Introduction

In this lab we were tasked with developing an IMU driver in ROS2. We began by writing the driver in Python. We created a Node called *IMUDriver* which takes in the serial port the IMU is connected to and the baud rate at which to communicate with the IMU at. We also need to configure the IMU to output data at 40 Hz, which we did by sending a command through the serial connection that configures the async data output frequency register to output at 40 Hz. We also configured the callback function to publish the IMU data on the *imu* topic at a frequency of 40 Hz as well, so we do not output duplicate data and to verify we collect each sample. We also created a custom message called *IMUmsg* to publish a custom message consisting of the standard ROS2 header, the IMU and Magnetic field sensor messages, and the raw IMU data output string. We also developed a launch script to make running our IMU node more efficient for actual robotics setting.

Once our driver was developed, we collected 15 minutes of stationary data and collected 5 hours of stationary data. In the next sections, we analyze the data to learn more about the variance and error found in these measurements.

Analysis

For this experiment, we collected time series data using the VN-100 IMU. The data was collected for 15 minutes with the IMU kept stationary in the middle of the room away from any disturbances. We recorded data for the 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer, and calculated the Euler angles, which we then analyzed below.

Accelerometer Analysis

For the accelerometer data collected, we calculated the mean and standard deviation which are shown in Figure 1a. We also plotted a time series and histogram of the recorded accelerometer data which are shown in Figure 1b and Figure 1c respectively.

	Accelerometer (m/s^2)		
	X	Y	Z
Mean	-0.360166286	0.708944446	-9.715062253
STD	0.012579930	0.014039725	0.017171982

Figure 1a) Accelerometer Statistics

Figure 1a reveals that the Z-axis has a much larger magnitude due to Earth's gravitational force (9.81 m/s^2). The X and Y axes show small mean values, as expected for a stationary IMU on a level surface. The histogram in Figure 1c indicates that all three axes follow a Gaussian distribution, with the Z-axis showing a slightly wider spread, consistent with its larger standard deviation. The time series plot (Figure 1b) demonstrates consistent noise distribution across axes. While X and Z axes show no clear drift, the Y axis exhibits a slight downward trend over time.

