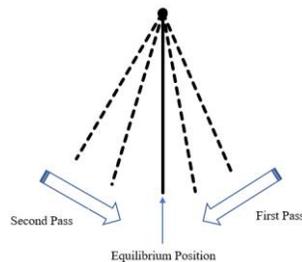
This lab will verify the validity of the equation  $T = 2\pi \sqrt{\frac{I}{mgh}}$  for a physical pendulum.

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## Glossary

- **Baseline:** Initial data taken for a predetermined period of time before motion occurs in order to zero the data. In this document, let the variable  $B_{avg}$  = the average of the baseline values.
- **Calibration:** The IMU will ideally show a reading of 0 g's for the X and Y axis, and 1 g for the Z axis when the module is at rest. The calibration process determines the bit count value by which the module varies from this “ideal”. This variance is recorded in the module’s permanent memory and accessed by the dashboard during each download in order to perform some of the Data Converter Template Tab calculations.
- **Equilibrium:** The point at which the module, being attached to the physical pendulum, is in a vertical position as shown in the following graphic.



- **Normalization (to zero):** The baseline of a select data set is averaged and subtracted from all values in that data set to establish the initial data offset. This has the overall mathematical effect of setting the origin point of the module’s coordinate system (0,0,0) to the initial resting point of the module at the beginning of any given trial. By normalizing the module it allows for the sensors to have vector components to the specific measurements; i.e. to have a “positive” and “negative” direction relative to that origin point.
- **Signed Data:** Bit values above 32768 represent negative data and data corresponding to those bit values are converted to negative integers by subtracting 65536 from the original data value. Any data at or below 32768 retains original value.
- **Unsigned Data:** Raw data represented as positive integers.

# Raw Data

## Tab Purpose:

Data from the module is imported into the workbook through the dashboard.

**DO NOT ALTER DATA ON THIS TAB AS IT WILL AFFECT ALL CALCULATIONS AND GRAPH OUTPUT IN REMAINING TABS.**

## Column Explanations

- Raw data is imported from dashboard into columns A-I beginning at row 3.
  - Columns A-C contain raw accelerometer data.
    - Column A = X-axis accel data
    - Column B = Y-axis accel data
    - Column C = Z-axis accel data
  - Columns D-F contain raw gyroscopic data.
    - Column D = X-axis gyro data
    - Column E = Y-axis gyro data
    - Column F = Z-axis gyro data
  - Columns G-I contain raw magnetometer data.
    - Column G = X-axis mag data
    - Column H = Y-axis mag data
    - Column I = Z-axis mag data
- Data is by bit count and is shown without any modification for sign, calibration offset, or “normalization”.
- Acceleration and Gyroscope data is shown one row for each sample-per-second (sps). That is, if on the dashboard parameters the sps is set to 960 (960 Hz<sup>1</sup>) then rows 3-963 of the tab represent data for the first one (1) second of the test; rows 966-1926 are the next second of the test, and so on.
- Magnetometer data is collected at 96 sps (96 Hz), therefore for each ten (10) samples of acceleration or gyroscope data, one (1) sample of magnetometer data is collected. For this reason, you will see data in rows 5, 15, 25, etc.

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<sup>1</sup> Samples per second and hertz are used interchangeably with the EduForce module as the internal clock of the module operates at 1 Hertz per second.

# Calibration & Parameters

## Tab Purpose:

Data from the module is imported into the workbook through the dashboard. Refer to the Dashboard User's Guide for specific information and an explanation of the calibration process.

**DO NOT ALTER DATA ON THIS TAB AS IT WILL AFFECT ALL CALCULATIONS AND GRAPH OUTPUT IN REMAINING TABS.**

## Column Explanations

- Calibration data is imported from dashboard into column A beginning at row 3
- Rows 3-5 Acceleration Data
  - Row 3 = X-axis accel data
  - Row 4 = Y-axis accel data
  - Row 5 = Z-axis accel data
- Rows 6-8 Gyroscope Data
  - Row 6 = X-axis gyro data
  - Row 7 = Y-axis gyro data
  - Row 8 = Z-axis gyro data
- Rows 9-11 Magnetometer Data
  - Row 9 = X-axis mag data
  - Row 10 = Y-axis mag data
  - Row 11 = Z-axis mag data
- Rows 12-16 Parameters (imported automatically from the dashboard)
  - Row 12 = Test Length in seconds
  - Row 13 = Accelerometer & Gyroscope Sample rate in Hz
  - Row 14 = Magnetometer Sample rate in Hz
  - Row 15 = Accelerometer Sensitivity in g's
  - Row 16 = Gyroscope Sensitivity in degrees-per-second
- Minimum and Maximum data points are imported from the dashboard with offsets being determined by taking  $(\text{min} + \text{max}) / 2$ .

# Input & Results

## Tab Purpose:

All **user-entered** input values are entered on this tab. In addition, all dashboard inputs and workbook calculations are carried to this tab.

## Explanations:

Fields outlined in **BLUE** = Values input by user.

