EECE 5554 - Robotics Sensing and Navigation

Lab 3: IMU Noise Characterization with Allan Variance

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Introduction

This report analyzes the noise characteristics of a VN-100 IMU by collecting 10-15 minutes of stationary data from its accelerometers, gyroscopes, and magnetometers at a 40 Hz rate. The data is processed to convert quaternions to Euler angles, and time series and histogram plots are used to examine the noise patterns. Additionally, Allan Variance analysis is performed to identify key noise parameters like bias instability and random walk.

10 -15 Minutes Data analysis

Data Collection and Processing

The VN-100 IMU was set up to output data at 40 Hz using a serial command. To minimize environmental interference, the IMU was kept stationary and positioned away from moving objects and electronic devices. Data was collected via a ROS2 bag file for a 10-minute period, capturing accelerations (x, y, z), angular velocities (x, y, z), and magnetic field data (x, y, z).

For analysis, quaternions were converted to Euler angles to simplify orientation visualization. The raw data was used without filtering or preprocessing to retain accuracy.

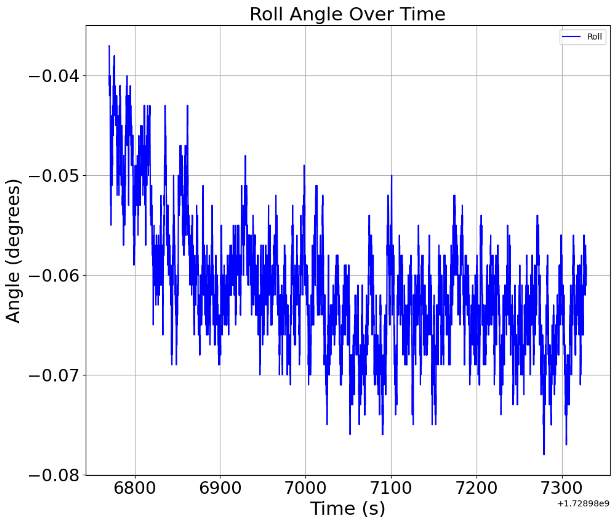
Roll, Pitch, and Yaw Analysis

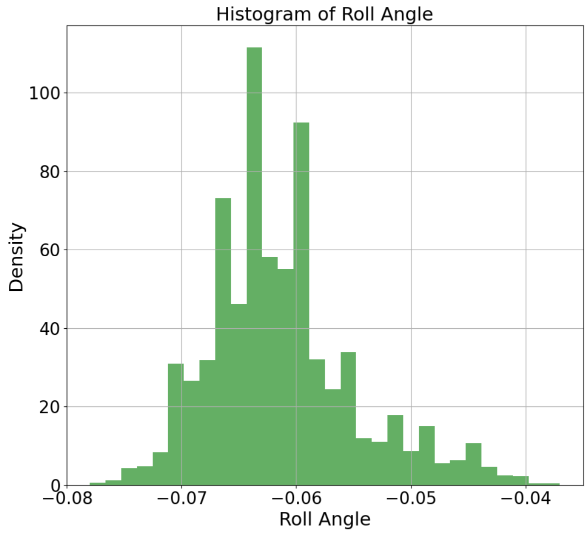
The time series plots and histograms for Roll, Pitch, and Yaw, the data distribution closely resembles a near-Gaussian distribution, indicating the presence of stationary noise. Despite keeping the IMU stationary, minor vibrations in the environment, such as background mechanical noise, could have introduced slight variations in the measurements. Table 1 summarizes the mean and standard deviation of the Euler angles for this dataset.