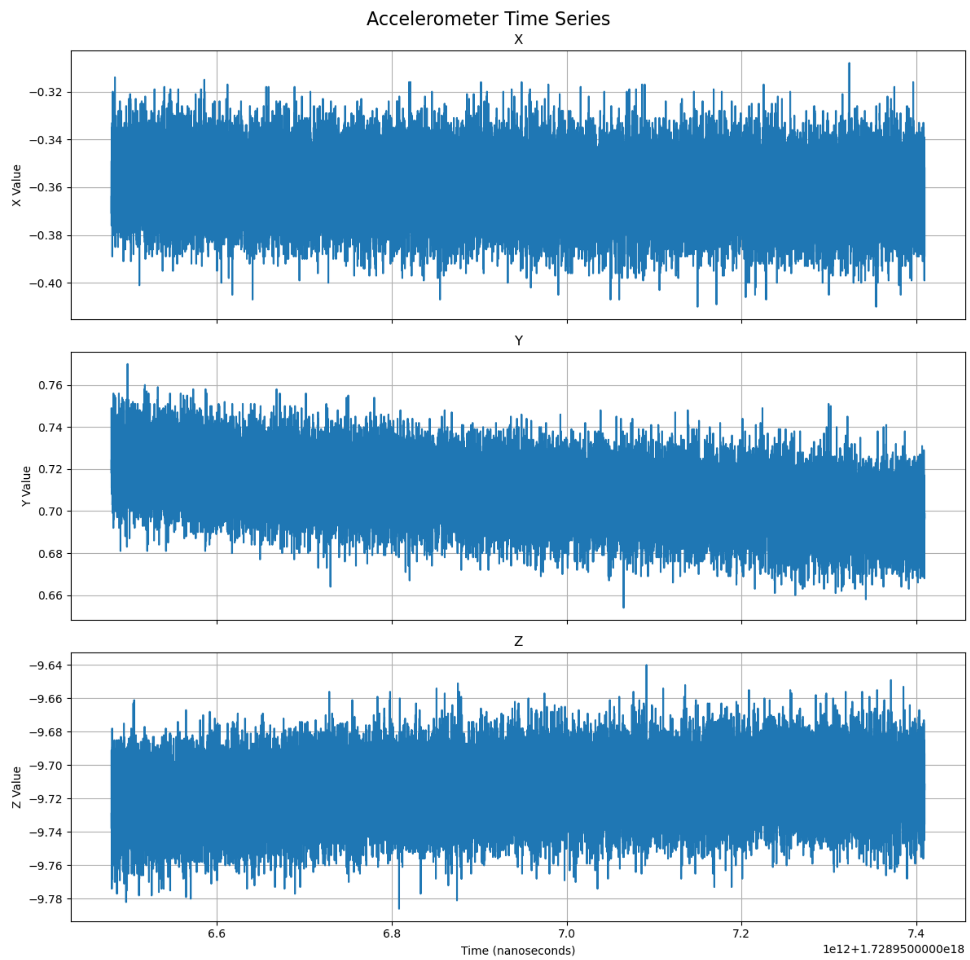


Figure 1b) Accelerometer Time Series Plot

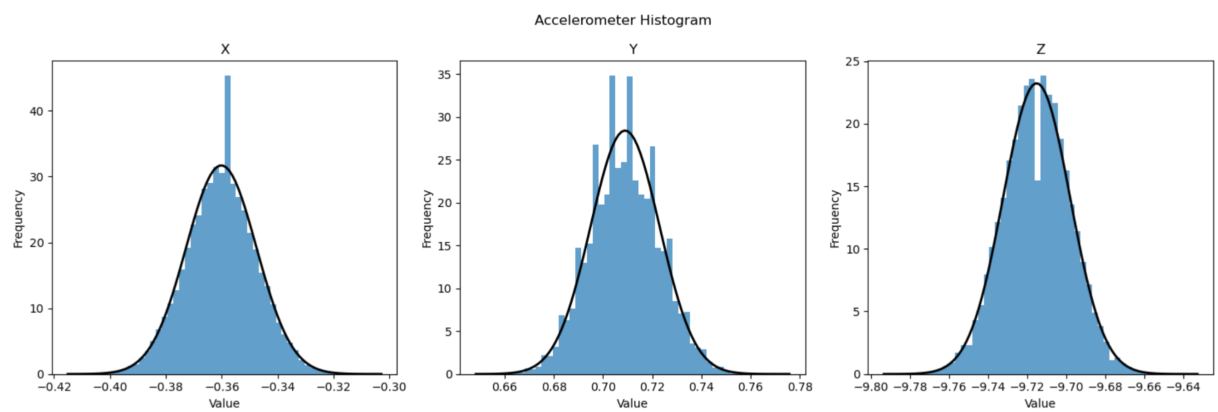


Figure 1c) Accelerometer Histogram Plot

Gyroscope Analysis

For the gyroscope data collected, we calculated the mean and standard deviation which are shown in Figure 2a. We also plotted a time series and histogram of the recorded gyroscope data which are shown in Figure 2b and Figure 2c respectively.

	Gyroscope (rad/s)		
	X	Y	Z
Mean	-0.000006600	0.000054281	-0.000034684
STD	0.000727211	0.000819400	0.001462281

Figure 2a) Gyroscope Statistics

Figure 2a shows that the means of all axes are close to zero, which is expected for a stationary IMU as the gyroscope measures rotational motion. The time series plot (Figure 2b) demonstrates consistent noise around zero for all axes. The Z-axis exhibits a greater magnitude of noise compared to X and Y, which is corroborated by its slightly higher standard deviation. Figure 2c, the histogram, clearly shows that the data for all axes is centered around zero and follows a Gaussian distribution. Comparing our results to the manufacturer's specified noise density of 0.0035°/s/√Hz, we calculated an equivalent noise density of approximately 0.0187°/s/√Hz for our highest observed standard deviation (Z-axis). This higher-than-specified noise level could be attributed to factors such as temperature fluctuations, vibrations, or electrical noise in the testing environment.