Pendulum Test 240-24 16G-92 2000dps-92 MAG-N 9MAY18			
<b>Data Inputs:</b>			<b>Calibration:</b>
Samples per Second	960		X Accel
Sensitivity Acceleration(Gs)	16		Y Accel
Sensitivity Angular Velocity (°/s)	2000		Z Accel
Length of Pendulum(m)	1		X Gyro
Mass of Pendulum(g)	55		Y Gyro
Mass of Module(g)	12		Z Gyro
Distance of Module from Axis of Rotation(m)	1.07		
Moving Average Acceleration:			
Up from start	-4	Total Rows	100
Moving Average Velocity:			
Up from start	-4	Total Rows	10
Advanced:			
Baseline Start(s)	0	Baseline Duration(s)	1
Chart Start(s)	0	Chart End(s)	18.73
Number of Samples	17976	Test Length(s)	18.73

- Samples-per-second, Sensitivity Acceleration/Angular Velocity, Calibration data, Number of Samples, and Test Length are input from the dashboard
- Length of Pendulum, Mass of Pendulum/Module and Distance are user-input fields.
- Moving Average Acceleration/Velocity “Up from start” and “Total Rows”, Baseline Start/Duration, and Chart Start/End are user-selected fields. See the Data Converter Template Tab for details.

# Data Converter Template

## Tab Purpose:

All fields on this tab are locked therefore there are no user inputs required on this tab. Raw data imported from the module (Raw Data Tab) is converted to usable position, velocity, and acceleration data through a series of algorithms.

## Explanations

Columns B -Y relate to the mathematical operations necessary to convert the IMU bit count data from the module into “g’s” and “degrees per second”. Columns Z-AP relate to the analysis of this data in order resolve position, velocity, and acceleration in all three axes for each sensor.

### Signed Data (Columns B-J)

Data from each sensor *and* axis is imported from the Raw Data tab. The formulas in these columns perform an operation which takes the original data and assigns a positive or negative value relative to the starting point of the module along a given axis. This allows the data to have a direction in addition to a magnitude. (i.e. the module moved “x” m/s in a positive direction along the Z-axis.)<sup>2</sup>

A note regarding the Magnetometer: The IMU within the module utilizes a magnetometer in which the X and Y axes are inverted relative to the Accelerometer and Gyroscope X and Y axes. The tab formula automatically transfers the corresponding X or Y axis information from the Raw Data tab to the appropriate X or Y axis column in the Data Converter tab.

### Calibration & Conversion from bit count (Columns K-S)

**Calibration** (Columns K-M): There is an inherent, small variation from “ideal” during the manufacturing of IMU sensors. The modules must be calibrated in order to calculate this variance. The calibration adjustment is recorded in the module’s permanent memory and accessed by the dashboard each time the dashboard pulls trial data from the module.<sup>3</sup>

Calibration is typically a one-time event; however, it is recommended that classroom instructors recalibrate the modules once per year. Users who are using the module for more sensitive experiments may want to consider recalibrating on a more frequent basis.

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<sup>2</sup> Accelerometer Data: If raw value is less than 32768, then  $A_{signed} = A_{raw}$ . If raw value is greater than 32768, then  $A_{signed} = A_{raw} - 65536$ .

Gyroscope Data: If raw value is less than 32768, then  $\omega_{signed} = \omega_{raw}$ . If raw value is greater than 32768, then  $\omega_{signed} = \omega_{raw} - 65536$ .

<sup>3</sup>  $A_{cal} = A_{signed} - C$ . C = Calibration value (imported from dashboard)

### Conversion to Acceleration in g's (Columns N-P):

Calibrated Accelerometer data is converted from a “bit count” to “acceleration in g's” and is dependent on the Accelerometer Sensitivity input selected by the user.<sup>4</sup> This input determines the scaling, or sensitivity, factor used in the calculation. The “smaller” the number input, the greater the resolution.<sup>5</sup> In other words, 2 g's is more sensitive than 16 g's. (Refer to the Dashboard User's Guide for more details.)

### Conversion Degrees per Second (dps) (Columns Q-S):

Calibrated Gyroscope data is converted from a “bit count” to “degrees-per-second” and is dependent on the Gyroscope Sensitivity input selected by the user.<sup>6</sup> This input determines the scaling, or sensitivity, factor used in the calculation. The “smaller” the number input, the greater the resolution. In other words, 250 dps is more sensitive than 2000 dps. (Refer to the Dashboard User's Guide for more details.)

### Normalized Data (Columns T-Y)

“Normalization” is the mathematical process by which all calculations are set to a common starting, or origin, point { i.e. (0,0,0) }. All changes in position, velocity, and acceleration are therefore from this calculated origin. In order to complete this, a “baseline average” is calculated for each sensor and each axis used in the trial.<sup>7</sup> This baseline average is then subtracted from the calibrated/converted reading to establish an initial data offset.<sup>8</sup> The baseline average result is shown at the top of each respective column.

