Anway Prasad Shirgaonkar

RSN LAB 3 - IMU Noise Characterization

Analysis of 10-minutes Stationary Data

The stationary data for IMU (Vectornav VN-100) was collected in the basement of Cullinane hall for a duration of 10 minutes. Below are the time and frequency plots of the gyroscope, magnetometer, and accelerometer which give an estimate of the distribution of the noise present in the IMU.

- ### Gyroscope

  A gyroscope is an inertial sensor that measures an object's angular rate with respect to an inertial reference frame.MEMS gyroscopes measure the angular rate by applying the theory of the Coriolis effect, which refers to the force of inertia that acts on objects in motion in relation to a rotating frame. The output of VN-100 IMU's gyroscope is obtained in rad/s.

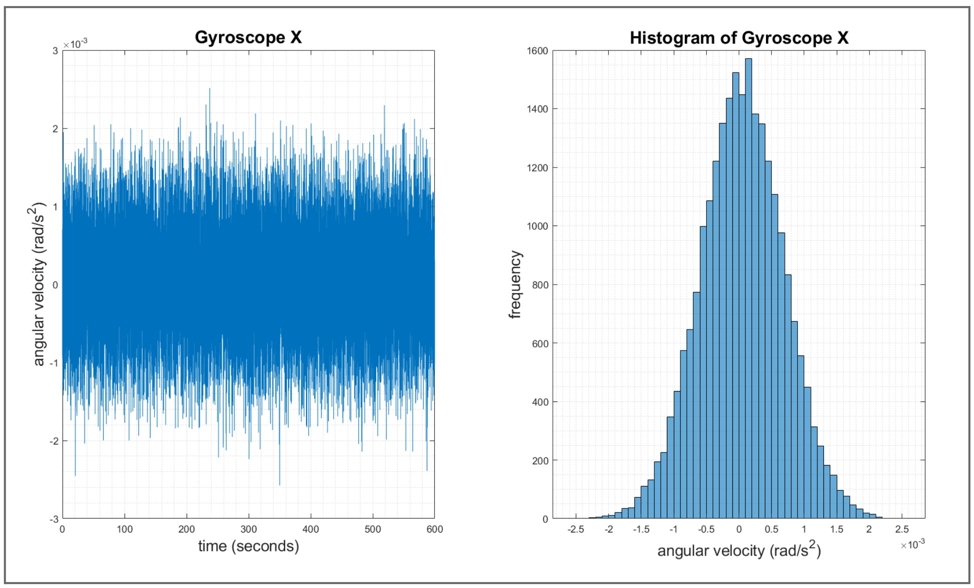

Fig. 1: Frequency and Time plots of Gyroscope X axis

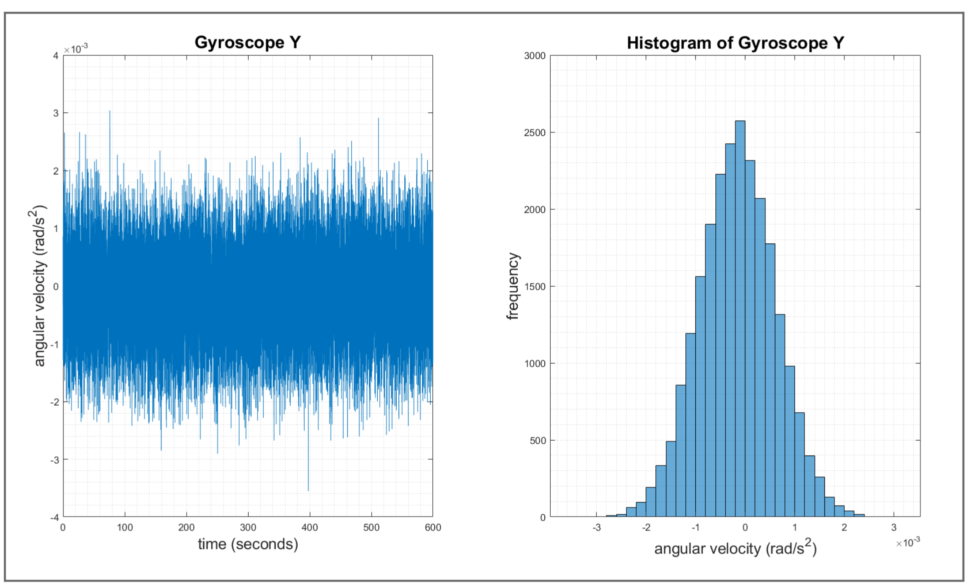

Fig. 2: Frequency and Time plots of Gyroscope Y axis

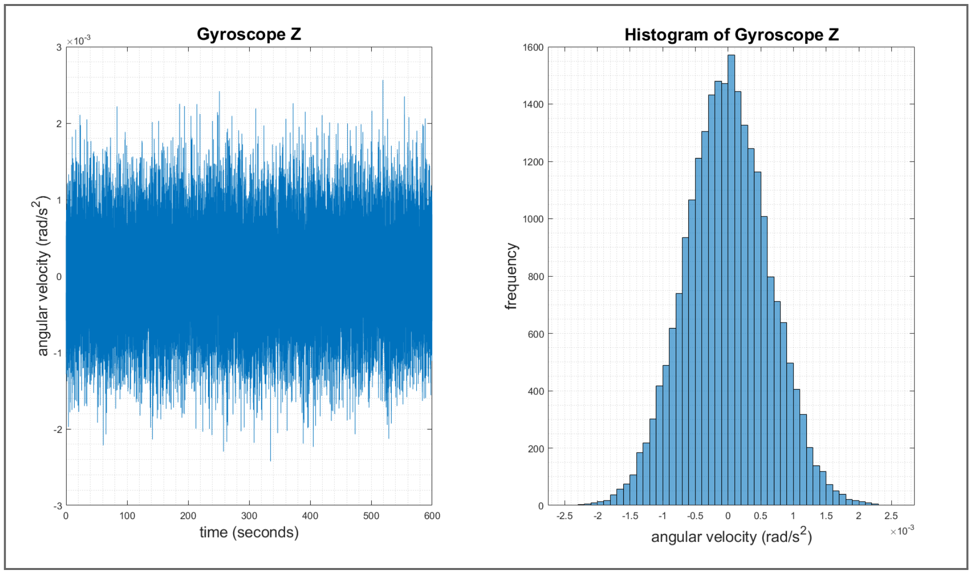

Fig. 3: Frequency and Time plots of Gyroscope Z axis

It is clear from the bell-shaped data observed in the frequency plot, that the distribution obtained in the frequency plot is a **Normal distribution.** The mean and standard deviation for each axis is given in the table below. Ideally, the gyroscope should read **0 rad/sec** about each axis as the IMU was taped to the ground. The small amount of drift from the true reading (which is the mean in this case) is the bias of the gyroscope.

Gyroscope Axis	Mean (rad/sec)	Standard Deviation (rad/sec)
Gyroscope X-axis	0.000051	0.000638
Gyroscope Y-axis	- 0.000152	0.000766
Gyroscope Z-axis	- 0.000009	0.000638

- ## Magnetometer

  Using a magnetometer is a common way to obtain a system's heading, particularly in applications that do not have access to GNSS. While seemingly straightforward, using a magnetometer to accurately estimate the heading can actually prove to be quite challenging. The Earth's magnetic field is quite weak and there often exists a number of different error sources that can impact the heading accuracy.

