LAB 3: Report

In this lab, Vectornav VN-100 IMU was used to collect data and perform analysis on stationary noise and allan variance analysis in order to understand how to characterize and choose IMU sensors for different robotic applications.

Stationary noise analysis:

For Stationary noise analysis, five minutes of IMU data containing 3 accelerometers, 3 angular rate gyros, 3- axis magnetometers was collected in with the instrument stationary and as far away as possible from your

computer or other computers and moving objects.

The Time series and Frequency distribution of all the IMU data (Yaw, Pitch, Roll, Angular Velocity, Linear Acceleration and Magnetic Field) are developed by plotting each axis versus time for time series plot and histogram plots were used to show frequency distribution.

1. Yaw, Pitch and Roll

The Time series plot for Yaw is illustrated below.

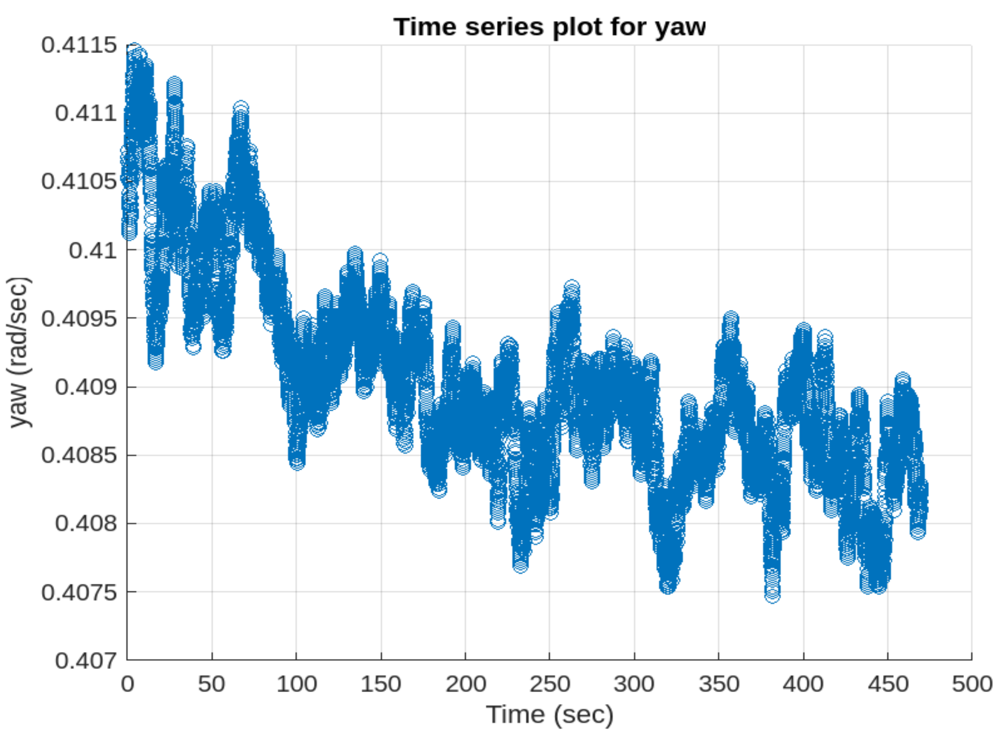


Fig 1.a: Time series plot of Yaw data

The noise characteristics of Yaw, Pitch and Roll data can be found by calculating the Mean and Standard Deviation.

The Mean and Standard deviation of Yaw are as follows: mean_yaw = 0.4090 and std_yaw = 7.3157e-04

The Time series plot for Pitch is illustrated below.

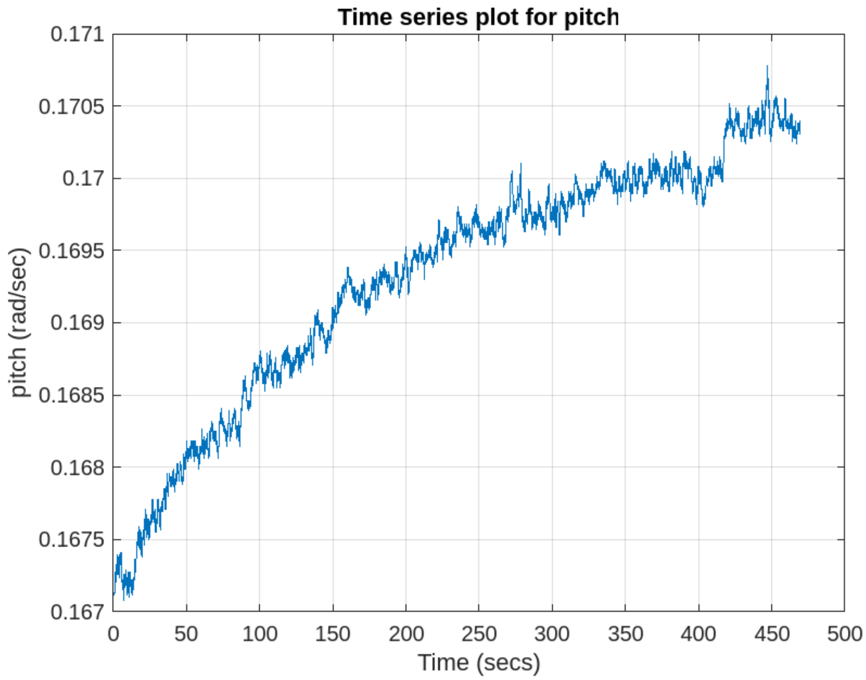


Fig 1.b: Time series plot of Pitch data

The Mean and Standard deviation of Pitch are as follows:

mean_pitch = 0.1693 and std_pitch = 8.5712e-04

The Time series plot for Roll is illustrated below.

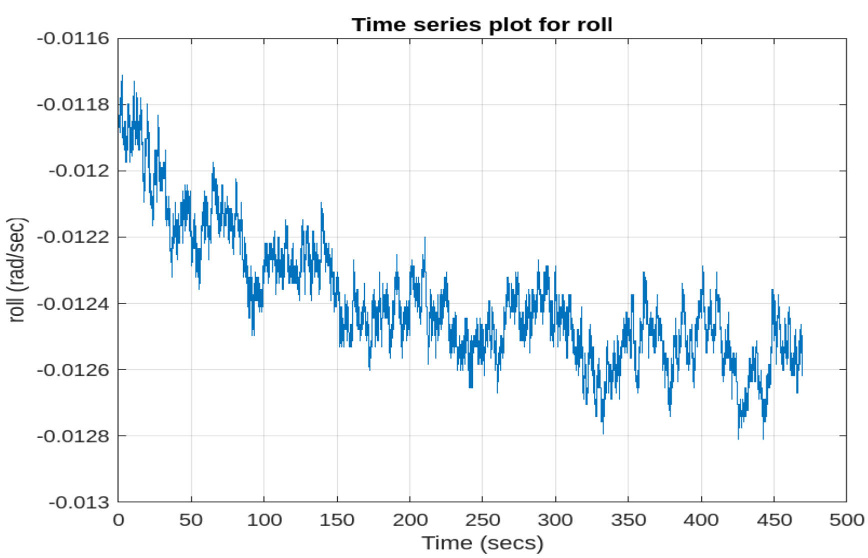


Fig 1.c: Time series plot of Roll data

The Mean and Standard deviation of Roll are as follows: mean_roll = -0.0124 and std_roll = 1.9563e-04

The Frequency distribution plots of Yaw, Pitch and roll are given below.