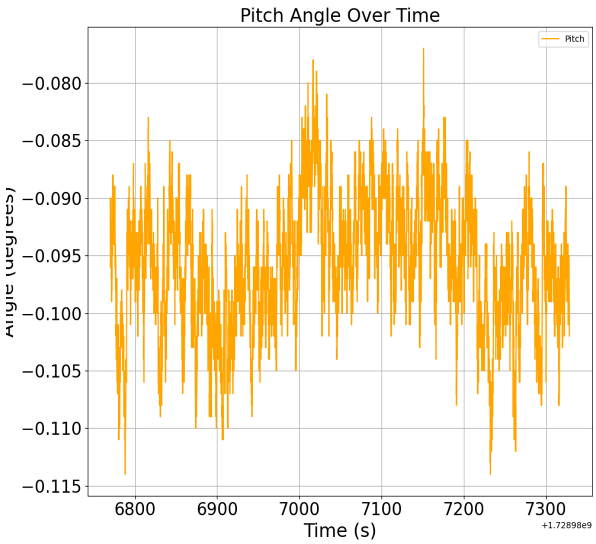
Table 1

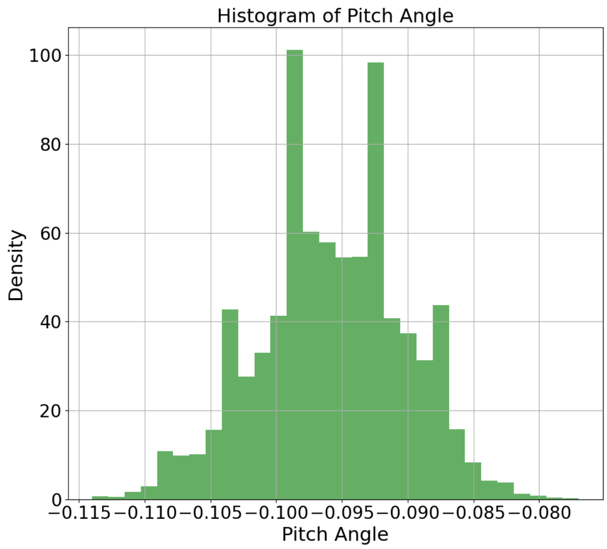
	Roll	**Pitch**	**Yaw**
Mean (μ)	*-0.0613*	*-0.0957*	*-85.3232*
Standard Deviation (σ)	*0.0064*	*0.0055*	*0.1266*