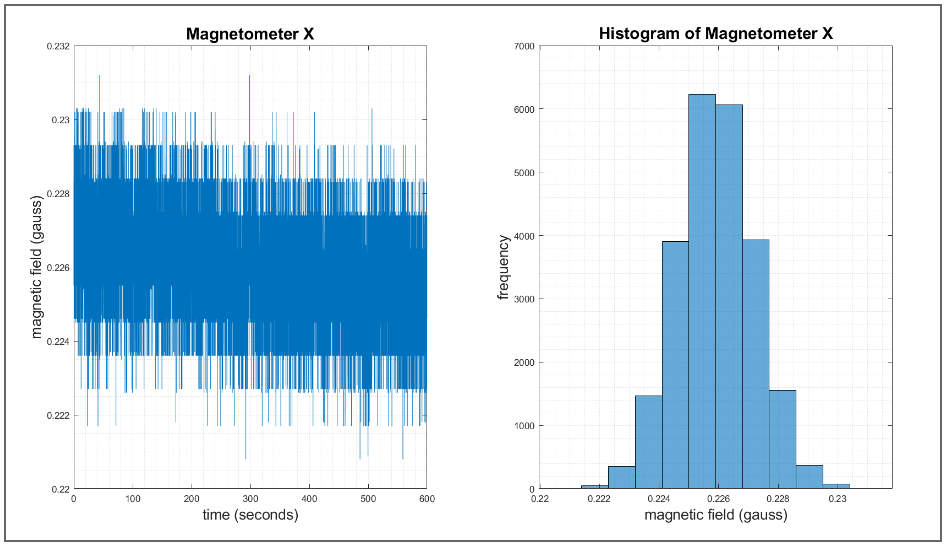

Fig. 4: Frequency and Time plots of Magnetometer X axis

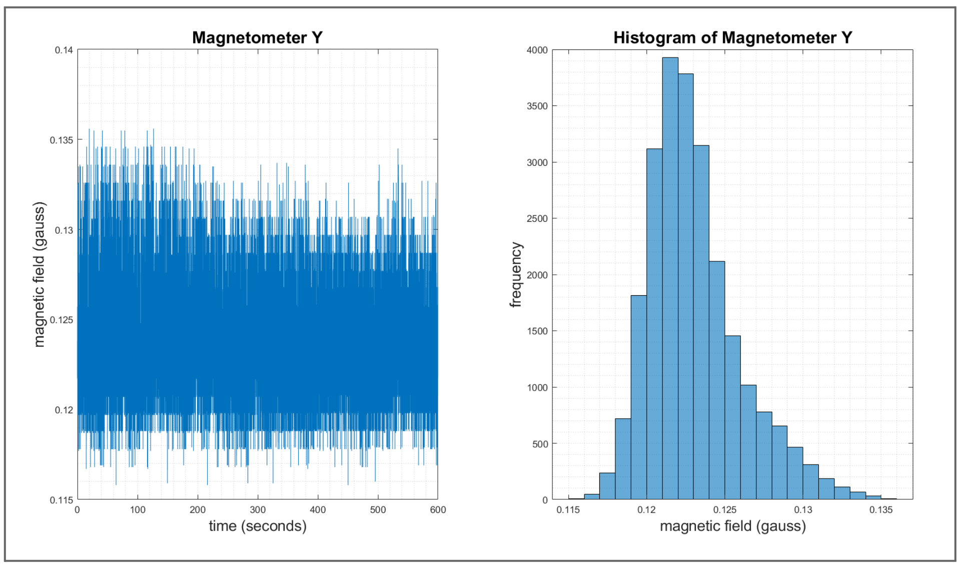

Fig. 5: Frequency and Time plots of the Magnetometer Y axis

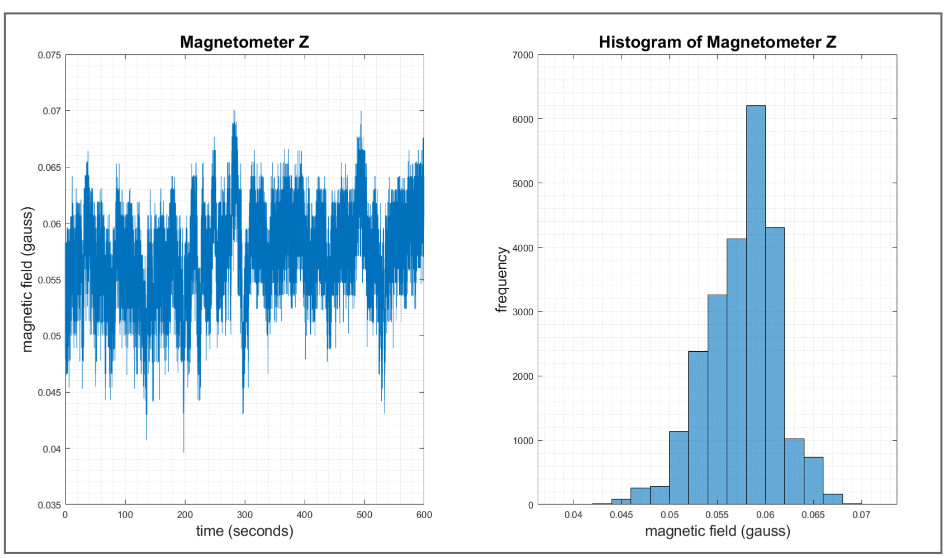

Fig. 6: Frequency and Time plots of the Magnetometer Z axis

It is clear from the bell-shaped data observed in the frequency plot, that the distribution obtained in the frequency plot is a **Normal distribution.** The mean and standard deviation for each axis is given in the table below. The norm of the mean obtained in each of the magnetometer axes is **0.630 gauss**, which is roughly equal to the magnetic field of the earth. It can be noted that the frequency plots do not appear to be a perfect bell curve. This happens due to the high sensitivity of the magnetometer to external ferromagnetic substances which may skew or shift the probability distribution.

Magnetometer Axis	Mean (gauss)	Standard Deviation (gauss)
Magnetometer X-axis	0.225998	0.001378
Magnetometer Y-axis	0.123310	0.002924
Magnetometer Z-axis	0.057567	0.003743

- ## Accelerometer

  An accelerometer is the primary sensor responsible for measuring inertial acceleration, or the change in velocity over time. When an accelerometer is subjected to a linear acceleration along the sensitivity axis, the acceleration causes the proof mass to shift to one side, with the amount of deflection proportional to the acceleration.