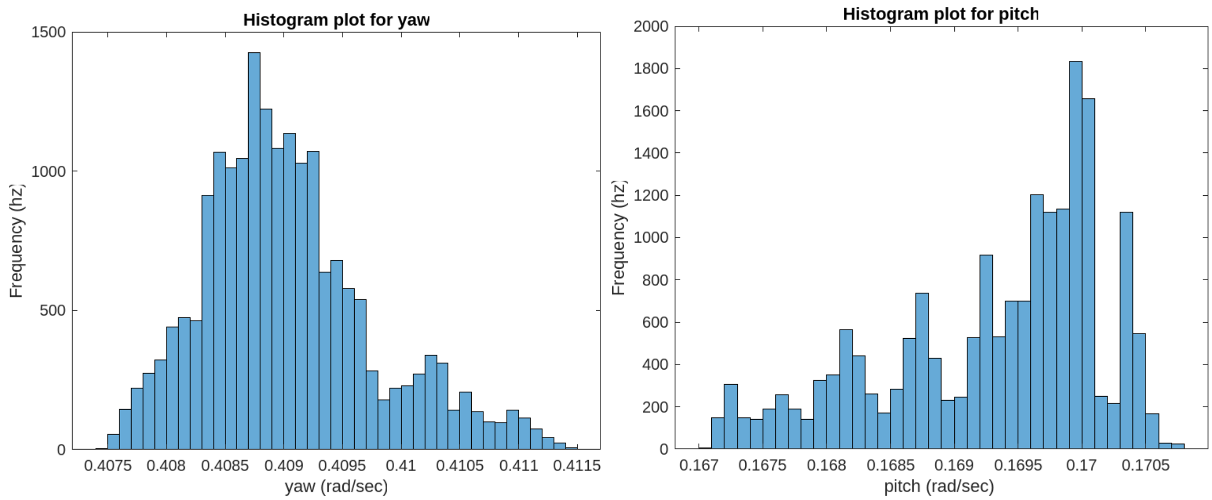


Fig 1.a1 & Fig 1.b2: Histogram plot of yaw and pitch data

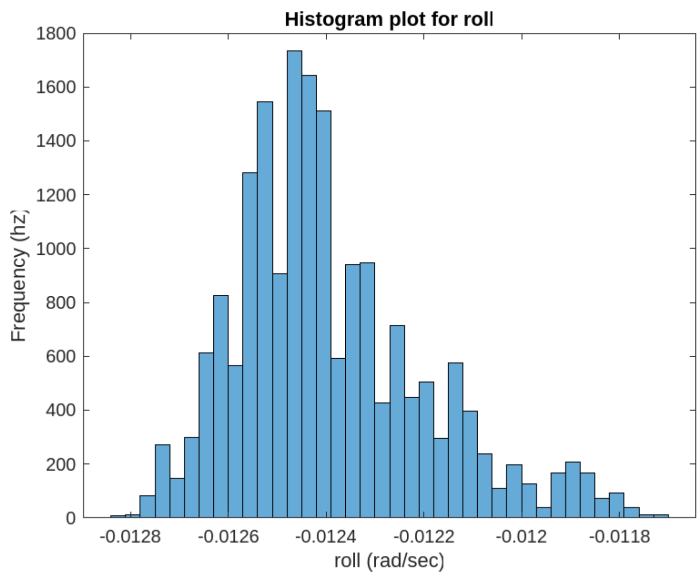


Fig 1.c3: Histogram plot of roll data

From the above figures we can say that the data of Yaw, Pitch and Roll follows almost follows a Gaussian frequency distribution

2. Angular velocity

The Time series plot for x-axis of Angular velocity is illustrated below.

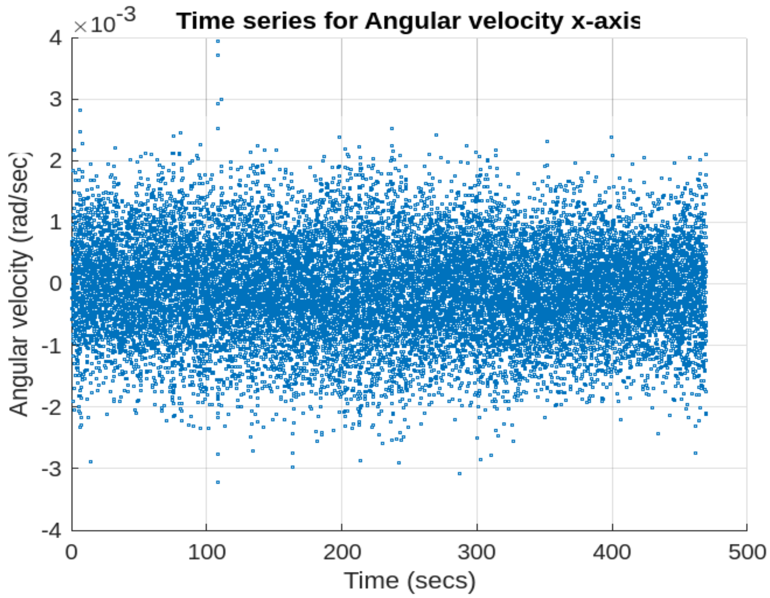


Fig 2.a: Time series plot of x-axis for Angular velocity

The noise characteristics of Angular velocity of x,y and z-axis data.

The Mean and Standard deviation of x-axis of Angular velocity is as follows: mean_ar_x = -9.9457e-05 and std_ar_x = 7.6489e-04

The Time series plot for the y-axis of Angular velocity is illustrated below.

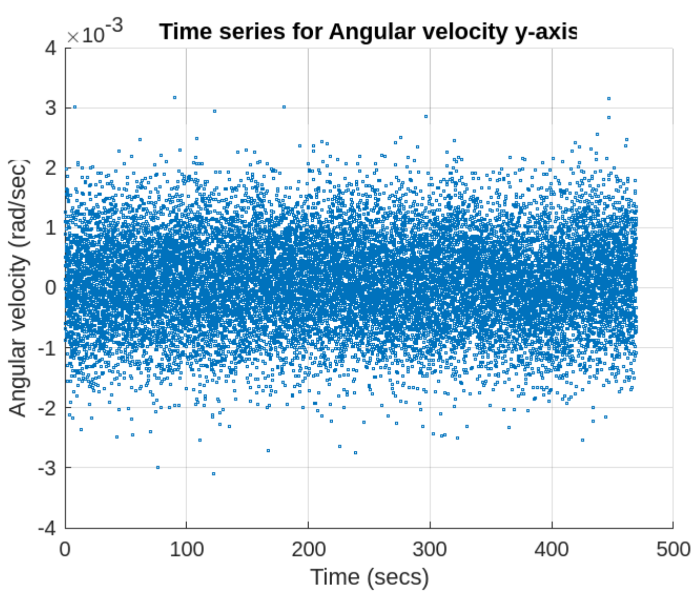


Fig 2.b: Time series plot of y-axis for Angular velocity

The Mean and Standard deviation of y-axis of Angular velocity is as follows: mean_ar_y = 9.0365e-05 and std_ar_y = 7.3154e-04.