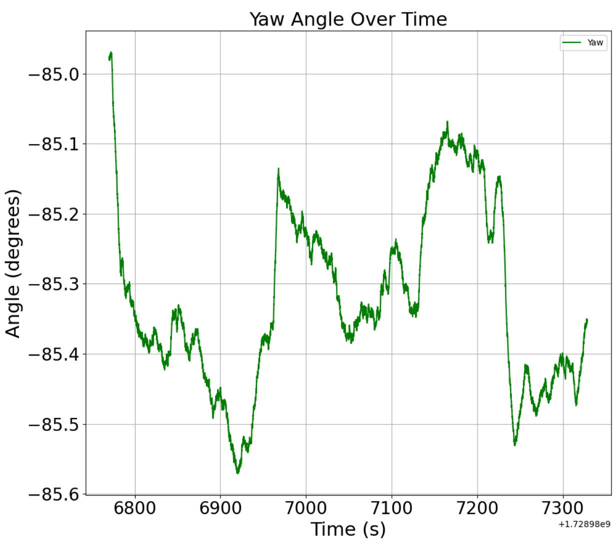
TIME SERIES **HISTOGRAM**

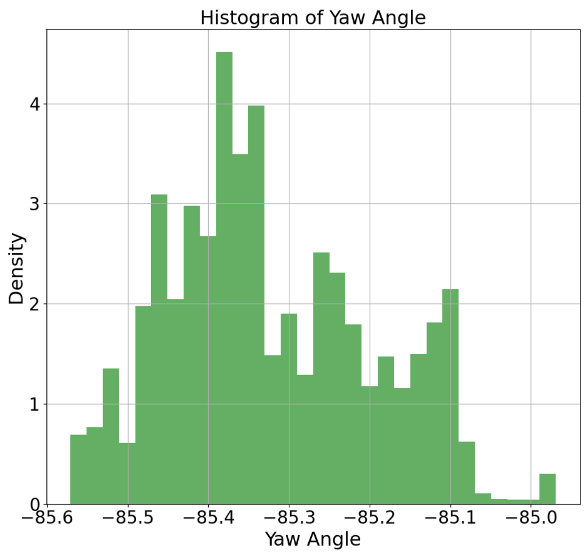












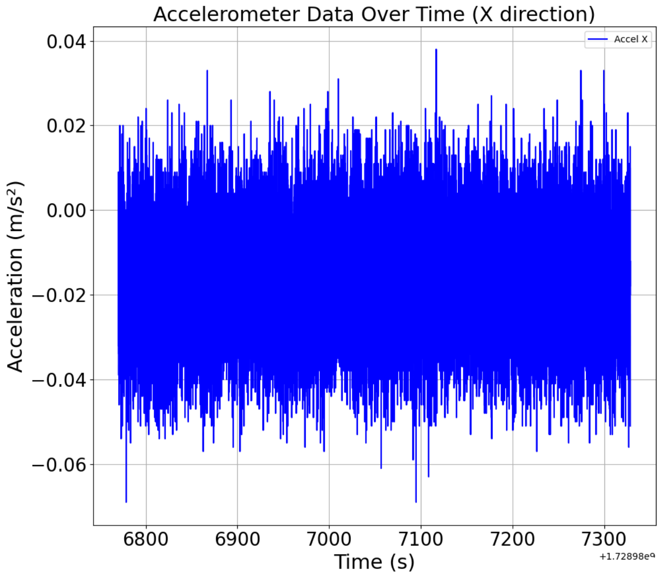
Linear Acceleration Analysis

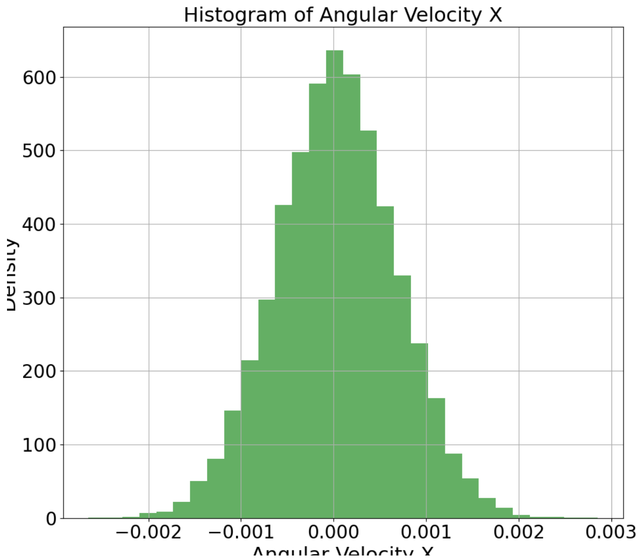
The time series and histograms for linear acceleration in the X, Y, and Z axes indicate that the data follows a Gaussian distribution. For the Z-axis, the data reflects the influence of gravity, with a mean value of approximately -9.64 m/s², which is slightly lower than the expected 9.8 m/s² due to environmental factors or minor sensor drift. Similar to the Z-axis, the X and Y axes also show small deviations around zero, reflecting minor noise in the data. See Table 2 for the exact mean and standard deviation values.