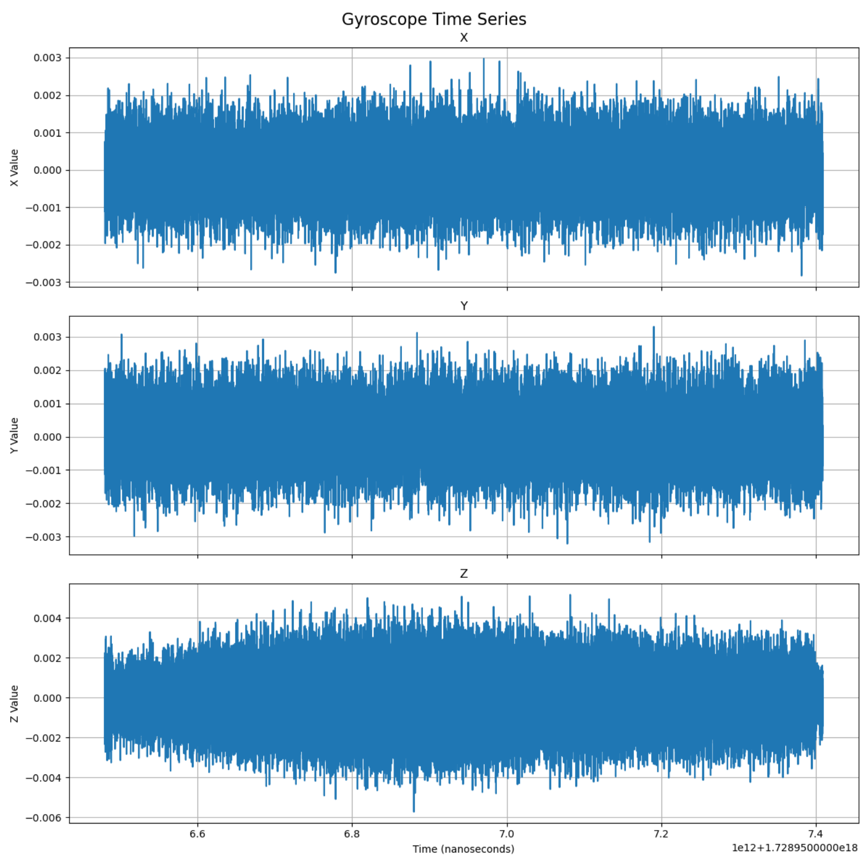


Figure 2b) Gyroscope Time Series Plot

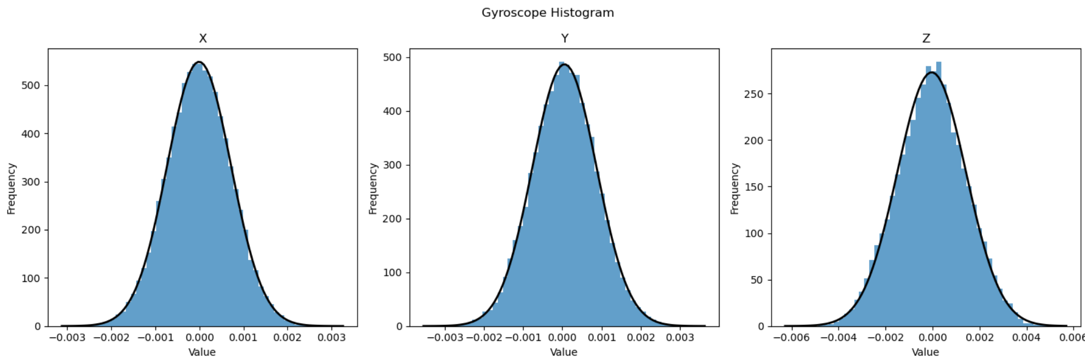


Figure 2c) Gyroscope Histogram Plot

Magnetometer Analysis

For the magnetometer data collected, we calculated the mean and standard deviation which are shown in Figure 3a. We also plotted a time series and histogram of the recorded magnetometer data which are shown in Figure 3b and Figure 3c respectively.

	Magnetometer (Tesla)		
	X	Y	Z
Mean	0.000011987	-0.000029265	0.000041217
STD	0.000000157	0.000000330	0.000001503

Figure 3a) Magnetometer Statistics

Figure 3a shows that the mean values for all axes are close to zero, which is expected for an IMU in a stationary, consistent magnetic field. This aligns with our data collection setup, where the IMU was placed in the center of the room away from electronics. The time series plot (Figure 3b) demonstrates distinct mean values for each axis with small fluctuations. These fluctuations are very small (> .000001 T) and can be considered normal within the operating parameters of the IMU, given its specified range. Figure 3c, the histogram, attempts to fit the data to a Gaussian distribution. However, all axes show slight skewness:

- The X-axis trends upward and shows signs of quantization, with data clumped into certain values.
- The Y-axis is more Gaussian but still shows a downward trend.
- The Z-axis is the most Gaussian and shows a slight downward trend.

