Study of Inertial Measurement Unit Sensor and its noise characteristics

1. INTRODUCTION

This report deals with the study of the Inertial Measurement Unit (IMU) sensor and the noise characteristics of IMU. The study is about the working of IMU and the analysis of its data, while the IMU is stationary, to identify the various types of noise present in it.

2. BACKGROUND

An Inertial Measurement Unit or IMU is defined as a 9-axis sensor that consists of a 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer (IMU can also consists of only accelerometer and gyroscope). An accelerometer measures the external forces acting on the sensor which consists of both the sensor's acceleration and the earth's gravity. A gyroscope measures the sensor's angular velocity which is the rate of change of its orientation. A magnetometer measures the magnetic field surrounding the sensor. With the fusion of these sensors, IMU can detect the current rate of acceleration and angular rate which can be integrated to provide position and orientation angles i.e., Yaw, Pitch and Roll [1]. Though these estimates are accurate on a short time scale but suffers from drifts due to integration over long time because of the presence of biases in the sensor. In order to overcome these drifts, inertial sensors are combined with additional sensors and models.

3. SETUP AND TEST

To understand the IMU data and its static performance for a short and long duration of time, two trials were conducted. To conduct the trial, IMU sensor was connected to the computer through serial port and sampling frequency was set to 40 Hz. The sensor was kept flat on the surface such that the Z axis of sensor is up, and the acceleration of gravity is downwards [2]. The data was logged for the two trials using ROS and analysis was done using MATLAB. The following data was collected from the IMU sensor:

- Orientation angles i.e., Yaw, Pitch and Roll in degrees
- Magnetic field values in X, Y and Z axis in gauss
- Linear Acceleration in X, Y and Z axis in m/s^2
- Angular Velocity about X, Y and Z axis in rad/s

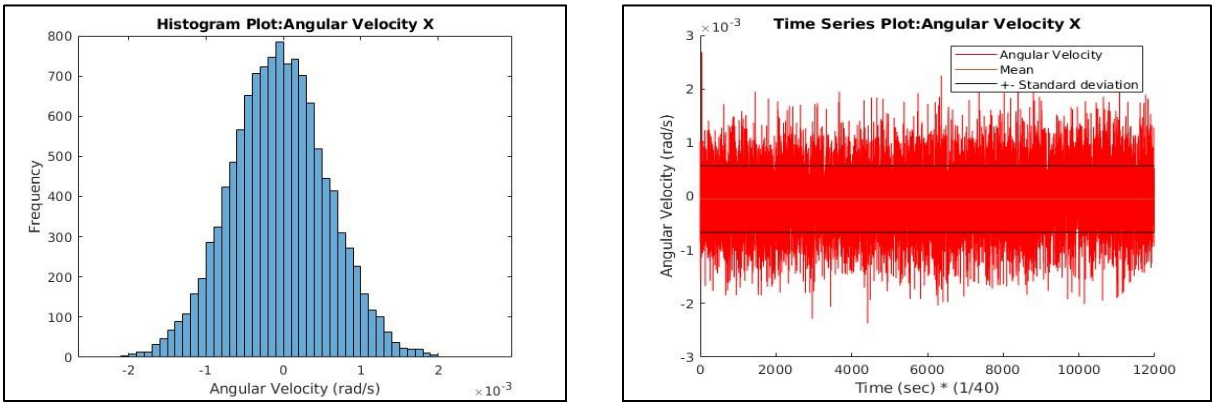
In the 1st test, the data was taken for 5 minutes to study the static performance of IMU for a short time. In the 2^{nd} test, the data was taken for 5 hours to study the change in static response over time. After collecting the data, analysis was done by plotting histogram, time series and Allan variance chart to study about the noises present in the data.

4. ANALYSIS AND RESULT

4.1. Analysis of data for short time interval (5 min)

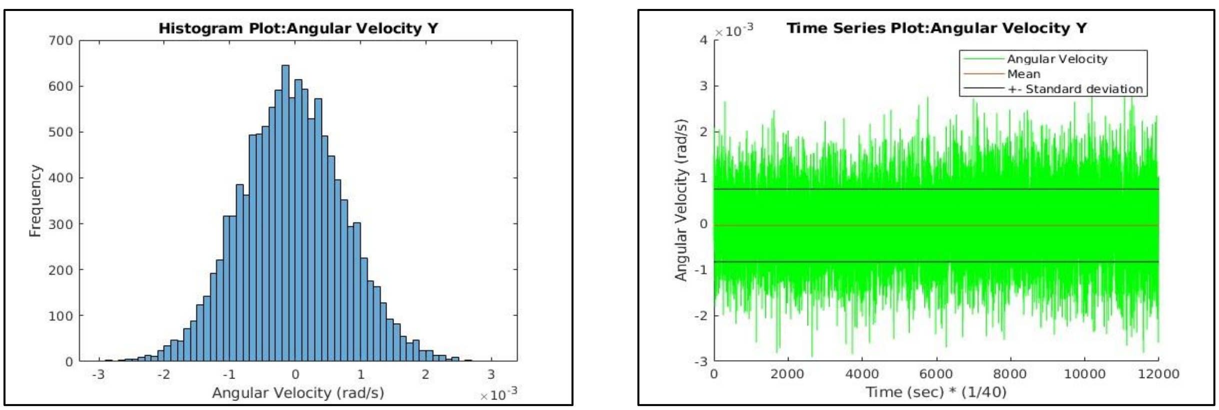
Below are the Histogram and Time series plots for different sensor outputs:

Gyroscope: Angular Rate, Yaw, Pitch and Roll



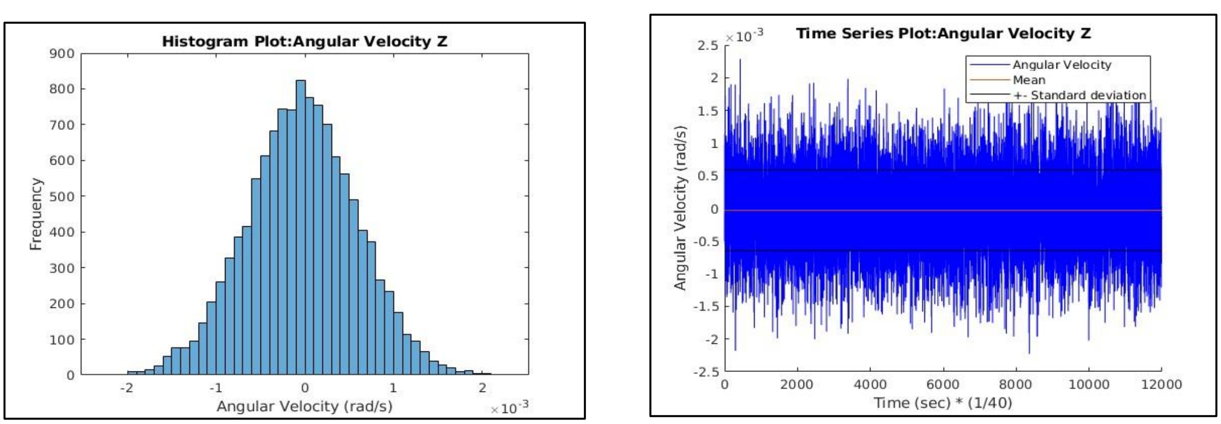
(a) (b)

Fig. 1. Plot for Angular Velocity about X (a) Histogram Plot (b) Time Series Plot



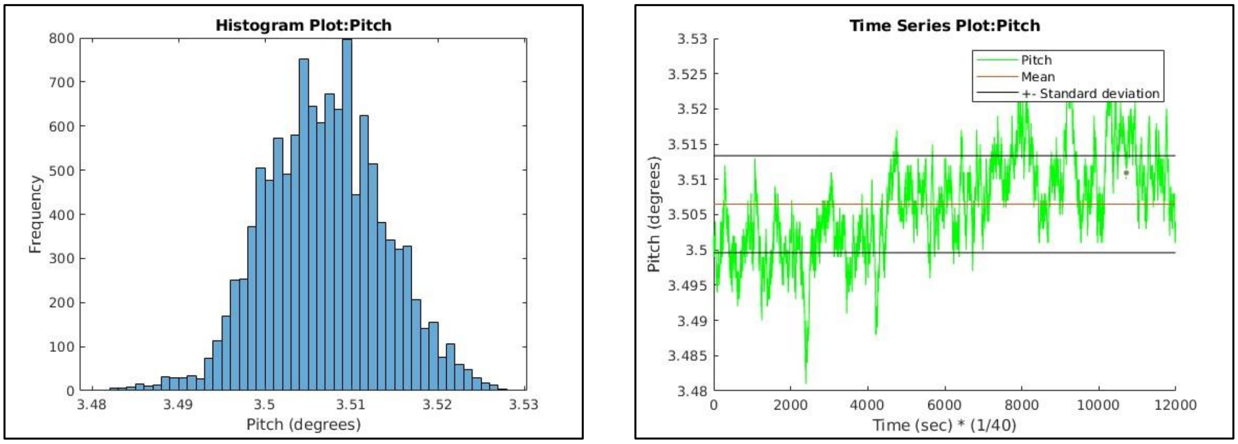
(a) (b)

Fig. 2. Plot for Angular Velocity about Y (a) Histogram Plot (b) Time Series Plot