The Time series plot for the z-axis of Angular velocity is illustrated below.

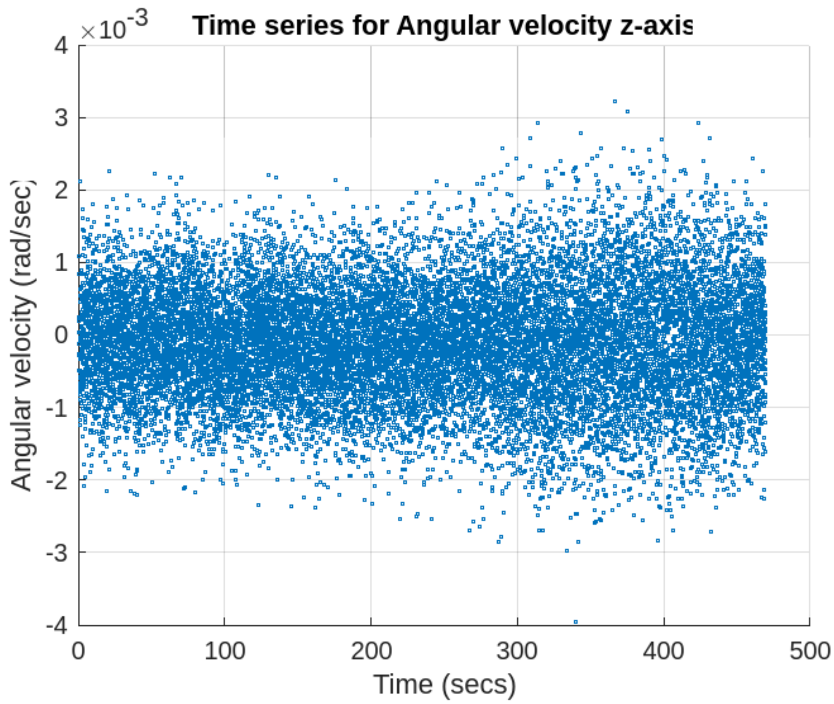
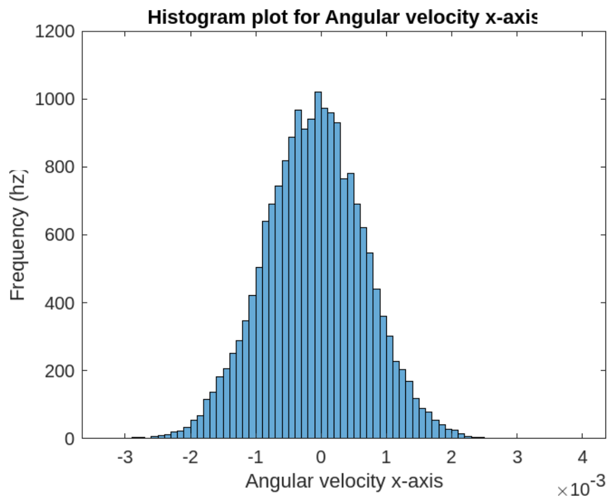


Fig 2.c: Time series plot of z-axis for Angular velocity

The Mean and Standard deviation of z-axis of Angular velocity is as follows:

mean_ar_z = -1.0843e-04 and std_ar_z = 7.8194e-04

The Frequency distribution plots of Angular velocity of x,y and z-axis data are given below.



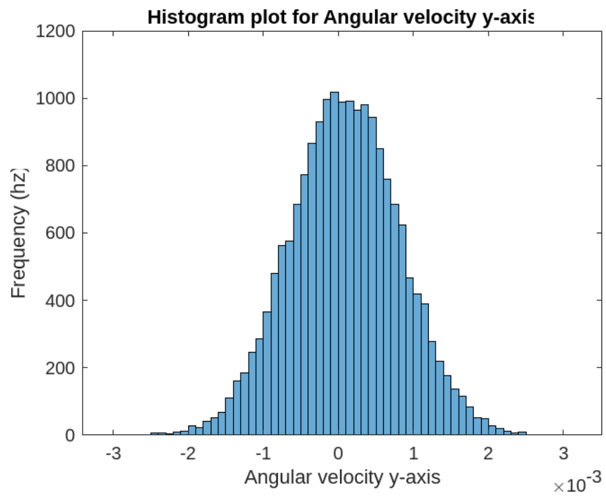


Fig 2.a1 & Fig 2.b1: Histogram plot of Angular velocity x-axis and Angular velocity y-axis data

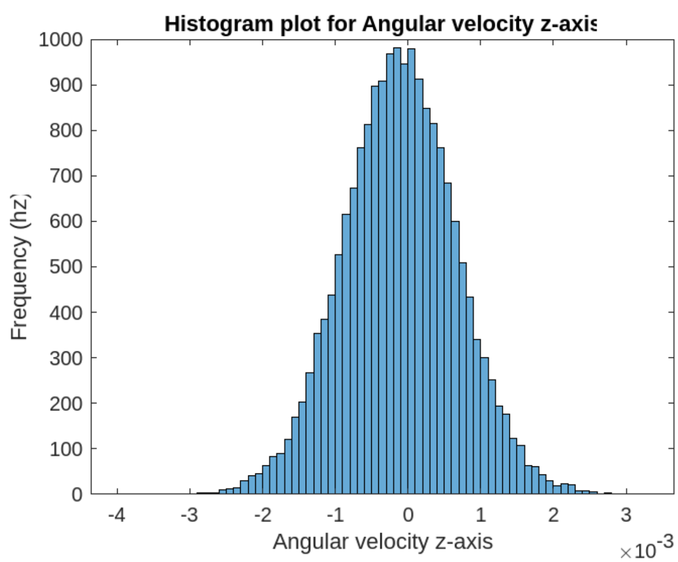


Fig 2.c3: Histogram plot of Angular velocity y-axis data

From the above figures we can say that the data of Angular Velocity x, y and z-axis perfectly follows a Gaussian frequency distribution.