Comparing our results to the manufacturer's specified noise density of 140 µGauss/√Hz, we calculated an equivalent noise density of approximately 3359 µGauss/√Hz for our highest observed standard deviation (Z-axis). This significantly higher noise level suggests possible external magnetic interference or that the sensor might require calibration.

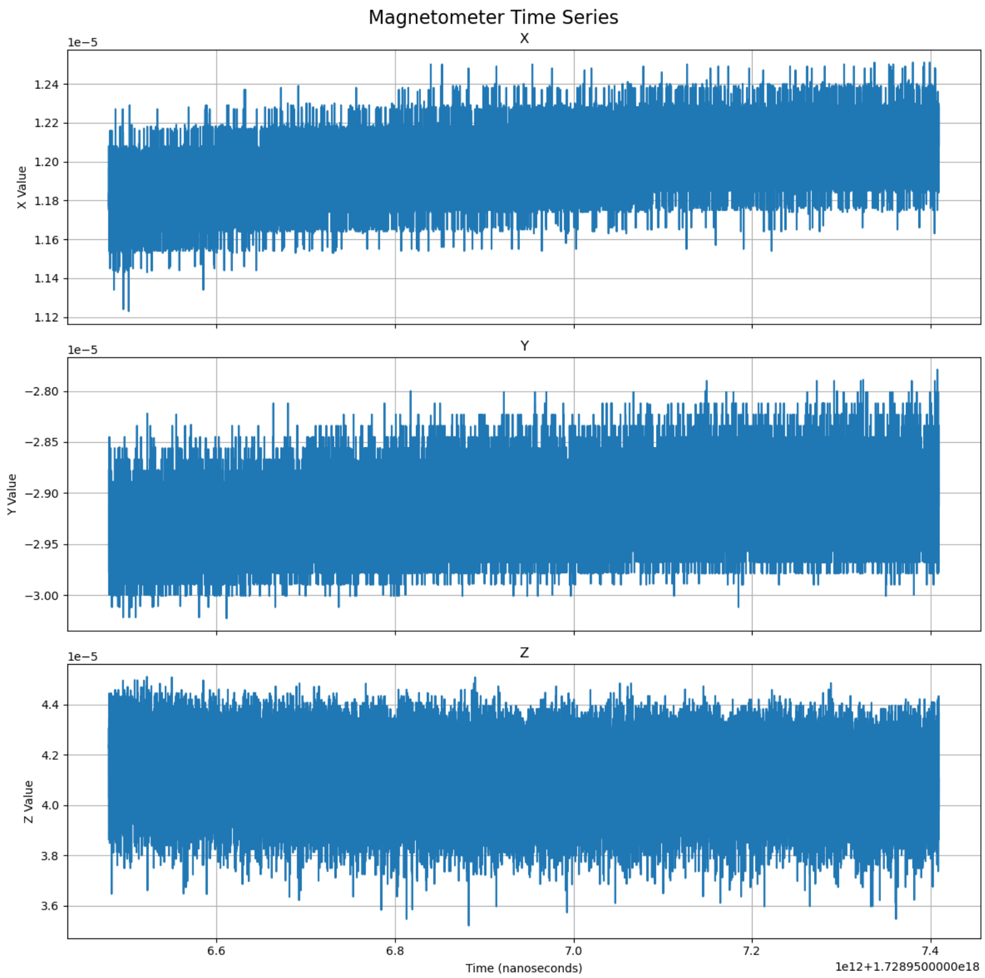


Figure 3b Magnetometer Time Series Plots

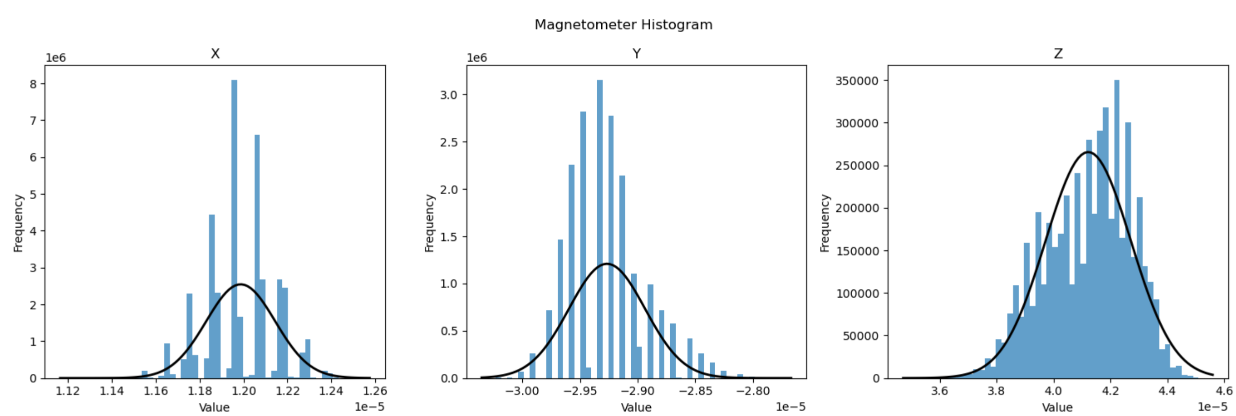


Figure 3c Magnetometer Histogram Plots

Euler Angles Analysis

For the Euler angles data derived from the IMU measurements, we calculated the mean and standard deviation as shown in Figure 4a. Time series and histogram plots are presented in Figures 4b and 4c respectively.

	Euler Angles (rad/s)		
	Roll	Pitch	Yaw
Mean	-0.072855128	-0.036891935	1.193763376
STD	0.000716388	0.000263918	0.003293854

Figure 4a) Euler Angles Statistics

Figure 4a shows the calculated mean and standard deviation for each of the Euler angles. The mean values for Roll and Pitch are close to zero, which is expected for a stationary IMU on a level surface. The Yaw mean of approximately 1.19 radians (about 68 degrees) likely represents the IMU's orientation relative to magnetic north. The time series plot (Figure 4b) reveals interesting trends for each angle:

- Roll shows a gradual upward trend over time.
- Pitch exhibits a slight downward trend.
- Yaw demonstrates a more pronounced downward drift.

These trends, despite the IMU being stationary, could indicate slight instabilities in the sensor fusion algorithm or environmental factors affecting the measurements. Figure 4c, the histogram, shows that the data for all three angles approximates a Gaussian distribution, but with some notable characteristics:

- Roll has a wider, slightly skewed distribution.
- Pitch shows the narrowest, most Gaussian-like distribution.
- Yaw exhibits a wider spread and some irregularities in its distribution.

The standard deviations indicate that Yaw has the highest variability, followed by Roll, with Pitch being the most stable. This aligns with typical IMU behavior, where Yaw (often derived from magnetometer data) is generally less stable than Roll and Pitch (primarily derived from accelerometer data).