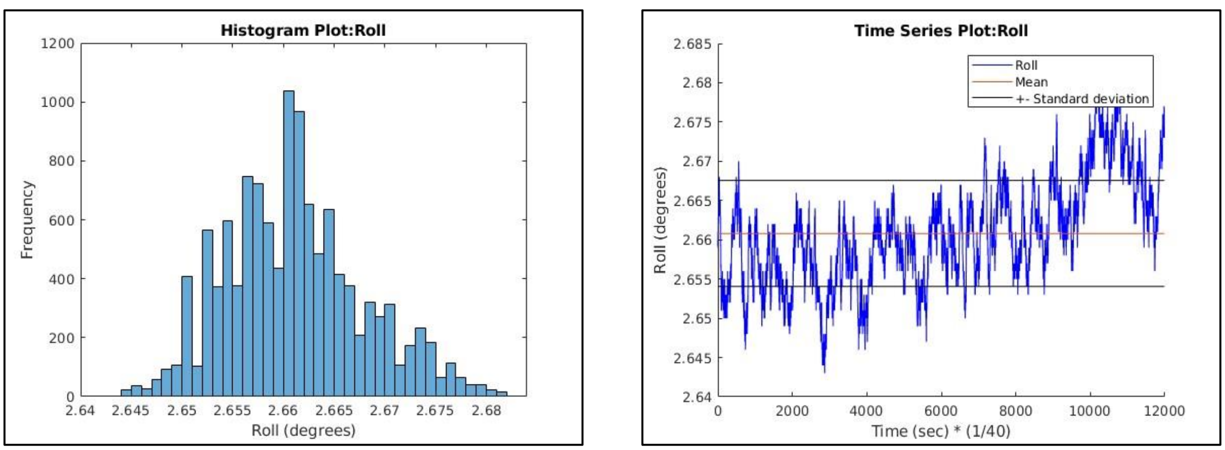
(a) (b)

Fig. 3. Plot for Angular Velocity about Z (a) Histogram Plot (b) Time Series Plot



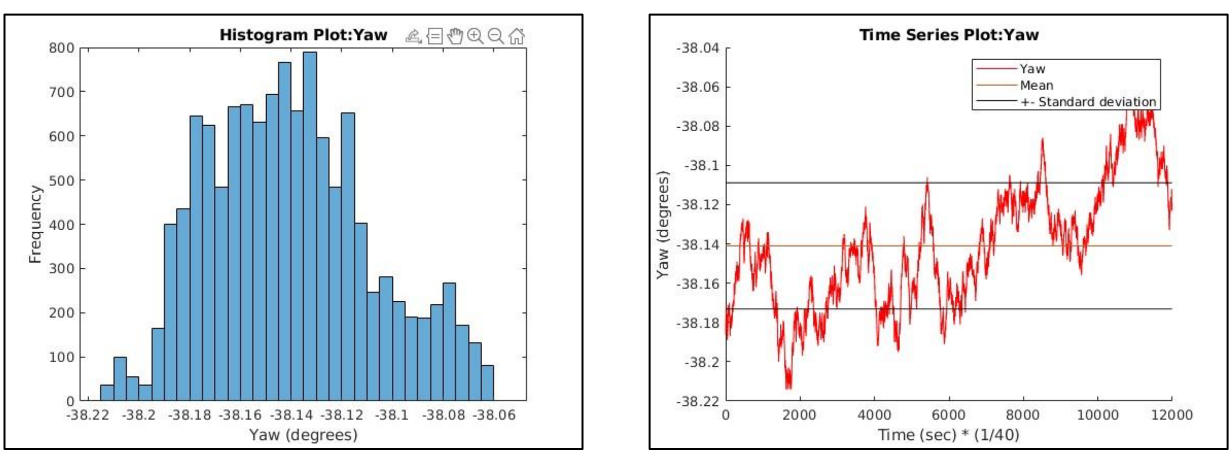
(a) (b)

Fig. 4. Plot for Pitch (a) Histogram Plot (b) Time Series Plot



(a) (b)

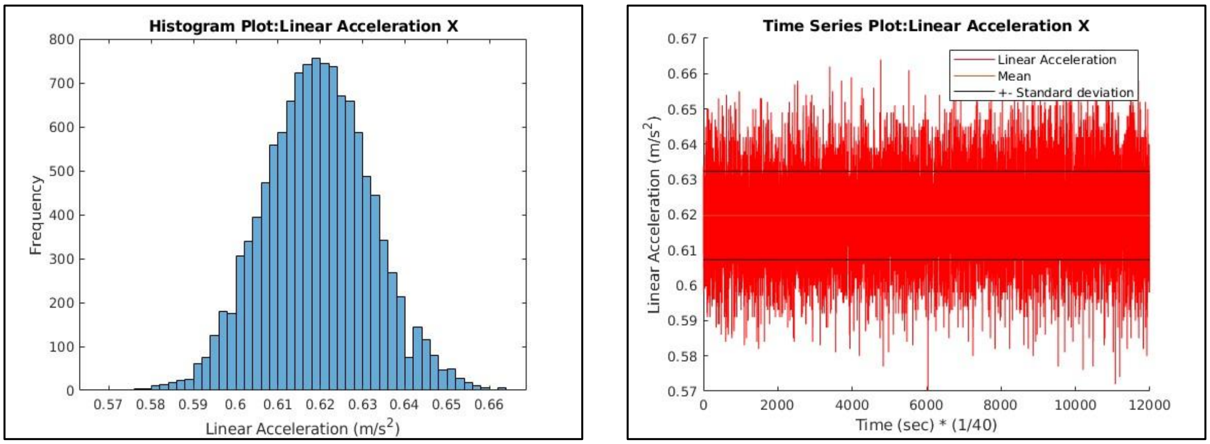
Fig. 5. Plot for Roll (a) Histogram Plot (b) Time Series Plot