3. Linear acceleration

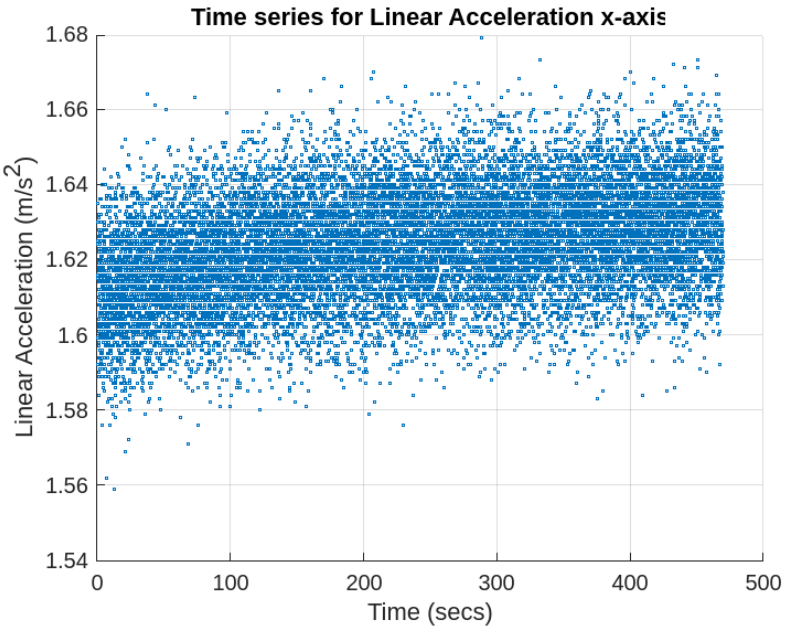


Fig 3.a: Time series plot of x-axis for Linear Acceleration

The noise characteristics of Linear Acceleration of x,y and z-axis data.

The Mean and Standard deviation of x-axis of Linear Acceleration is as follows: mean_la_x = 1.6239 and std_la_x = 0.0140

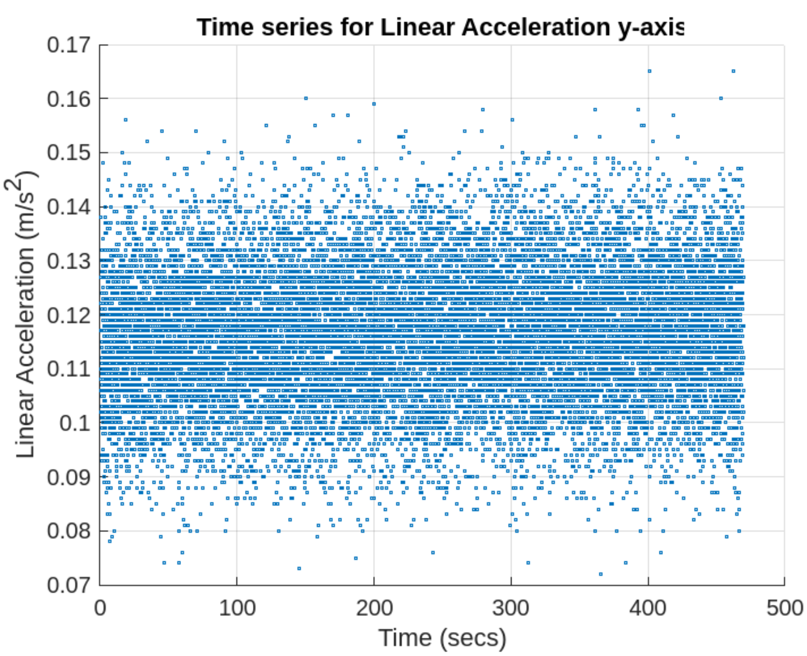


Fig 3.b: Time series plot of y-axis for Linear Acceleration

The Mean and Standard deviation of y-axis of Linear Acceleration is as follows: mean_la_y = 0.1164 and std_la_y = 0.0120

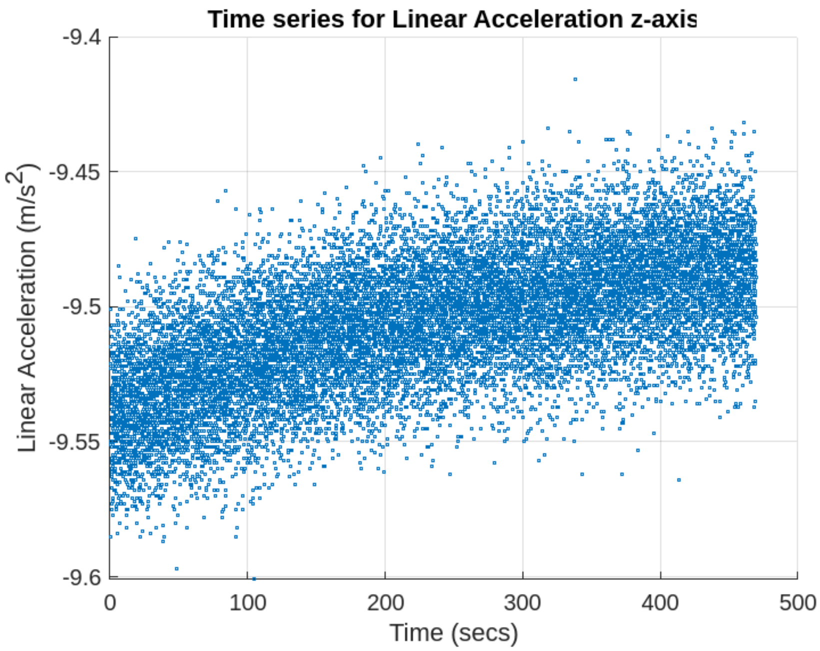


Fig 3.c: Time series plot of z-axis for Linear Acceleration

The Mean and Standard deviation of z-axis of Linear Acceleration is as follows:

mean_la_z = -9.5061 and std_la_z = 0.0238

The Frequency distribution plots of Linear acceleration of x,y and z-axis data are given below.

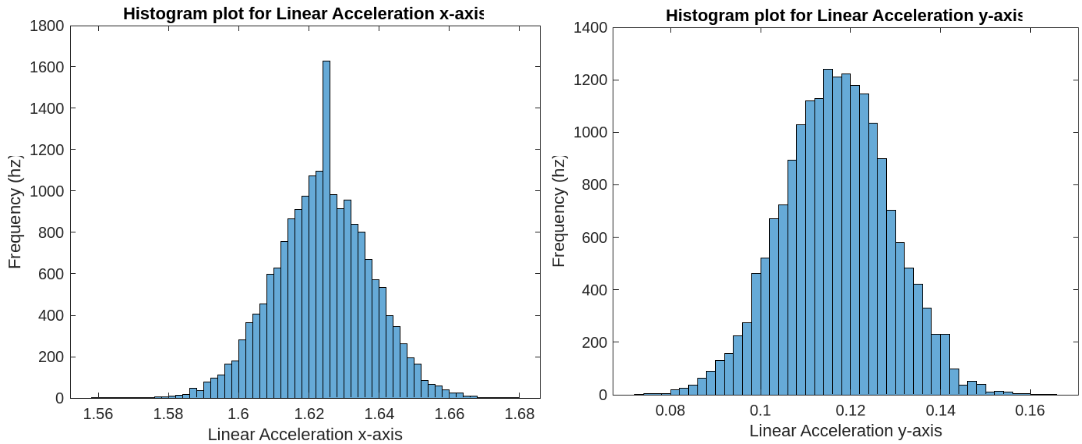


Fig 2.a1 & Fig 2.b1: Histogram plot of Linear Acceleration x-axis and Linear Acceleration y-axis data