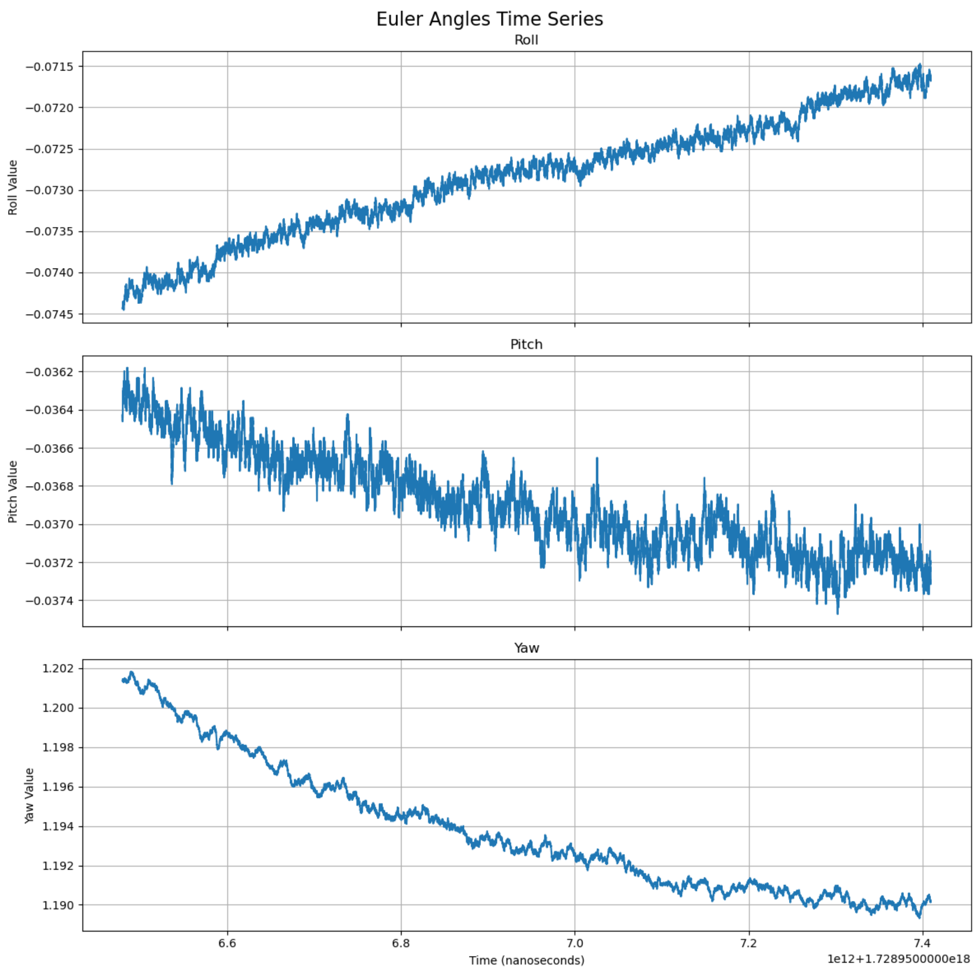


Figure 4b Euler Angles Time Series Plots

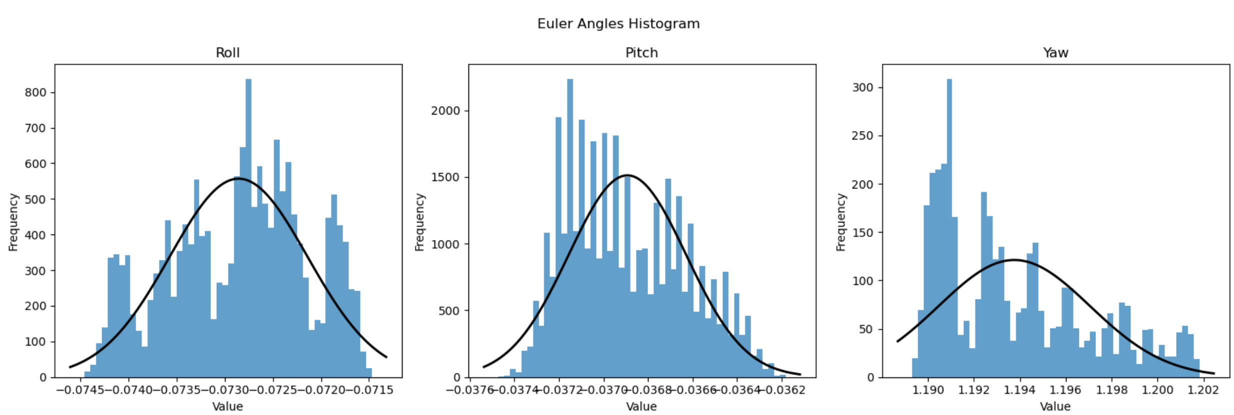


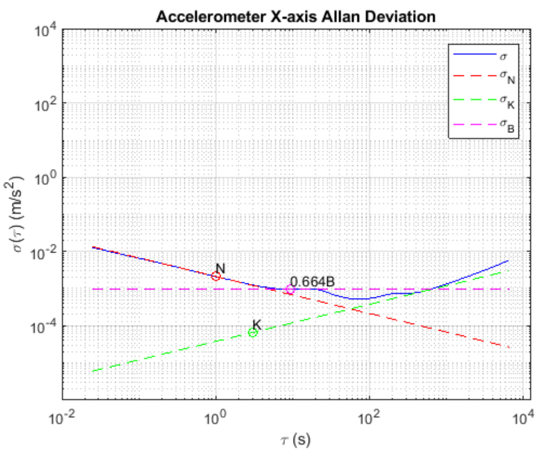
Figure 4c Euler Angles Histogram Plots

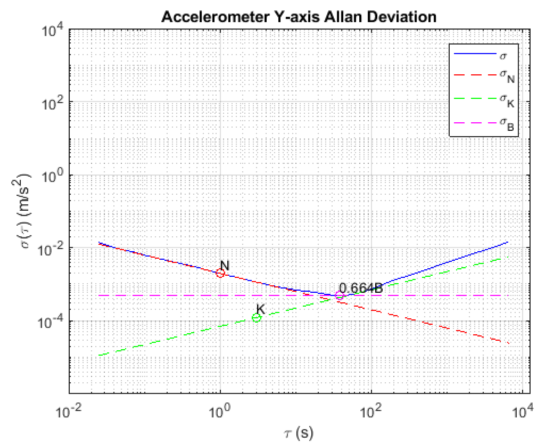
Allan Variance Data Analysis

Next, we recorded 5 hours of data using the IMU. With the dataset collected, we analyzed our data for Allan variance. Allen variance lets us analyze time series data to characterize noise and stability in systems, which is particularly useful is accelerometers and gyroscopes. It is calculated by finding the variance of the difference between successive averages of the data over different time periods. Using Allan variance, we can identify several noise parameters such as the angle random walk (ARW), rate random walk (RRW), and bias instability (BI).