(a) (b)

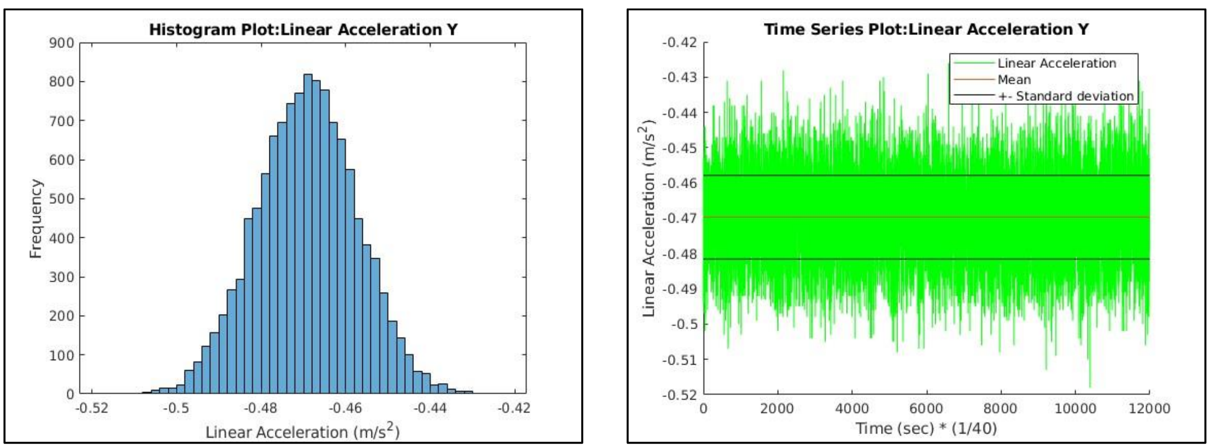
Fig. 6. Plot for Yaw (a) Histogram Plot (b) Time Series Plot

Accelerometer: Linear Acceleration



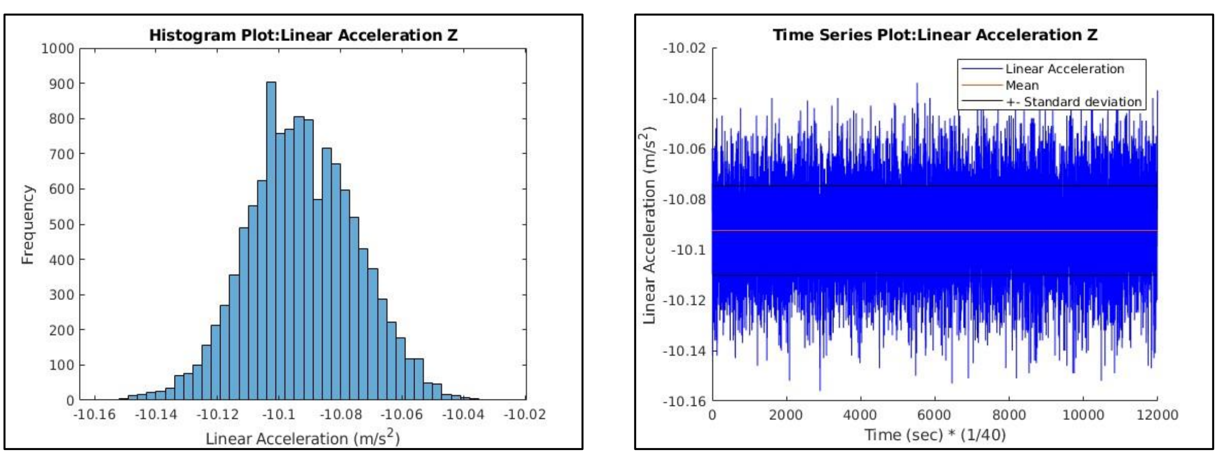
(a) (b)

Fig. 7. Plot for Linear Acceleration in X (a) Histogram Plot (b) Time Series Plot



(a) (b)