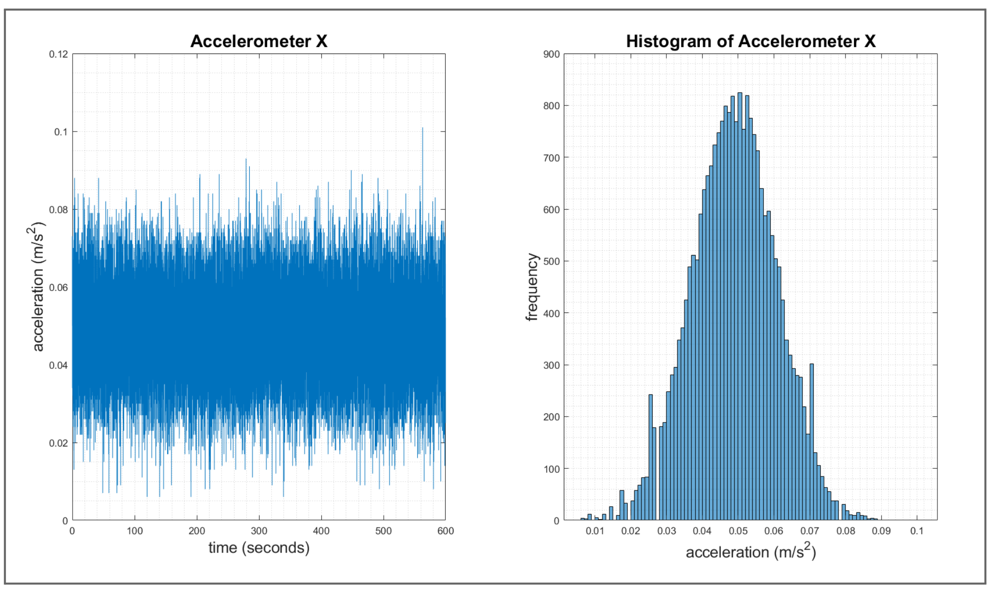

Fig. 7: Frequency and Time plots of the Accelerometer X axis

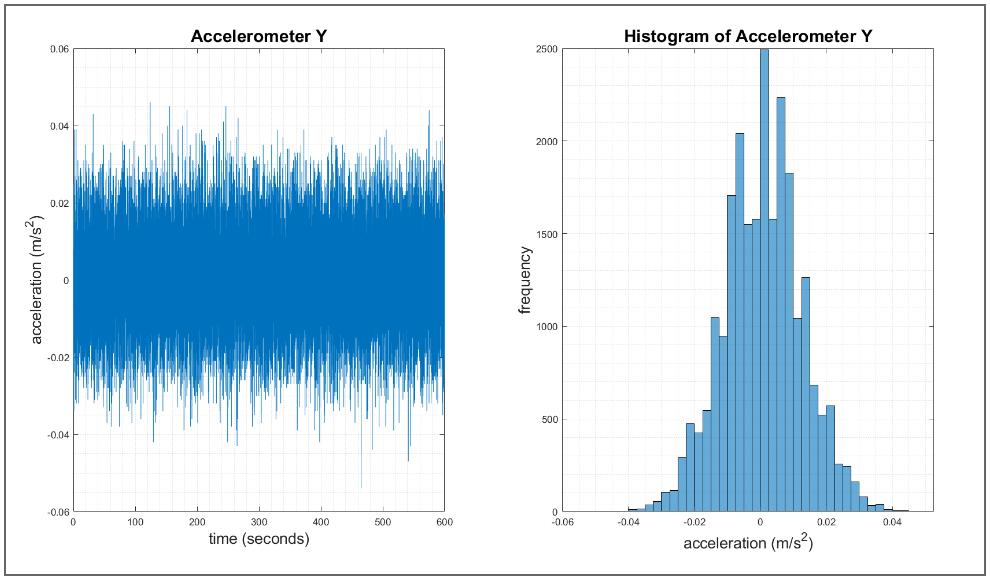

Fig. 8: Frequency and Time plots of the Accelerometer Y axis

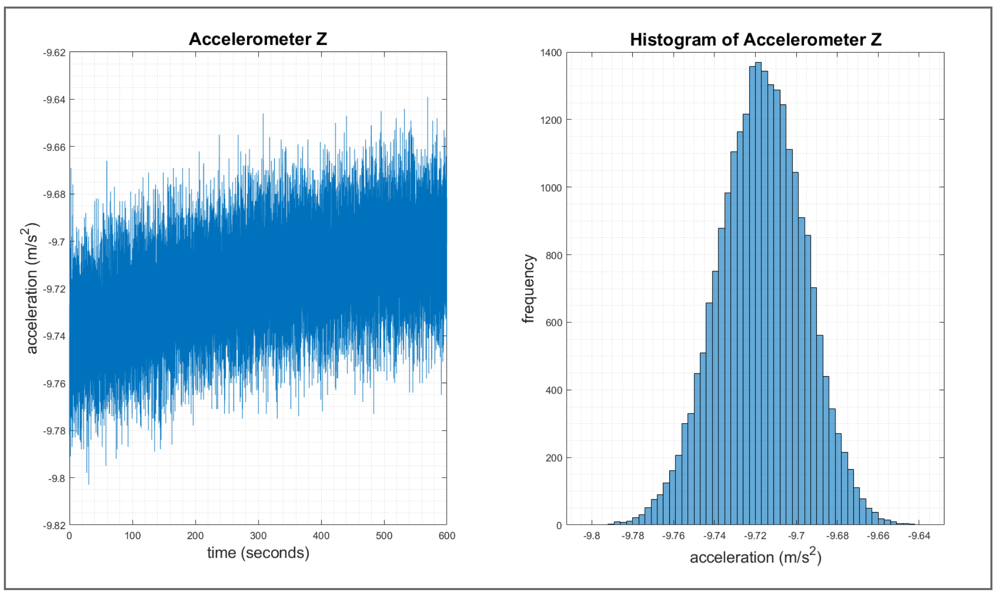

Fig. 9: Frequency and Time plots of the Accelerometer Z axis

It is clear from the bell-shaped data observed in the frequency plot, that the distribution obtained in the frequency plot is a **Normal distribution.** The mean and standard deviation for each axis is given in the table below. We measure **-9.717405** m/s^2 in the direction of the Z-axis due to the fact that the proof mass shifts in the direction of acceleration caused by gravity. Due to this factor, when the accelerometer is in a state of free fall along the Z-axis, it will measure an acceleration of 0 m/s^2

Accelerometer Axis	**Mean** (m/s^2)	**Standard Deviation** (m/s^2)
Accelerometer X-axis	0.048526	0.011822
Accelerometer Y-axis	0.000759	0.011932
Accelerometer Z-axis	-9.717405	0.020968

- ## Orientation

The measurements from the gyroscope, accelerometer, and magnetometer are combined to provide an estimate of a system's orientation, often using a Kalman filter. This estimation technique uses these raw measurements to derive an optimized estimate of the attitude, given the assumptions outlined for each individual sensor. The Kalman filter estimates the gyro bias, or drift error of the gyroscope, in addition to the attitude.