Accelerometer Allan Variance Analysis

We utilized MATLAB to write a script that can calculate and plot the Allan variance, along with its noise parameters. The graphs for the accelerometer measurements are shown in Fig. 5. The calculated noise parameters are shown in Fig. 6.





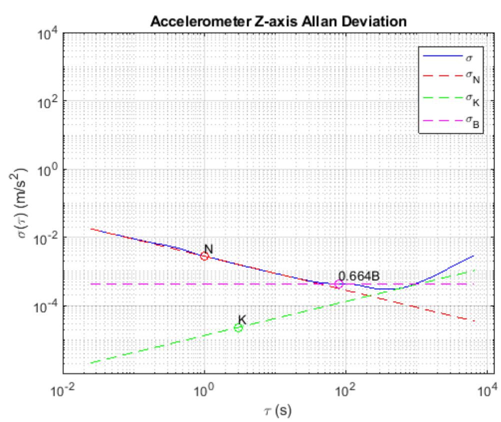


Fig. 5) Accelerometer Allan Deviation for XYZ axes

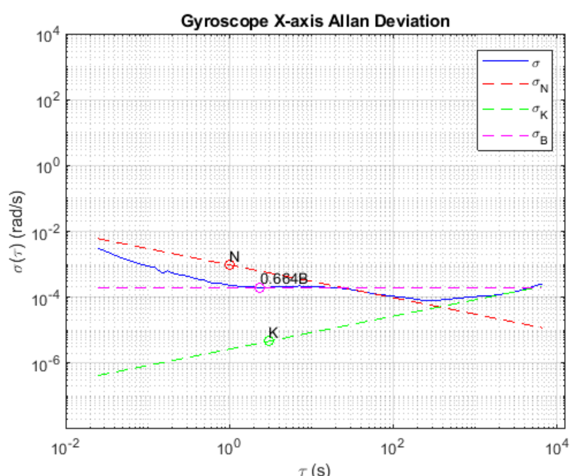
Using the Allan deviation plots, we identified three main sources of noise in the accelerometer data: ARW, RRW, and BI. ARW is represented by the line σ_N and is the white noise spectrum of the accelerometer. The RRW is the random walk process that affects the rate change of the bias. It is represented as σ_K on the plots. The BI represents the flicker noise of the accelerometer. We measure ARW at $\tau = 1\ second$, RRW at $\tau = 3\ seconds$, and the BI is measured at the minimum point of the Allan variance plot. Using the VN-100 datasheet, we found that the given noise density (ARW) is $< 0.14\, mg = 0.0013729\, m/s^2$, which is slightly lower than our measured values which are shown in Fig. 6 below. We also found the given bias stability to be $< 0.04mg = .0003923\, m/s^2$, which is again lower than the BI. The datasheet does not provide information on the RRW to analyze.

Accelerometer Noise Parameters			
	ARW	RRW	BI
X-Axis	0.0021225 m/s/√Hz	6.5026e-05 m/s^2/√Hz	0.0014049 m/s^2 at tau = 9.35 s
Y-Axis	0.0019846 m/s/√Hz	0.00012103 m/s^2/√Hz	0.000736 m/s^2 at tau = 37.375 s
Z-Axis	0.0028128 m/s/√Hz	2.2915e-05 m/s^2/√Hz	0.00064911 m/s^2 at tau = 79.6 s

Fig. 6 Accelerometer Noise Parameters

Gyroscope Allan Variance Analysis

The graphs for the gyroscope measurements are shown in Fig. 7. The calculated noise parameters are shown in Fig. 8.