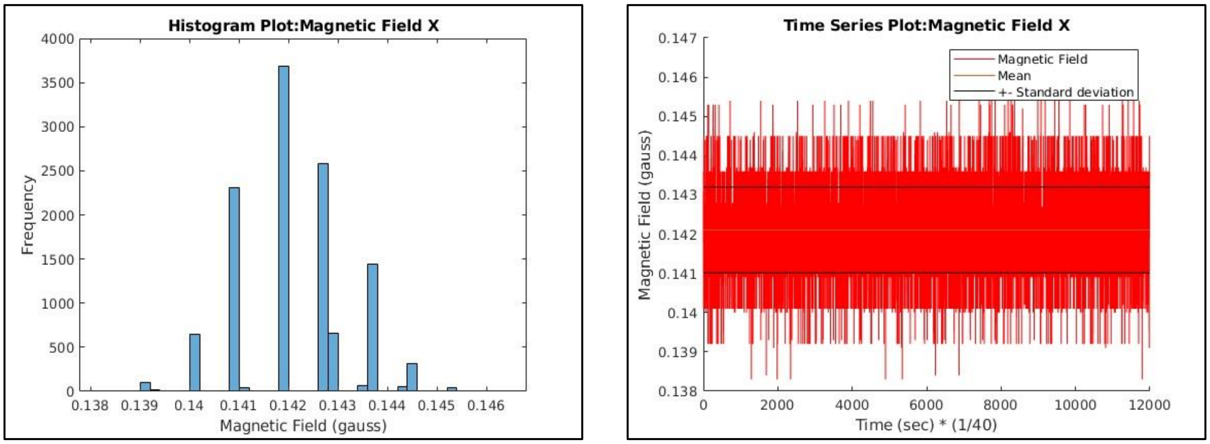
Fig. 8. Plot for Linear Acceleration in Y (a) Histogram Plot (b) Time Series Plot



(a) (b)

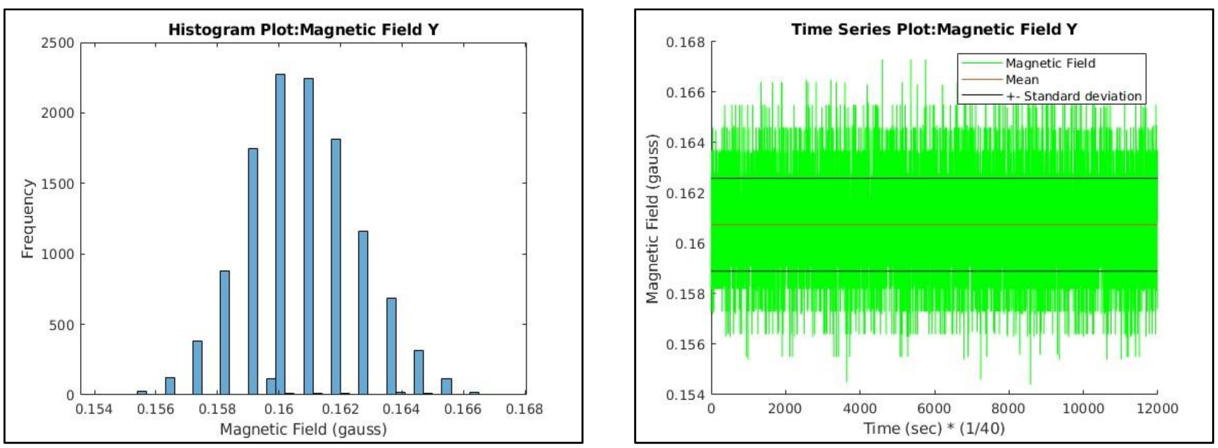
Fig. 9. Plot for Linear Acceleration in Z (a) Histogram Plot (b) Time Series Plot

Magnetometer: Magnetic Field



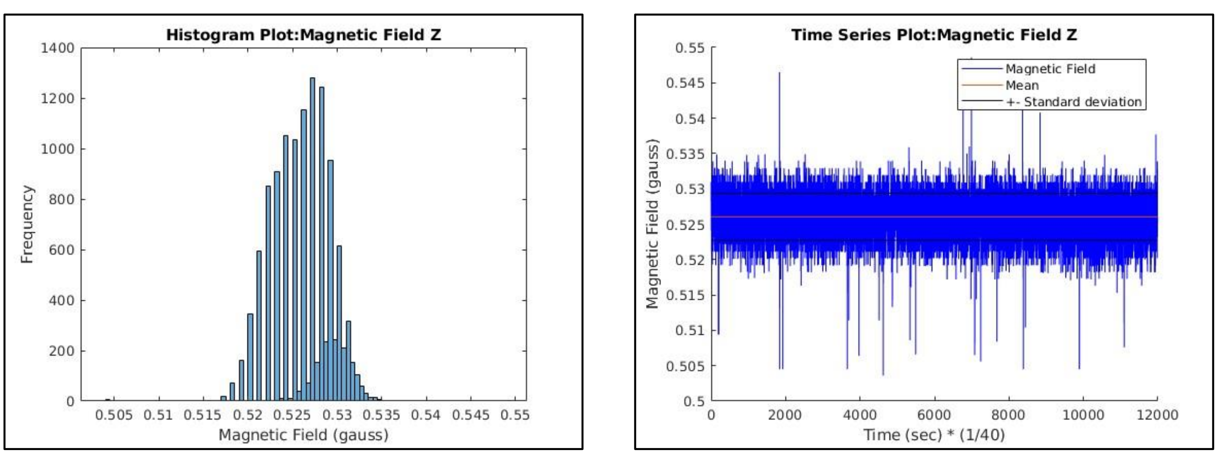
(a) (b)