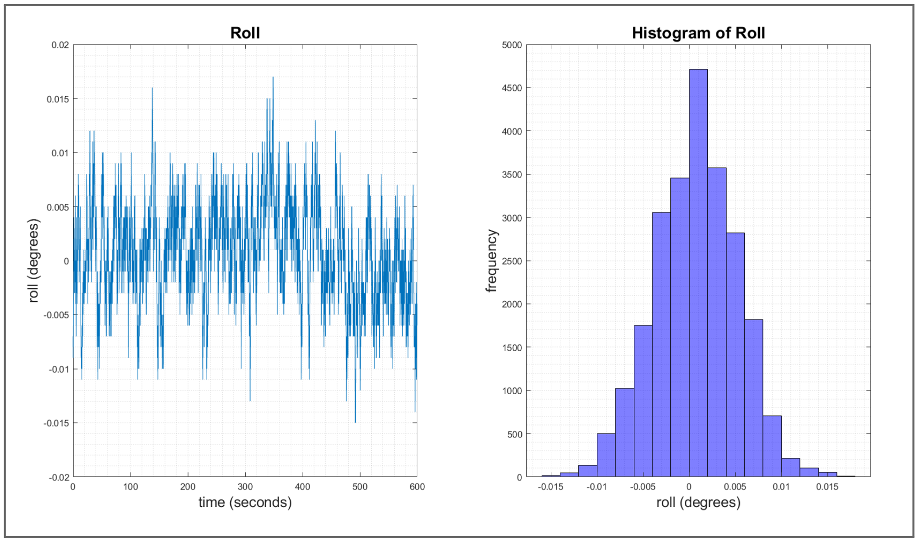

Fig. 10: Frequency and Time plots of Roll

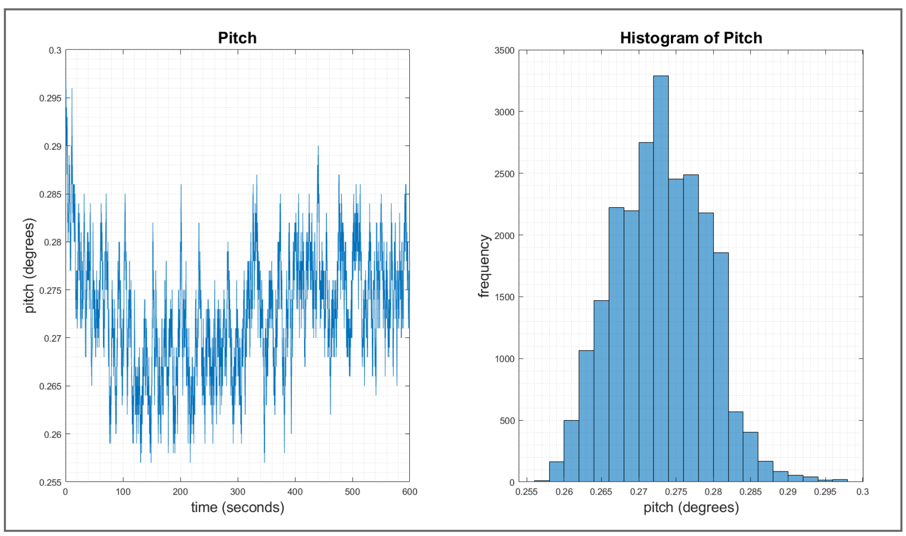

Fig. 11: Frequency and Time plots of Pitch

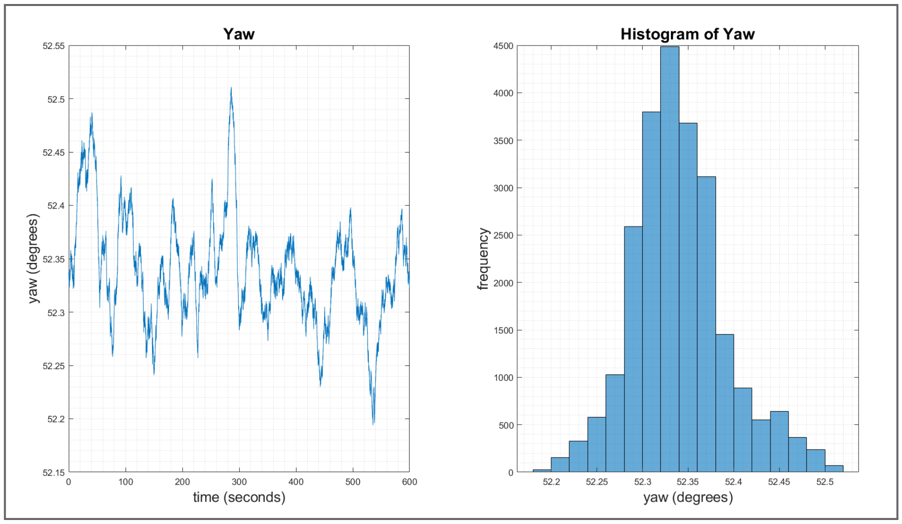

Fig. 12: Frequency and Time plots of Yaw

It is clear from the bell-shaped data observed in the frequency plot, that the distribution obtained in the frequency plot is a **Normal distribution.** The mean and standard deviation for each axis is given in the table below

Orientation	Mean (degrees)	Standard Deviation (degrees)
Roll	0.000704	0.004488
Pitch	0.272679	0.006165
Yaw	52.339768	0.051601

Note that the **standard deviation of Yaw is significantly greater** than that of Roll and Pitch. This is due to the fact that the estimation of Yaw is heavily dependent on the value of the Magnetometer which is extremely susceptible to errors, given the weak magnitude of the earth's magnetic field.

Anway Prasad Shirgaonkar

Noise characterization with Allan Variance

An Allan Variance test is a method used for identifying the noise properties of an inertial sensor. A sensor is mounted statically with data logged at a high rate for an extended period. The data is downsampled at various time constants, and the variances of each of these downsampled measurements can be calculated at each of the different time constants.