### Gyroscope Analysis & Graphing Data

Columns AL-AP analyze the converted data and, through a series of numerical integrations and averaging calculations, determine angular velocity, displacement and offset from equilibrium. Gyroscope velocity and period calculations are carried to the Results Tab.

### Time in seconds (Column AL)

At 960 Hz (960 samples per second) each sample represents 1/960<sup>th</sup> of a second or, .00104 seconds per sample.

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<sup>4</sup>  $A_g = \frac{A_{cal}}{32768} * S_{accel}$  where  $S_{accel}$  = Accelerometer Sensitivity

<sup>5</sup> At a lower input value (2 g versus 16 g), the sensitivity factor is larger. Therefore; each sample is divided into more parts increasing the overall resolution. This is much like a photo. When there are more dots, or pixels, per inch (each inch is divided into a greater number of parts) the picture is sharper or in other words has greater resolution.

<sup>6</sup>  $\omega_{dps} = \frac{\omega_{signed}}{32768} * S_{gyro}$  where  $S_{gyro}$  = Angular Velocity Sensitivity

<sup>7</sup> The baseline average is calculated by taking a mathematical average of each sensor/axis column, the starting and ending data points of which are a user-selected variables input on the Results Tab. The user should “hold the module still” for a moment at the beginning of a trial (1-3 seconds), once the module is turned on, to allow it to “normalize”. This time period is the start/end point entered into the Results Tab. See the Dashboard User's guide for more details.

<sup>8</sup> Accelerometer  $A_{norm} = A_g - B_{avg}$ , and Gyroscope  $\omega_{norm} = \omega_{dps} - B_{avg}$ ; where  $B_{avg}$  = baseline average.

### **Moving Average Angular Velocity (Column AM)**

A moving average is taken of the Z-axis Normalized Gyroscope Data<sup>9</sup> (in dps) using an initial offset and number of rows specified by the user in the Results Tab.

### **Angular Displacement (Column AN)**

Moving Average Angular Velocity<sup>10</sup> is numerically integrated using the trapezoidal rule to obtain Angular Displacement from the starting point<sup>11</sup>.

### **Angular Position in degrees (Column AO)**

The calculated Angular Displacement (AN) is added to the prior sample (the initial starting point for the first sample) to obtain angular position for each sample period.

### **Angular Acceleration in dps<sup>2</sup> (Column AP)**

Moving Average Angular Velocity (column AM) is numerically differentiated over intervals of five samples (.00521 seconds) to approximate Angular Acceleration in dps<sup>2</sup>.<sup>12</sup>

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<sup>9</sup>  $Gyro\ M_{ave} = \frac{\sum_{x=n+h}^{n+h+r-1} G_{norm}}{r}$  where; n = starting cell row, h = "up from start" value, and r = "total rows" value

<sup>10</sup>  $\Theta_n = \frac{\Delta t(G_n + G_{n-1})}{2} + \Theta_{n-1}$  where, n = starting cell row, and  $\Theta$  = Angular Displacement

<sup>11</sup> Average angular displacement over one period of oscillation is calculated to obtain the initial angle at which the pendulum was dropped.

<sup>12</sup>  $\alpha_n = \frac{\omega_n - \omega_{n-4}}{\Delta t}$

## Accelerometer Analysis

The accelerometer analysis is not needed to calculate the pendulum's period in this lab; however, the analysis is included here as a point of reference for other labs which will utilize the accelerometer.

### **Moving Average Acceleration** (Columns Z-AB)

A moving average is taken of the normalized acceleration data ( $m/s^2$ ) using an initial offset and number of rows specified by the user in the Results Tab.

$$Accel M_{ave} = \frac{\sum_{x=n+h}^{n+h+r-1} A_{norm}}{r} \quad \text{where; } n = \text{starting cell row, } h = \text{“up from start” value, and } r = \text{“total rows” value}$$

### **Acceleration in $m/s^2$** (Columns AC-AE)

Moving average acceleration (g's) is multiplied by 9.81 to convert to acceleration in  $m/s^2$ .

$$A_{mps} = A_{moving\ average} * 9.81$$

### **Velocity in m/s** (Columns AF-AH)

Acceleration  $m/s^2$  is numerically integrated using the trapezoidal rule to obtain velocity in m/s.

$$V_n = \frac{\Delta t(A_n + A_{n-1})}{2} + V_{n-1}, \text{ where } n = \text{starting cell row}$$

### **Moving Average Velocity** (Columns AI-AK)

A moving average is taken of the velocity data (m/s) using an initial offset and number of rows input by the user in the Results tab.

$$Vel M_{ave} = \frac{\sum_{x=n+h}^{n+h+r-1} V_{m/s}}{r} \quad \text{where; } n = \text{starting cell row, } h = \text{“up from start” value, and } r = \text{“total rows” value}$$

## Gyro Data Graph

Angular Position in degrees (AO) [**green** curve] and Angular Velocity Graph (AM) [**blue** curve] are plotted on the graph as a function of time in seconds (AL).