Fig. 10. Plot for Magnetic in X (a) Histogram Plot (b) Time Series Plot



(a) (b)

Fig. 11. Plot for Magnetic Field in Y (a) Histogram Plot (b) Time Series Plot



(a) (b)

Fig. 12. Plot for Magnetic Field in Z (a) Histogram Plot (b) Time Series Plot

The test was done in static condition and in this condition the output of the sensor should be constant over the entire time interval. Any change in output during static test indicates the error in the sensor which is due to presence of measurement noise and slowly time-varying sensor bias.

Observations:

From the histogram plots, it is clear that the IMU data follows a gaussian distribution which confirms the presence of Gaussian error. The time series plots also supports this result as data is distributed about mean and almost 70% lies within +/- Standard deviation and it shows the data is gaussian distributed.

For Angular Velocity, the mean is close to 0 (Table 1) and the these is no visual correlation in data confirms the presence of white noise in the sensor.

For Orientation, the mean shows the orientation of the sensor at the time of data collection.

For Linear Acceleration, the mean of Z shows the value of acceleration due to gravity and is acting in negative Z direction. Small deviation from the 0 mean shows the presence of bias in the sensor.

For Magnetic Field, the magnetic strength in Boston has high inclination and thus have high vertical component (0.5 gauss) and less horizontal component (0.2 gauss). The IMU output for magnetic strength in Z is comparable with the actual magnetic field showing high strength in Z as compared to X and Y. Also, the histogram plot of Z axis shows the presence of another magnetic field which can be due to presence of laptop, phones and chargers.

Hence, the plots confirm the presence of Gaussian White Noise and bias in the sensor.

Table 1. Mean and Standard deviation for each output of IMU

Parameter	**Direction**	**Mean**	**Standard Deviation**
Angular Velocity (rad/s)	X	-0.00005284	0.0006219
	Y	-0.00004427	0.0007906
	Z	-0.00003051	0.0006189
Euler Angles (degrees)	Yaw	-38.1410	0.0321
	Pitch	3.5065	0.0069
	Roll	2.6608	0.0068
Linear Acceleration (m/s^2)	X	0.6198	0.0125
	Y	-0.4697	0.0119
	Z	-10.0925	0.0177
Magnetic Field (gauss)	X	0.1421	0.0011
	Y	0.1607	0.0018
	Z	0.5261	0.0033

4.2. Analysis of data for long time interval (5 hrs.)

For analyzing the data over a longer period of time and characterizing the noises, Allan variance is used. Allan Variance is used to identify and quantify the different noises that are present in the sensor. The results from this method gives five types of noise which are quantization noise, angle(velocity) random walk, bias instability, rate random walk and rate ramp. But we will be focusing on the angle random walk, bias instability and rate random walk in our plots.

Allan Variance

It is an analysis of a signal in time domain, consists of computing its Allan deviation as a function of different averaging times tau and then analyzing the characteristics region in a log-log plot of Allan deviation with tau and finding the slopes of curve in these regions to identify the different noise in the sensor [3].

Below are the plots of Allan deviation for Linear Acceleration of Accelerometer and Angular Velocity of Gyroscope:

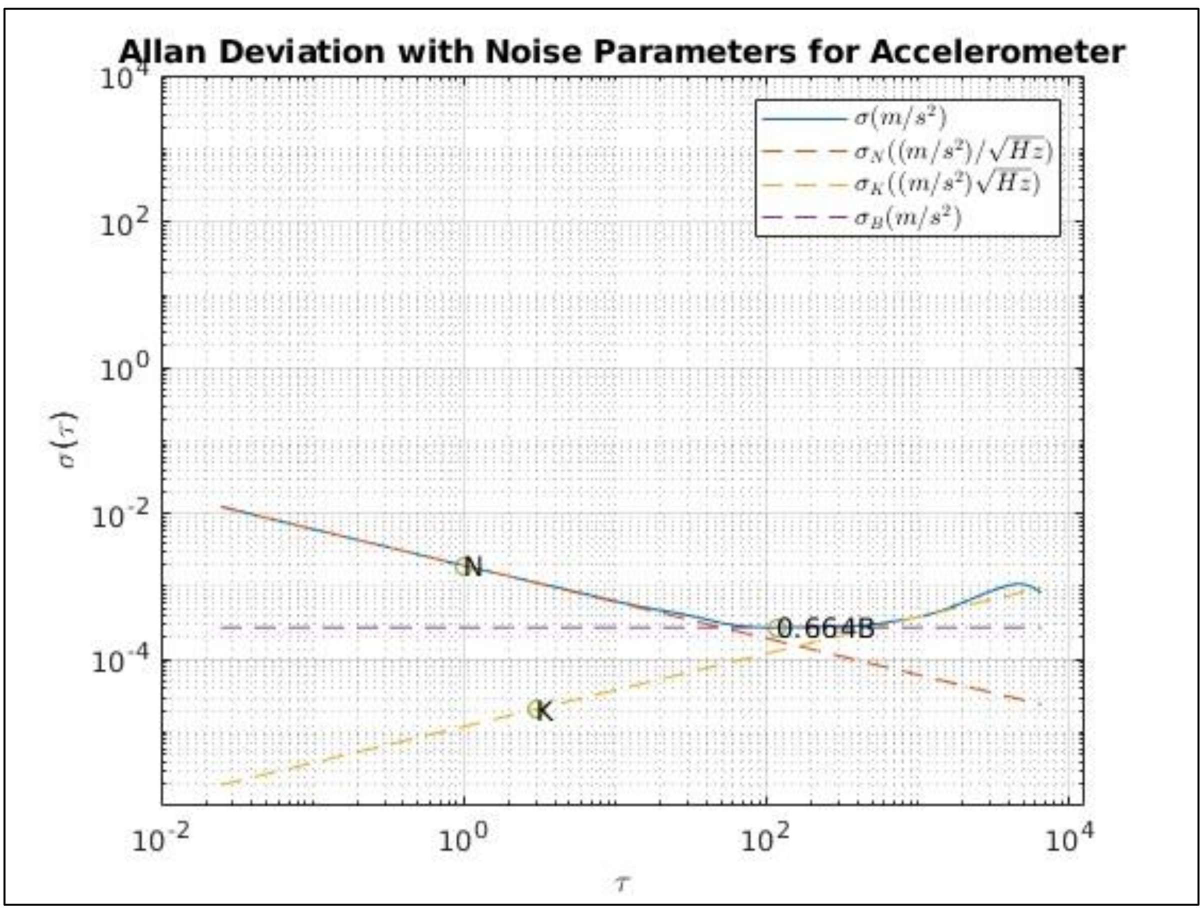


Fig. 13. Allan Deviation plot with Noise parameters for Accelerometer

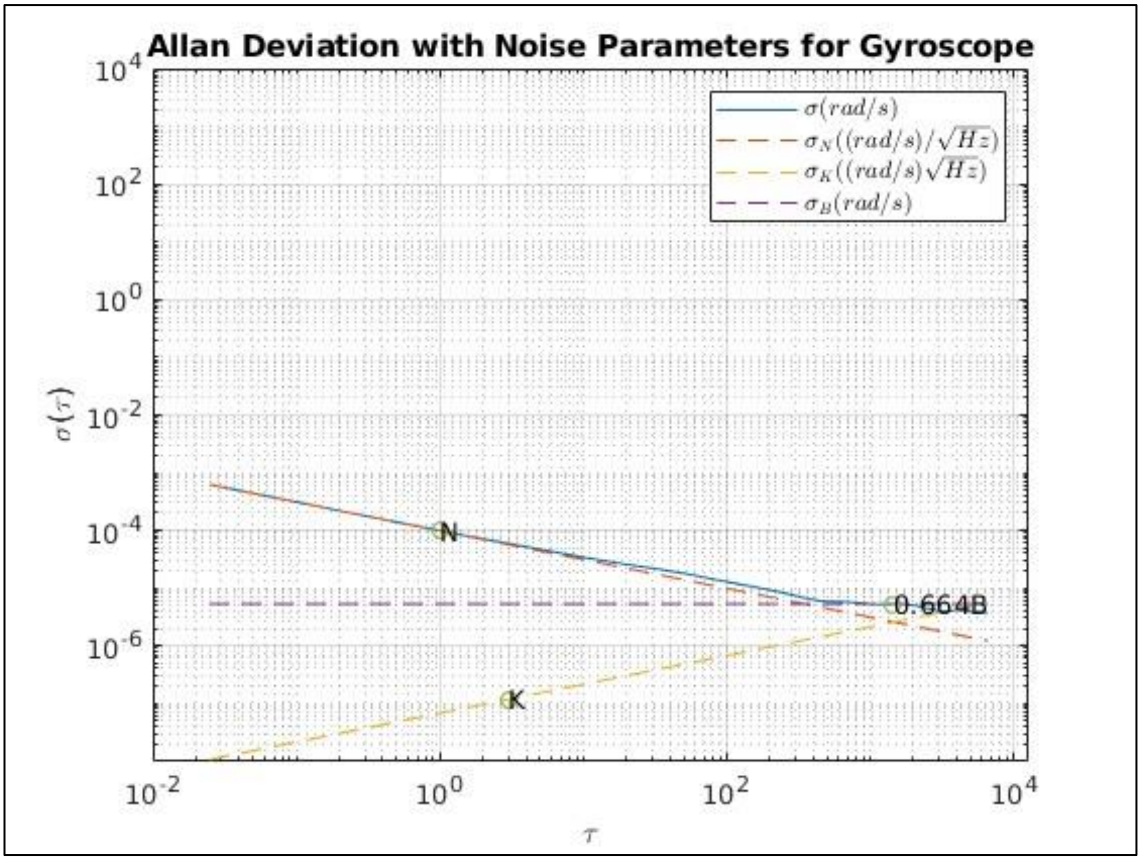


Fig. 14. Allan Deviation plot with Noise parameters for Gyroscope

Figure 13 and 14 shows the Allan Deviation with Noise parameters where N represents the value of Angle/Velocity Random Walk, K represents the Rate Random Walk and 0.664B represents the Bias instability.

In Figure 14, the curve has just started to rise at the end and needed more duration of time to properly show the Rate random walk region of the curve.

Table 2 shows the values of different Noise Parameter for Gyroscope and Accelerometer and also the result is compared with the datasheet of the sensor. As it can be seen that the measured value of Angle/Velocity Random walk is higher than the Data sheet value and it can be due to presence of vibrations which affected the value of white noise. Rest of the measured value closely matches the performance mentioned in the datasheet.

Table 2. Noise Parameter from Allan Deviation Plot

Sensor	Parameter	Datasheet Value	Measured Value
Gyroscope	Angle Random Walk (deg/√s)	0.0035	0.005
	Bias Instability (deg/hr)	10	1.6
	Rate Random Walk (deg/hr/√hr)	-	1.4
Accelerometer	Velocity Random Walk (m/s/√s)	0.0014	0.0019
	Bias Instability (mg)	0.04	0.04
	Rate Random Walk ($m/s^2/\sqrt{hr}$)	-	0.001

Noise Identification and Measurement:

Slopes of Allan Deviation plot represents the presence of different types of noise in the sensor. Since the regions of varying gradient are distinct in the above plots, various noises are identified and measured as follows:

- **White Noise:**
  i) The Angle Random Walk for Gyroscope or Velocity Random Walk for Accelerometer is modeled by the White Noise spectrum [4] and appears on the plot as a slope with gradient -0.5.
  ii) White noise has zero mean, constant variance and is uncorrelated in time and sources of white noise can be due to thermal or vibrations.
  iii) The Random walk measurement for this noise is obtained by fitting a straight line with slope -0.5 and measuring the value of Allan deviation at tau = 1.