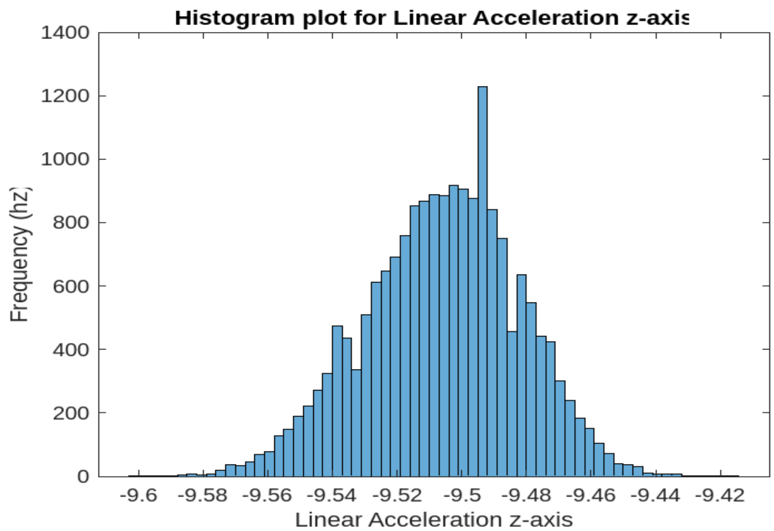


Fig 2.c3: Histogram plot of Linear Acceleration y-axis data

From the above figures we can say that the data of Linear Acceleration x, y and z-axis perfectly follows a Gaussian frequency distribution except one value in x and z-axis.

4. Magnetic field

The time series plots for the x, y and z axis of the Magnetic Field are shown below.

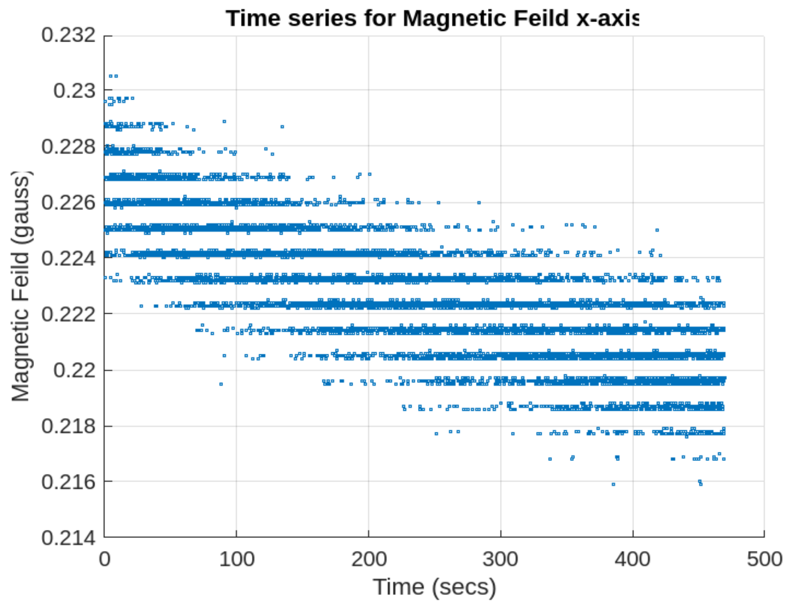


Fig 4.a: Time series plot of x-axis for Magnetic Field

The noise characteristics of Magnetic Field of x,y and z-axis data.

The Mean and Standard deviation of x-axis of Magnetic Field are as follows: mean_mf_x = 0.2227 and std_mf_x = 0.0022

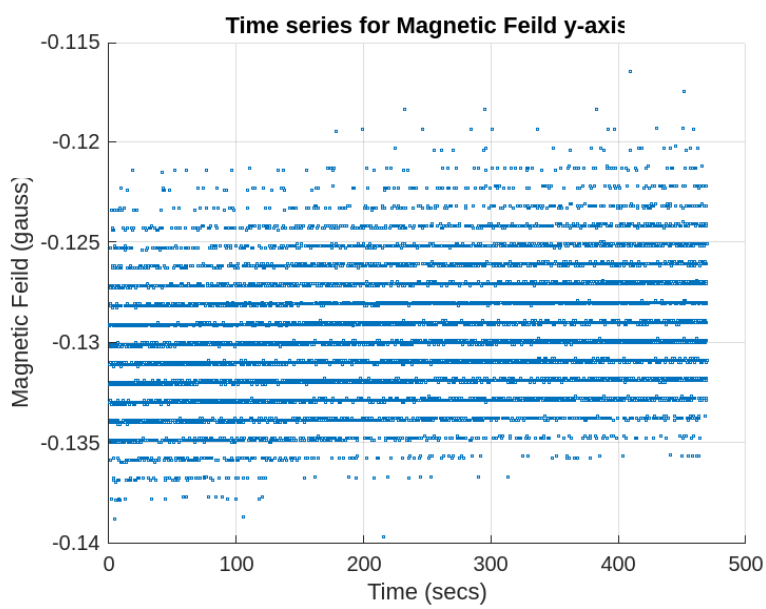


Fig 4.b: Time series plot of y-axis for Magnetic Field

The Mean and Standard deviation of y-axis of Magnetic Field are as follows: mean_mf_y = -0.1299 and std_mf_y = 0.0029

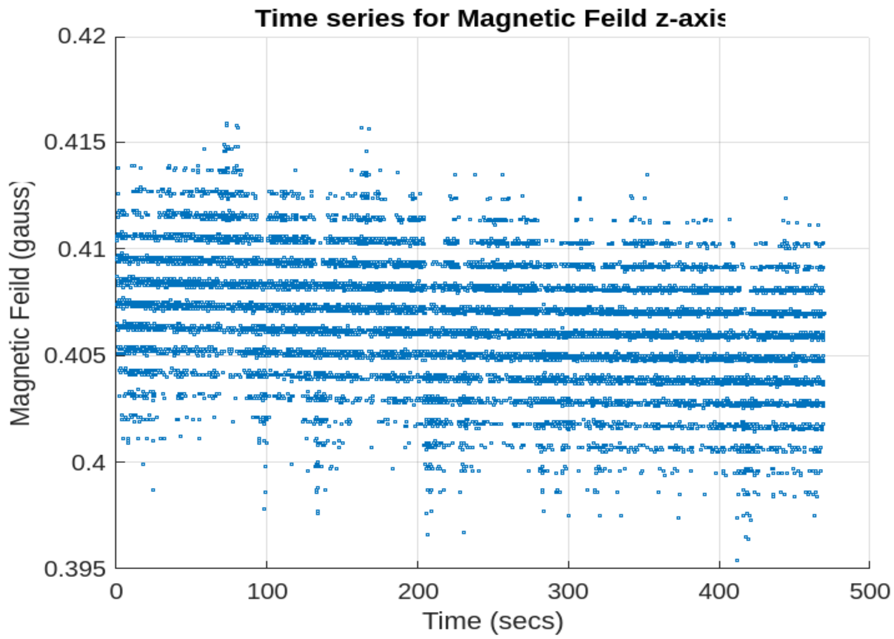


Fig 4.c: Time series plot of z-axis for Magnetic Field

The Mean and Standard deviation of z-axis of Magnetic Field are as follows: mean_mf_z = 0.4065 and std_mf_z = 0.0027