There are 3 sets of data recorded for the Allan Variance test as the results obtained after each test were not satisfactory. I am using the best set of data among the three in which the calculated noise parameters come close to the one mentioned in the datasheet of VectorNav VN-100. This data was collected in the basement of Cullinane Hall for a duration of 5 hrs. Following is the noise characterization of the gyroscope and the accelerometer performed on Y-axis. The noise parameters estimated from these plots are:

- ### 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. 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

  - Steps to compute Angle Random Walk (ARW)
    1. Find the index where the slope of the log-scaled Allan deviation is equal to - 0.5
    2. Now, compute the y-intercept of the line with slope = - 0.5
    3. Determine the Allan deviation value on this line at $\tau = 1$. This yields the value of ARW in deg/sec. Then, we multiply this by 60 to get angle random walk in $deg/\sqrt{hr}$.

  - Steps to compute Rate Random Walk (RRW)
    1. Find the index where the slope of the log-scaled Allan deviation is equal to 0.5
    2. Now, compute the y-intercept of the line with slope = 0.5
    3. Determine the Allan deviation value on this line at $\tau = 3$. This yields the value of RRW in deg/sec. Then, we multiply this by 216000 to get RRW in $deg/hr^{3/2}$.

  Same steps should be followed to calculate Velocity Random Walk (VRW) and Rate Random Walk (RRW) for accelerometer with change in the units as $m/s/\sqrt{hr}$ for VRW and $m/s/hr^{3/2}$ for RRW

- ### 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.

