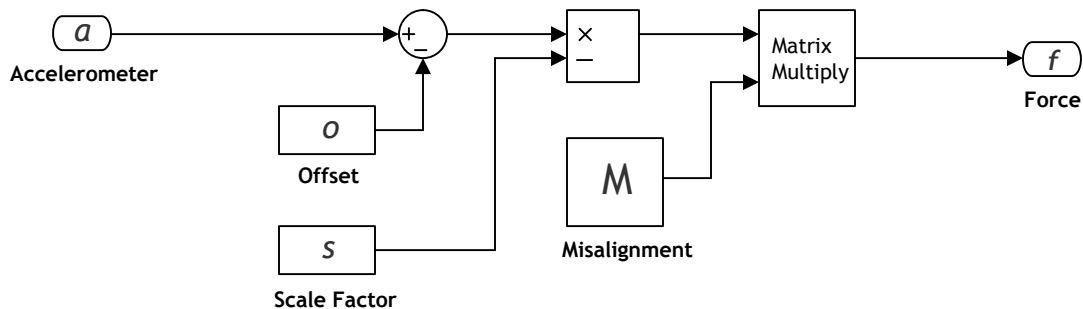


## MEMS IMU Calibration Example

### Tri-axial Accelerometer Calibration

Calibration compensates for individual accelerometer offset, scale factor and misalignment to the orthogonal reference.

Data sets are collected from 14 static orientations at a constant temperature (23°C). A general least squares algorithm is applied to the data sets to obtain the best least squares fit. The outputs of the calibration algorithm are offset and scale factor for individual accelerometers, and the misalignment compensation matrix.



Accelerometer offset, scale factor and misalignment compensation

The tri-axial accelerometer compensation equation:

$$\begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = M \begin{bmatrix} 1/s_x & 0 & 0 \\ 0 & 1/s_y & 0 \\ 0 & 0 & 1/s_z \end{bmatrix} \begin{bmatrix} a_x - o_x \\ a_y - o_y \\ a_z - o_z \end{bmatrix} \quad (1)$$

$f$  is the specific force in g units,  $a$  is the accelerometer output,  $o$  is the offset,  $s$  is the scale factor and  $M$  is the 3x3 misalignment matrix.

Finally, the compensated accelerometer data from the 14 data sets are compared to the reference data from the rate table.

Sensor outputs were averaged over 8 seconds for each data set.

### Accelerometer Compensation Parameters:

Parameter	Values
Scale factor, s	3.42956237906491e3, 3.47757814808255e3, 3.41831215173097e3
Offset, o	-8.54501650844584e3, 9.35920799812876e3, -8.87182916555241e3
Misalignment, M	0.99981443298128, -0.01110418114328, 0.01962280224898, -0.00098861677507, 1.00047714011799, 0.02015717687048, -0.01917127287255, 0.01482647389745, 1.00031874735289

### Accelerometer Compensation Results:

The errors of each data set are given below, where Error is the difference between the reference data and compensated sensor data.

Data Set	Reference (g)	Compensated Sensor (g)	Error (g)	Data Set	Reference (g)	Compensated Sensor (g)	Error (g)
1	X 0.0000	0.0002	-0.0002	8	X 0.7071	0.7074	-0.0002
	Y 0.0000	0.0002	-0.0002		Y 0.0000	-0.0002	0.0002
	Z 1.0000	1.0006	-0.0006		Z 0.7071	0.7068	0.0003
2	X -0.7071	-0.7081	0.0010	9	X 0.0000	0.0007	-0.0007
	Y 0.0000	0.0005	-0.0005		Y 0.7071	0.7070	0.0001
	Z 0.7071	0.7076	-0.0005		Z 0.7071	0.7066	0.0006
3	X 0.0000	-0.0002	0.0002	10	X 1.0000	1.0002	-0.0002
	Y -0.7071	-0.7070	-0.0001		Y 0.0000	-0.0004	0.0004
	Z 0.7071	0.7077	-0.0006		Z 0.0000	-0.0001	0.0001
4	X -1.0000	-1.0000	0.0000	11	X 0.0000	-0.0003	0.0003
	Y 0.0000	-0.0001	0.0001		Y 1.0000	0.9997	0.0003
	Z 0.0000	-0.0005	0.0005		Z 0.0000	-0.0003	0.0003
5	X 0.0000	-0.0002	0.0002	12	X 0.7071	0.7063	0.0008
	Y -1.0000	-1.0001	0.0001		Y 0.0000	0.0007	-0.0007
	Z 0.0000	-0.0007	0.0007		Z -0.7071	-0.7068	-0.0003
6	X -0.7071	-0.7063	-0.0008	13	X 0.0000	-0.0003	0.0003
	Y 0.0000	-0.0005	0.0005		Y 0.7071	0.7074	-0.0003
	Z -0.7071	-0.7071	0.0000		Z -0.7071	-0.7067	-0.0004
7	X 0.0000	0.0005	-0.0005	14	X 0.0000	-0.0001	0.0001
	Y -0.7071	-0.7072	0.0001		Y 0.0000	0.0002	-0.0002
	Z -0.7071	-0.7072	0.0001		Z -1.0000	-0.9997	-0.0003