The Frequency distribution plots for the Magnetic field of x,y and z-axis data are given below.

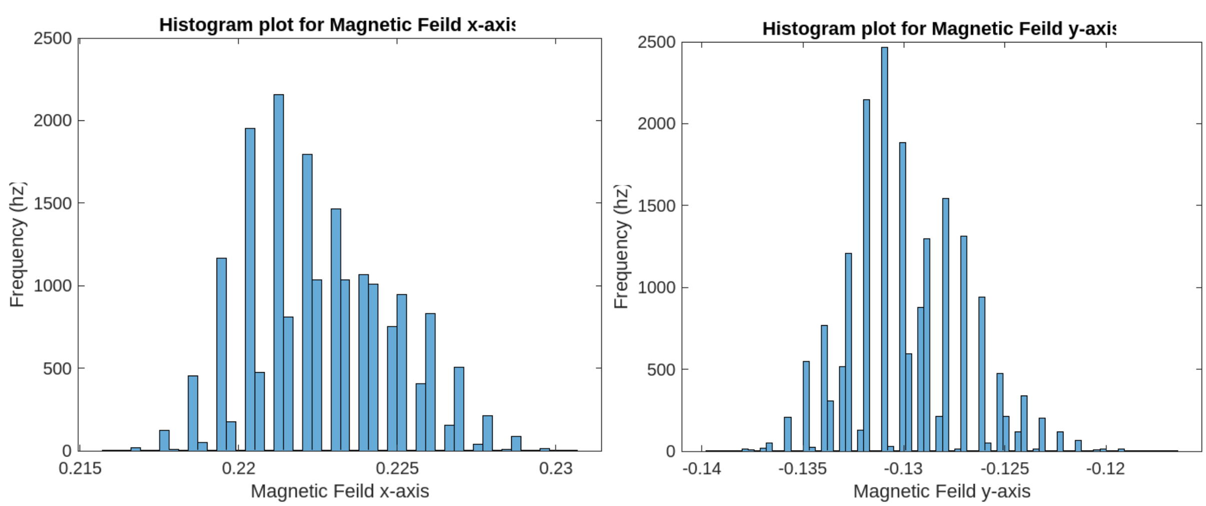


Fig 2.a1 & Fig 2.b1: Histogram plot of Magnetic field x-axis and Magnetic field y-axis data

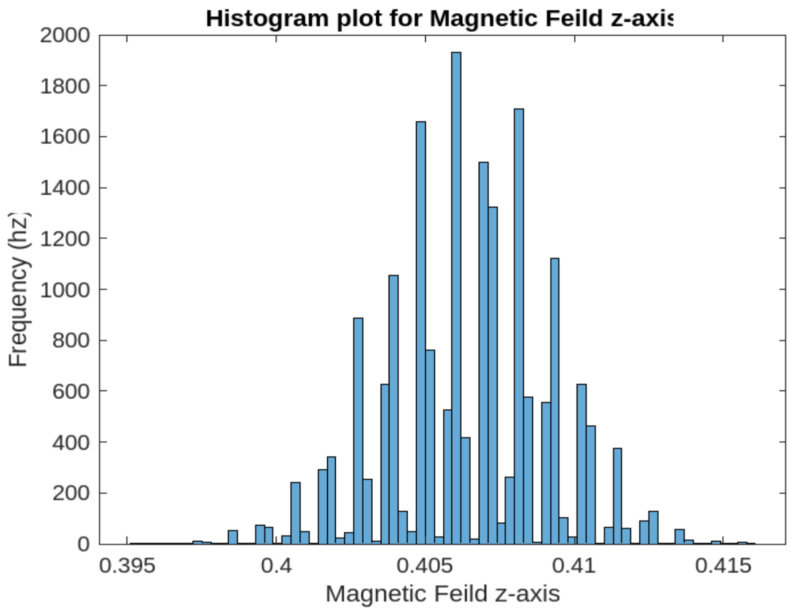


Fig 2.c3: Histogram plot of Magnetic field y-axis data

From the above figures we can say that the data of the Magnetic Field of x, y and z-axis almost follows a Gaussian frequency distribution except few slight variations at some points.

The errors and sources of noise that can be present in IMU data are as follows:

1. Bias Instability

The in-run bias stability, or often called the bias instability, is a measure of how the bias will drift during operation over time at a constant temperature. This parameter also represents the best possible accuracy with which a sensor's bias can be estimated. Due to this, in-run bias stability is generally the most critical specification as it gives a floor to how accurately a bias can be measured.

2. Random Walk

If a noisy output signal from a sensor is integrated, for example integrating an angular rate signal to determine an angle, the integration will drift over time due to the noise. This drift is called random walk, as it will appear that the integration is taking random steps from one sample to the next. The two main types of random walk for inertial sensors are referred to as angle random walk (ARW), which is applicable to gyroscopes, and velocity random walk (VRW), which is applicable to accelerometers. By multiplying the random walk by the square root of time, the standard deviation of the drift due to noise can be recovered.

3. Scale factor error

The scale factor will not be perfectly calibrated and will have some error in the estimated ratio. This error is categorized as one of two equivalent values, either as a parts per million error (ppm), or as an error percentage. The scale factor error causes the output reported to be different from the true output. For example, if the z-axis of an accelerometer only measures gravity (9.81 m/s^2), then the bias-corrected sensor output should be 9.81 m/s^2.

4. Scale factor nonlinearity

The scale factor can also have errors associated with the ratio being non-linear, known as nonlinearity errors. The linearity error of the scale factor is also described as either a parts per million error (ppm), or as a percentage of the full scale range of the sensor.

5. Orthogonally errors

When mounting and aligning sensors to an IMU, it is impossible to mount them perfectly orthogonal to each other. As a result, orthogonality errors are caused by a sensor axis responding to an input that should be orthogonal to the sensing direction. The two main types of orthogonality errors are cross-axis sensitivity and misalignment, both of which are often used interchangeably.