  - Steps to compute Bias Instability
    1. As we can see in the Allan deviation plot, the data reaches a minimum before increasing again. First, determine the Allan deviation at this minimum point in deg/sec.
    2. Then, we divide this value by 0.664 and multiply the result by 3600. This yields bias instability in deg/hr.

       The 0.664 is a dimensionless value specified in IEEE Standard 952-1997 and is a constant.

- Gyroscope Y-axis Allan deviation plot

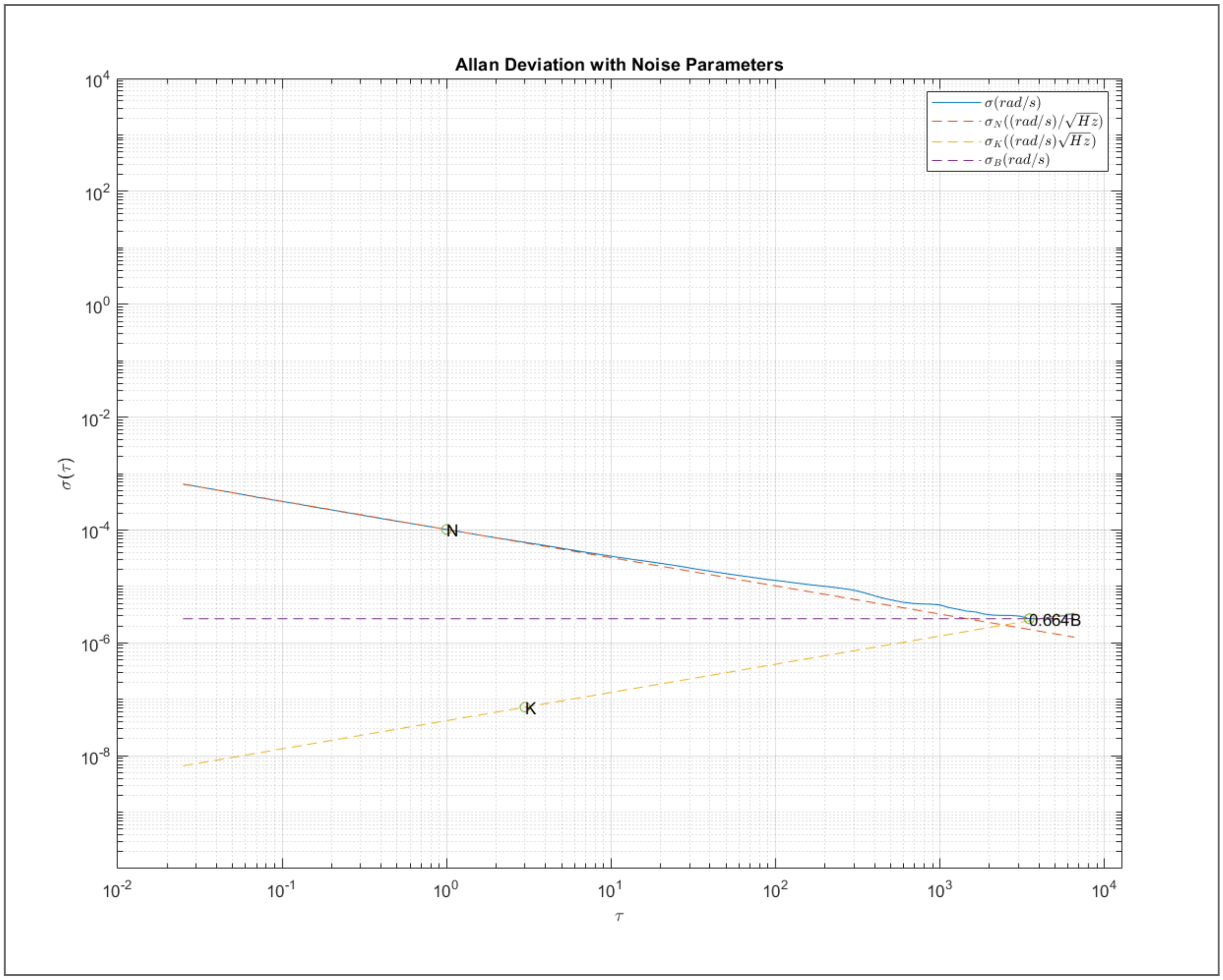

Fig. 13: Noise Parameters of Gyroscope Y-Axis

The computed noise parameters are listed in the table below:

Parameter	Value Calculated	Value as per Datasheet
Angle Random Walk	0.354 $deg/\sqrt{hr}$	0.2 $deg/\sqrt{hr}$
Rate Random Walk	0.8969 $deg/hr^{3/2}$	-
Bias Instability	0.83016 deg/hr	5-7 deg/hr