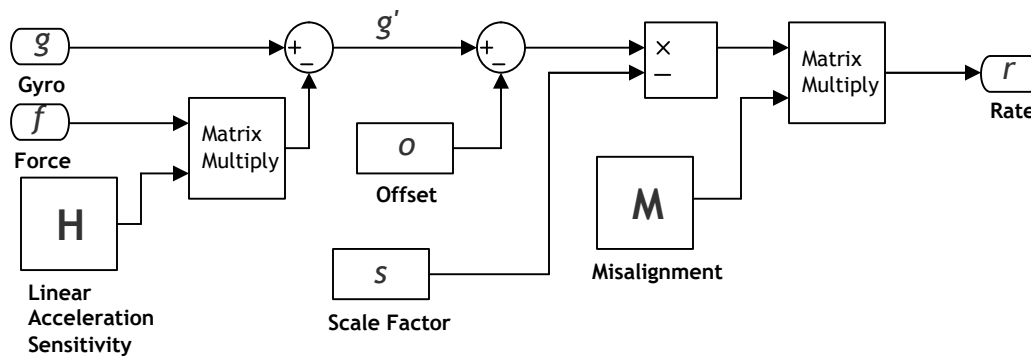
### Accelerometer Compensation Summary:

Root Mean Square of Errors (g)	0.0004		
Max. Error Magnitude (g)	X	0.0010	At data set 2
	Y	0.0007	At data set 12
	Z	0.0007	At data set 5

## Tri-axial Gyro Calibration

Calibration compensates for individual gyro offset, scale factor and misalignment to the orthogonal reference.

Data sets are collected from 15 rotations at a constant temperature (23°C). A general least squares algorithm is applied to the data sets to obtain the best least squares fit. The outputs of the calibration algorithm are offset and scale factor for individual gyros, and the misalignment compensation matrix.



### Gyro offset, scale factor and misalignment compensation

The tri-axial gyro compensation equation:

$$\begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix} = M \begin{bmatrix} 1/s_x & 0 & 0 \\ 0 & 1/s_y & 0 \\ 0 & 0 & 1/s_z \end{bmatrix} \begin{bmatrix} g_x - o_x \\ g_y - o_y \\ g_z - o_z \end{bmatrix} \quad (2)$$

$r$  is the compensated rotation rate in  $^{\circ}/\text{sec}$  units,  $g$  is the gyro output,  $o$  is the offset,  $s$  is the scale factor and  $M$  is the 3x3 misalignment compensation matrix.

To compensate for bias change due to linear accelerations in gyros:

$$\begin{bmatrix} g_x' \\ g_y' \\ g_z' \end{bmatrix} = \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix} - H \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} \quad (3)$$

$f$  is the specific force from (1),  $g$  is the gyro output and  $H$  is the 3x3 linear acceleration compensation matrix.  $g'$  is then input to (2) to obtain the fully compensated rates.

Finally, the compensated gyro data from the 15 data sets are compared to the reference data from the rate table.

Sensor outputs were averaged over 8 seconds for each data set.

### Gyro Compensation Parameters:

Parameter	Values
Scale factor, s	43.22518317790169, 42.37729270593920, 42.68176103898502
Offset, o	-8.12543150587021e3, -8.90606425339348e3, -7.70073387395307e3
Misalignment, M	1.00001921781021, -0.00430608383029, 0.01102980463992, 0.00038782503533, 1.00009604791486, 0.00256998306821, -0.02383123079302, -0.01606493507948, 0.99975991068276
Linear Acceleration Sensitivity, H	1.22042997236889, 18.51726079249416, -25.23591021444856, -3.32870078982815, -5.00887057113933, -10.93366938718006, 4.04508325592701, 5.21419080988085, 4.63055162843148

### Gyro Compensation Results:

The errors of each data set are given, where Error is the difference between the reference data and compensated sensor data.