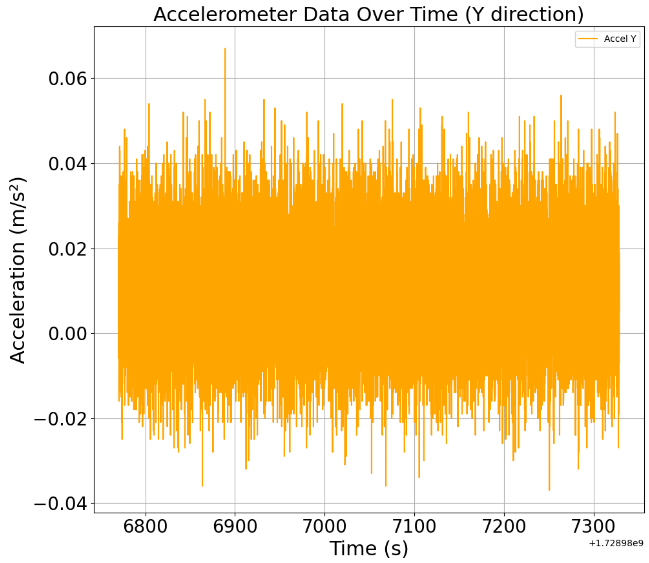
Table 2

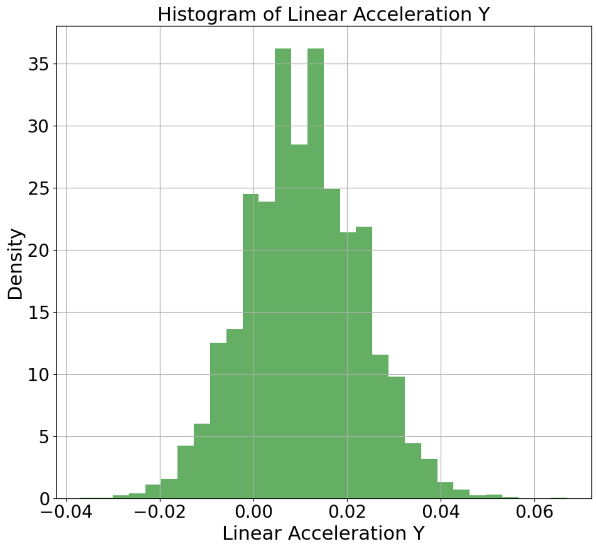
Axis	**Mean (m/s²)**	**Standard Deviation (m/s²)**
X	***-0.0162***	***0.0128***
Y	***0.0107***	***0.0121***
Z	***-9.6411***	***0.0171***