  iv) Angle Random walk for Gyroscope is 0.005 deg/√s and Velocity Random Walk for Accelerometer is 0.0019 m/s/√s.
- **Pink Noise:**
  i) The Bias Instability is modeled by the Pink Noise spectrum [4] and appears on the plot as a flat region around the minimum.
  ii) The bias instability measures how the bias of the gyroscope/accelerometer changes over time.
  iii) The Bias Instability can be measured from the Allan deviation at slope 0 (minima of plot) and scaling it by a factor of 0.664.
  iv) From the Table 2, the Bias Instability for Gyroscope is 1.6 deg/hr and for Accelerometer is 0.04 mg.
- **Red Noise (Brownian Noise):**
  i) The Rate Random Walk is modeled by the Red Noise spectrum and appears on the plot as a slope with gradient 0.5.
  ii) Red Noise has zero mean, constant variance and is serially corelated in time and sources of Red Noise is the Brownian motions of particles.
  iii) The Rate Random Walk for this noise can be obtained by fitting a straight line with slope 0.5 and measuring the value of Allan deviation at tau = 3.
  iv) Rate Random Walk for Gyroscope is 1.4 deg/hr/√hr and for Accelerometer is 0.001 m/s^2/√hr.

5. CONCLUSION

This report dealt with the noise characteristics of an IMU sensor and how it the static performance changes with time. Histogram and time series plots confirmed that the errors follow a Gaussian distribution and the Noise parameters are identified and quantified using the Allan Deviation plot.

REFERENCES

[1] Manon Kok, Jeroen D. Hol and Thomas B. Schon (2017), "Using Inertial Sensors for Position and Orientation Estimation", *Foundations and Trends in Signal Processing*: Vol. 11: No. 1-2, pp 1-153.

[2] Kristian Jambrosic, M. Krhen, M. Horvat, T. Jagust. “Measurement of IMU sensor quality used for head tracking in auralization systems”, *Forum Acusticum*, Dec 2020, Lyon, France. pp.2063-2070.

[3] “Allan Variance: Noise Analysis for Gyroscopes”, 0, 2/2015 Freescale Semiconductor, Inc.

[4] “Inertial Sensor Noise Analysis using Allan Variance” Accessed Oct. 22,2022. [Online.] Available: https://www.mathworks.com/help/nav/ug/inertial-sensor-noise-analysis-using-allan-variance.html