Data Set		Reference (°/sec)	Compensated Sensor (°/sec)	Error (°/sec)	Data Set		Reference (°/sec)	Compensated Sensor (°/sec)	Error (°/sec)
1	X	0.000	0.048	-0.048	9	X	-60.000	-59.992	-0.008
	Y	0.000	0.024	-0.024		Y	0.000	-0.010	0.010
	Z	0.000	-0.037	0.037		Z	0.000	-0.004	0.004
2	X	0.000	0.030	-0.030	10	X	60.000	59.995	0.005
	Y	0.000	-0.039	0.039		Y	0.000	0.008	-0.008
	Z	30.000	30.017	-0.017		Z	0.000	0.016	-0.016
3	X	0.000	0.015	-0.015	11	X	0.000	-0.005	0.005
	Y	0.000	-0.032	0.032		Y	0.000	-0.013	0.013
	Z	-30.000	-30.014	0.014		Z	0.000	0.002	-0.002
4	X	0.000	-0.011	0.011	12	X	0.000	-0.018	0.018
	Y	0.000	-0.022	0.022		Y	-30.000	-29.980	-0.020
	Z	60.000	59.992	0.008		Z	0.000	-0.028	0.028
5	X	0.000	-0.004	0.004	13	X	0.000	0.002	-0.002
	Y	0.000	-0.025	0.025		Y	30.000	30.021	-0.021
	Z	-60.000	-59.993	-0.007		Z	0.000	0.024	-0.024
6	X	0.000	-0.072	0.072	14	X	0.000	0.035	-0.035
	Y	0.000	-0.028	0.028		Y	-60.000	-59.933	-0.067
	Z	0.000	0.012	-0.012		Z	0.000	0.039	-0.039
7	X	-30.000	-30.039	0.039	15	X	0.000	0.025	-0.025
	Y	0.000	0.009	-0.009		Y	60.000	60.067	-0.067
	Z	0.000	0.016	-0.016		Z	0.000	0.013	-0.013
8	X	30.000	29.987	0.013					
	Y	0.000	-0.029	0.029					
	Z	0.000	-0.024	0.024					

### Gyro Compensation Summary:

Root Mean Square of Errors (°/sec)	0.028		
Max. Error Magnitude (°/sec)	X	0.072	At data set 6
	Y	0.067	At data set 14
	Z	0.039	At data set 14

## Higher Order Calibration

The first order calibration/compensation schemes outlined above are sufficient for most inertial systems based on MEMS sensors. For higher-grade sensors such as FOG (fiber optic gyros), it may be desirable to compensate for higher order errors such as scale factor non-linearity and temperature dependency. Sentera Technology provides expertise to analyze and determine the best compensation function for each sensor and streamline the calibration process according to the needs of the customer.

## Sentera Data Acquisition System Interface

Client sensor data is transmitted serially to the data acquisition PC via RS-232.

A typical digital data collection interface for the Sentera Data Acquisition System is described below. Client specific needs may be accommodated as required.

### Sensor Data Packet Format

Byte Number	Content
1	First header byte 0xBD
2	Second header byte 0xDB
3	LSB of X Gyro
4	MSB of X Gyro
5	LSB of Y Gyro
6	MSB of Y Gyro
7	LSB of Z Gyro
8	MSB of Z Gyro
9	LSB of X Accelerometer
10	MSB of X Accelerometer
11	LSB of Y Accelerometer
12	MSB of Y Accelerometer
13	LSB of Z Accelerometer
14	MSB of Z Accelerometer
15	LSB of X Temperature
16	MSB of X Temperature
17	LSB of Y Temperature
18	MSB of Y Temperature
19	LSB of Z Temperature
20	MSB of Z Temperature

### Serial communication settings

- Baud rate: 57600 bps
- Data bits: 8
- Stop bits: 1
- Parity: None
- Flow Control: None

All sensor data are scaled 16-bit signed integers.

16-bit analog data acquisition is also available.