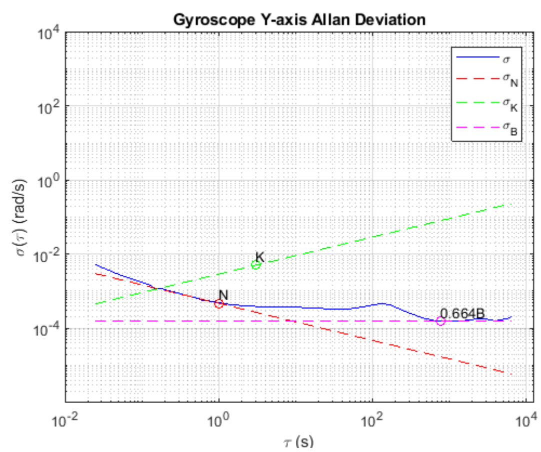
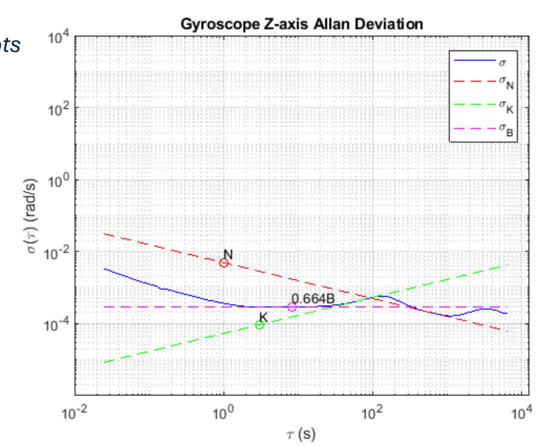


Figure 7. Gyroscope Allan Deviation Plots



Gyroscope Noise Parameters			
	ARW	RRW	BI
X-Axis	0.0009528 rad/√Hz	4.5315e-06 rad/s/√Hz	0.00029688 rad/s at tau = 2.35 s
Y-Axis	0.00047117 rad/√Hz	0.0050267 rad/s/√Hz	0.00023458 rad/s at tau = 769.175 s
Z-Axis	0.0049137 rad/√Hz	9.15e-05 rad/s/√Hz	0.00043781 rad/s at tau = 8.25 s

Fig. 8 Gyroscope Noise Parameters

We again compare our measured noise parameters against the datasheets given parameters. The given noise density for the gyroscope is $6.1087E - 5\ rad/s$, which means that our ARW measurements is still larger than the given ARW. We were also given the in in-run bias stability to be $0.0000484\ rad/s$ which is much smaller than our measured BI values.

Results

15 Minute Data Results

Our analysis of the IMU data reveals several key characteristics across the accelerometer, gyroscope, magnetometer, and derived Euler angles. The accelerometer's Z-axis shows the expected gravitational influence (-9.715 m/s²), while the X and Y axes have near-zero means, as expected for a stationary IMU.

The gyroscope data centers around zero for all axes, consistent with a non-rotating body. The Z-axis demonstrates higher noise levels compared to X and Y.

Magnetometer readings show mean values near zero, indicating consistent magnetic field exposure. The data exhibits slight skewness and quantization effects, particularly in the X-axis.

Euler angles derived from the IMU data show Roll and Pitch means near zero, with Yaw indicating the IMU's orientation relative to magnetic north. Time series analysis reveals gradual drifts in all angles despite the IMU being stationary. Yaw exhibits the highest variability, followed by Roll, with Pitch being the most stable.

Overall, the IMU performed as expected for a stationary device. The data generally follows Gaussian distributions, but with deviations in the magnetometer and Euler angles. These findings highlight the importance of sensor characterization for precise applications and suggest that additional calibration and filtering should be used in real-world scenarios.

Allan Variance Results

Based on our analysis of the IMU's Allan Variance data over a 5-hour period, we can learn about the different noise parameters in our IMU data. The accelerometer measured Angle Random Walk values ranging from 0.0019846 to 0.0028128 m/s/√Hz, with Bias Instability between 0.00064911 and 0.0014049 m/s² at time constants of 9.35 to 79.6 seconds. The gyroscope shows varied performance across axes, with Angle Random Walk values from 0.00047117 to 0.0049137 rad/√Hz, and Bias Instability between 0.00023458 and 0.00043781 rad/s at time constants ranging from 2.35 to 769.175 seconds. Both sensors demonstrate higher noise levels and instability compared to the VN-100 datasheet, specifically in the gyroscope's Z-axis ARW and Y-axis RRW. These findings show the importance of individual sensor characterization for precise applications and suggest that careful calibration and error modeling would be necessary for accurate navigation and control in robotics.