- Accelerometer Y-axis Allan deviation plot

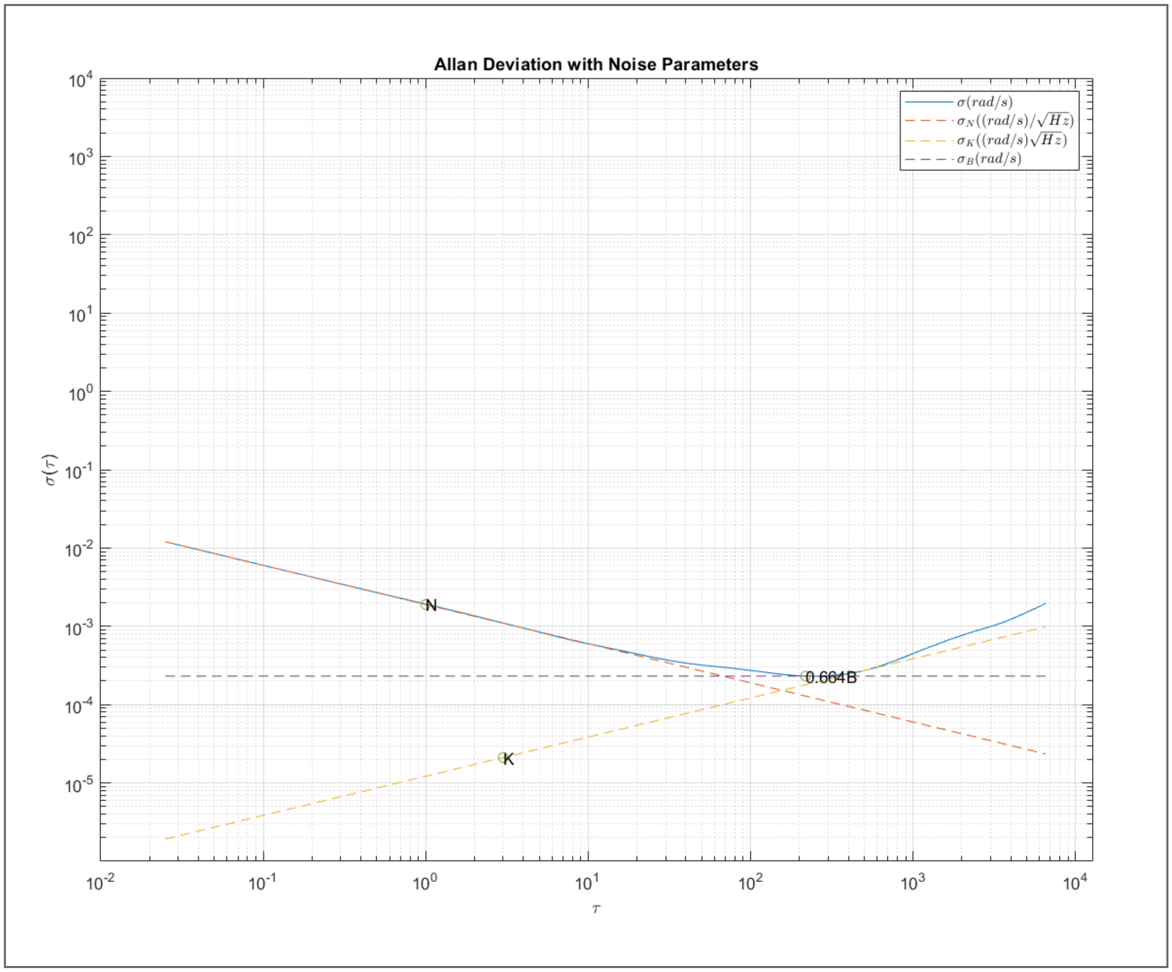

Fig. 14: Noise of Accelerometer Y-Axis

The computed noise parameters are listed in the table below:

Parameter	Value Calculated	Value as per Datasheet
Velocity Random Walk	0.114 $m/s/\sqrt{hr}$	0.1 $m/s/\sqrt{hr}$
Rate Random Walk	4.559 $m/s^{3/2}$	-
Bias Instability	0.03555 mg	<0.4 mg

Concluding Statements:

1. In a short duration of operation, **angle random walk is characterized by white noise** which leads to the normal distribution in the frequency plots of the 10-min stationary data.

2. If the stationary data of IMU is recorded over a long period of time, then we can estimate the **bias instability, which is characterized by pink noise**. Furthermore, **the rate random walk is characterized by brown noise** which kicks in the sensor after extremely long periods of operation.

3. The noise parameters of the sensor specified in the VN-100 datasheet are recorded under ideal and temperature-controlled environments. Thus, we can observe a significant difference in the bias instability (gyroscope) of VN-100 mentioned in the datasheet and the one obtained from my calculation. **Although, the parameters estimated are sufficient to conclude that the IMU provided is of 'Industrial grade'.**