6. Cross-axis sensitivity

Cross-axis sensitivity is an orthogonality error caused by a sensor axis being sensitive to an input on a different axis.

7. Misalignment

It is an orthogonality error resulting from a rigid-body rotation that offsets all axes relative to the expected input axes, while maintaining strict orthogonality between the sensing axes.

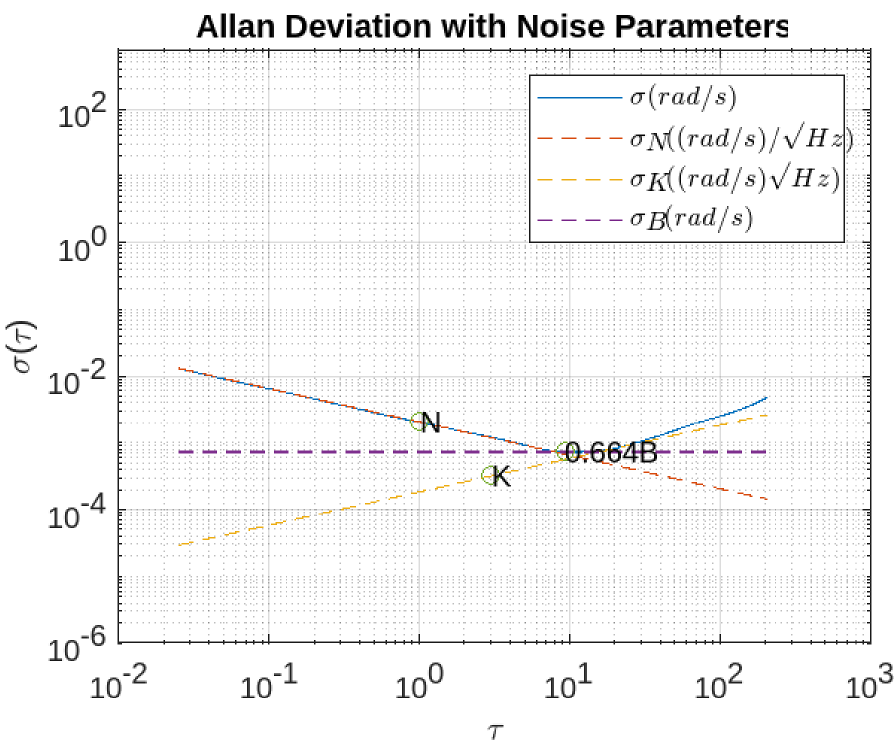
8. Acceleration sensitivity for gyroscopes

Gyroscopes are susceptible to linear accelerations due to their asymmetrical design and manufacturing tolerances.

Allan Variance analysis

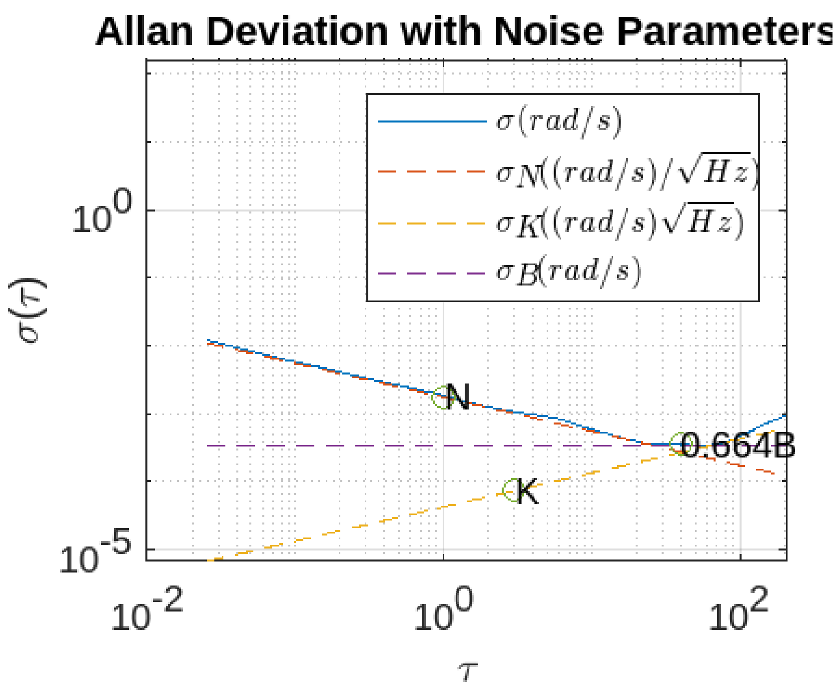
For the Allan Variance analysis, the stationary IMU data was collected for five hours at a location that is not subject to any kind of vibrations. Allan deviation is performed for all three axes of Linear Acceleration data with Noise parameters.

Allan deviation for Linear Acceleration:

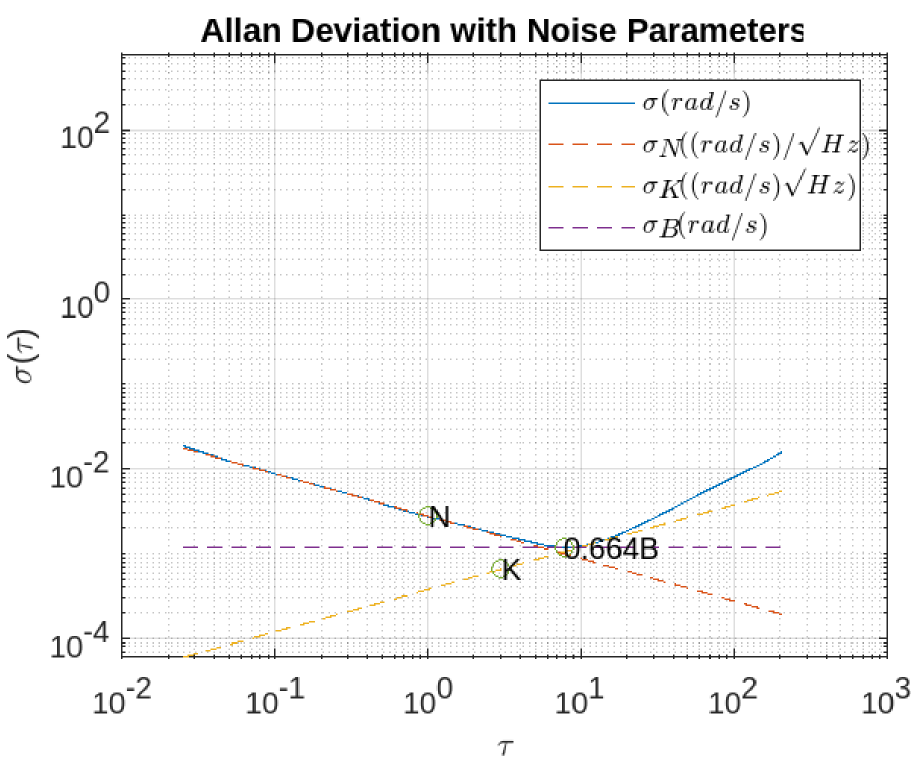


The noise parameter values of Linear Acceleration x-axis are:

N (angle random walk) = 0.0021, *K* (rate random walk) = 3.1925e-04 and *B* (bias instability) = 0.0011



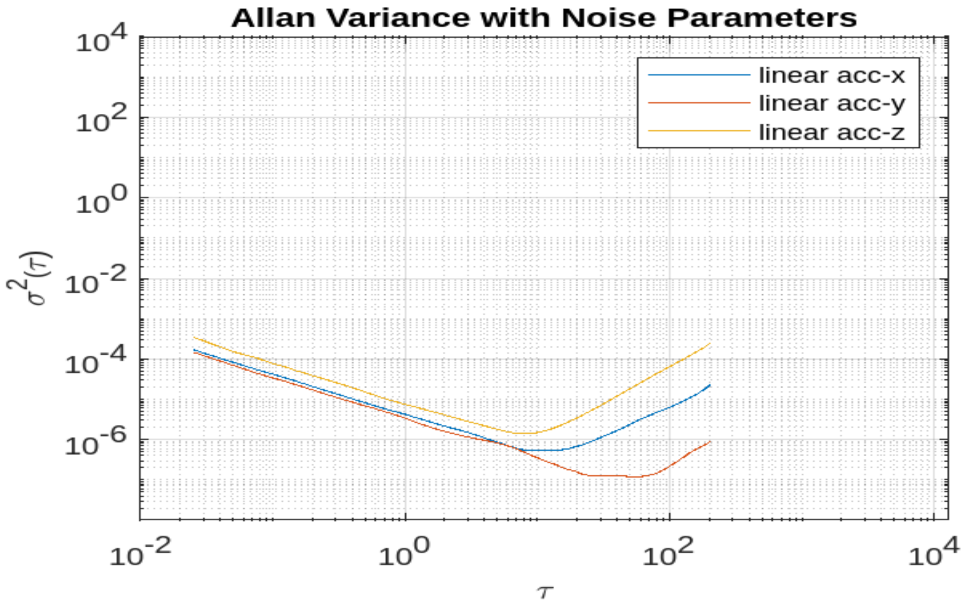
The noise parameter values of Linear Acceleration y-axis are: *N* (angle random walk) = 0.0017, *K* (rate random walk) = 7.3851e-05 and *B* (bias instability) = 5.2834e-04



The noise parameter values of Linear Acceleration z-axis are:

N (angle random walk) = 0.0028, *K* (rate random walk) = 6.5580e-04 and *B* (bias instability) = 0.0018

Allan Variance for Linear Acceleration:



The Allan Variance *for Linear Acceleration have the following noise parameters:*

Linear acceleration in x-axis: N (angle random walk) = 0.0021, *K* (rate random walk) = 3.1925e-04 and *B* (bias instability) = 0.0011

Linear acceleration in y-axis: N (angle random walk) = 0. 0017, *K* (rate random walk) = 7.3851e-05 and *B* (bias instability) = 5.2834e-04

Linear acceleration in z-axis: N (angle random walk) = 0. 0028, *K* (rate random walk) = 6.5580e-04 and *B* (bias instability) = 0.0018

Modeling the errors using Allan Variance

Noise parameters of a MEMS gyroscope. These parameters can be used to model the gyroscope in simulation.

The gyroscope measurement is modeled as:

$$\Omega(t) = \Omega_{Ideal}(t) + Bias_N(t) + Bias_B(t) + Bias_K(t)$$

The three noise parameters are *N* (angle random walk), *K* (rate random walk), and *B* (bias instability)

Angle Random Walk:
The angle random walk is characterized by the white noise spectrum of the gyroscope output. The PSD is represented by:

$$S_\Omega(f) = N^2$$

where

N = angle random walk coefficient

Substituting into the original PSD equation and performing integration yields:

$$\sigma^2(\tau) = \frac{N^2}{\tau}$$

The above equation is a line with a slope of -1/2 when plotted on a log-log plot of $\sigma(\tau)$ versus τ. The value of *N* can be read directly off of this line at $\tau = 1$. The units of *N* are $(rad/s)/\sqrt{Hz}$.

Rate Random Walk:
The rate random walk is characterized by the red noise (Brownian noise) spectrum of the gyroscope output. The PSD is represented by:

$$S_\Omega(f) = (\frac{K}{2\pi})^2 \frac{1}{f^2}$$

where

K = rate random walk coefficient

Substituting into the original PSD equation and performing integration yields:

$$\sigma^2(\tau) = \frac{K^2 \tau}{3}$$

The above equation is a line with a slope of 1/2 when plotted on a log-log plot of $\sigma(\tau)$ versus τ. The value of *K* can be read directly off of this line at $\tau = 3$. The units of *K* are $(rad/s)\sqrt{Hz}$.

Bias Instability:

The bias instability is characterized by the pink noise (flicker noise) spectrum of the gyroscope output. The PSD is represented by:

$$S_\Omega(f) = \begin{cases} (\frac{B^2}{2\pi})\frac{1}{f} & : f \le f_0 \\ 0 & : f > f_0 \end{cases}$$

where

B = bias instability coefficient

f_0= cut-off frequency

Substituting into the original PSD equation and performing integration yields:

$$\sigma^2(\tau) = \frac{2B^2}{\pi}[\ln 2 + -\frac{sin^3 x}{2x^2}(sinx + 4xcosx) + Ci(2x) - Ci(4x)]$$

where

$x = \pi f_0 \tau$

Ci = cosine-integral function

When τ is much longer than the inverse of the cutoff frequency, the PSD equation is:

$$\sigma^2(\tau) = \frac{2B^2}{\pi}\ln 2$$

The above equation is a line with a slope of 0 when plotted on a log-log plot of $\sigma(\tau)$ versus τ. The value of B can be read directly off of this line with a scaling of $\sqrt{\frac{2\ln 2}{\pi}} \approx 0.664$. The units of B are rad/s.

The measurements are compared with the performance listed in the VN100 datasheet. Considering the Bias Instability and Angle random walk values of Linear Acceleration in IMU data to compare the same with the datasheet values.

	Data Sheet values	Measured values	Data Sheet values	Measured values
	Bias instability (B) (mg)		Angle Random Walk (N) (mg/sqrt(hz))	
Linear Acceleration, x-axis	< 0.04	0.0016	0.0014	0.0021
Linear Acceleration, y-axis	< 0.04	0.0004	0.0014	0.0017
Linear Acceleration, z-axis	< 0.04	0.0027	0.0014	0.0028

Fig : Comparison of Bias Instability and Angle random walk between measured values and datasheet values.

Conclusion:

The measured Bias Instability values according to the datasheet values whereas the Angle random walk values slightly high. Even after collecting the data for three to four times the values of Angle random walk are high compared to the data sheet.