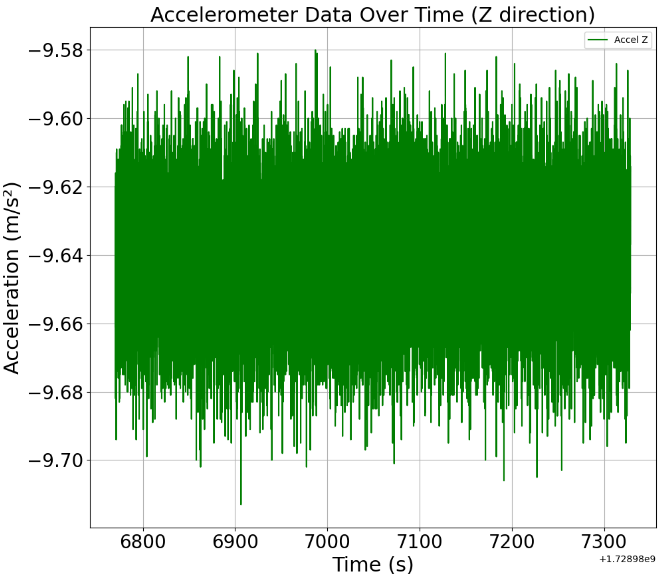
TIME SERIES **HISTOGRAM**

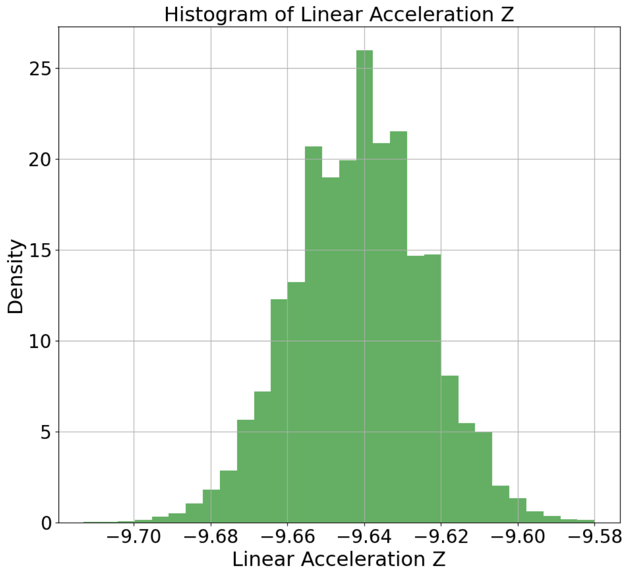












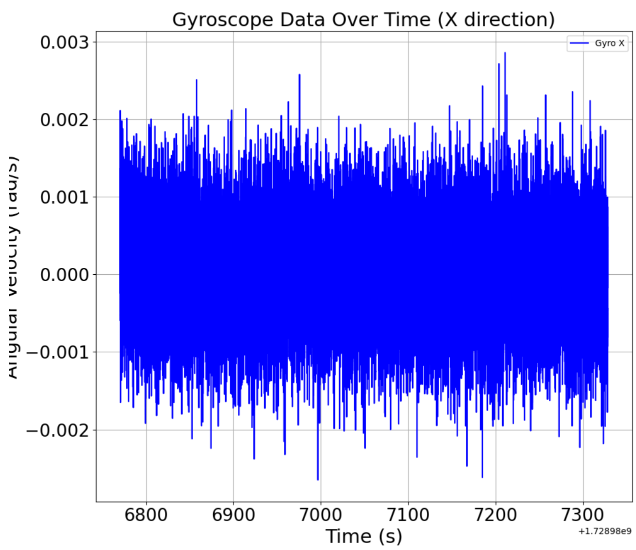
Angular Velocity Analysis

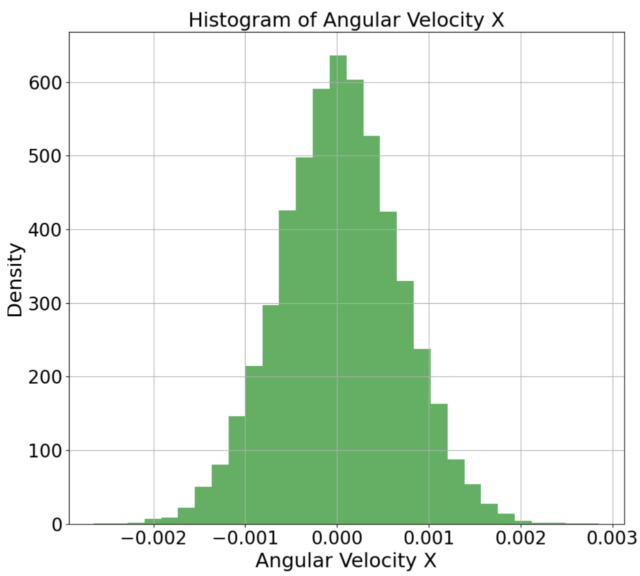
The angular velocity data (X, Y, Z axes) demonstrated minimal variation around zero, as expected for a stationary IMU. The histograms for each axis show a near-Gaussian distribution, with slight variations attributed to sensor noise. As the IMU was not in motion, the mean angular velocity values were effectively zero for all axes. The small standard deviations reflect the precision of the gyroscope in detecting rotational changes.

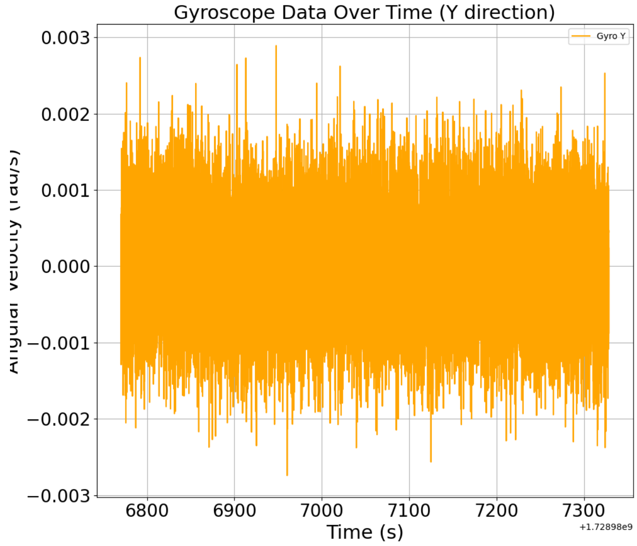
Table 3

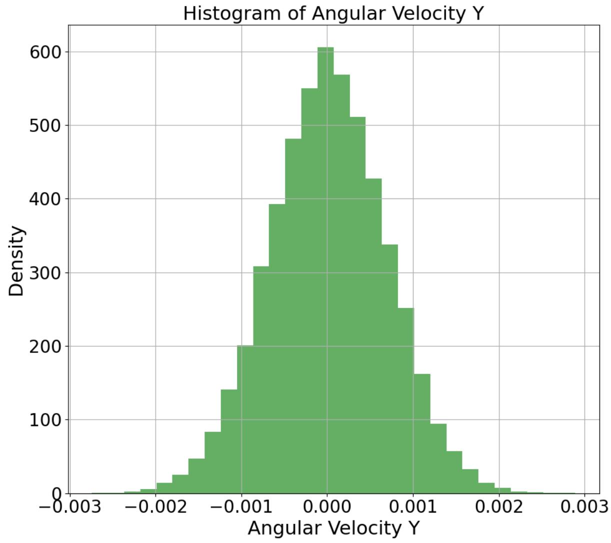
Axis	**Mean (rad/s)**	**Standard Deviation (rad/s)**
Angular Velocity X	*0.0000*	*0.0006*
Angular Velocity Y	*0.0000*	*0.0007*
Angular Velocity Z	*0.0000*	*0.0007*

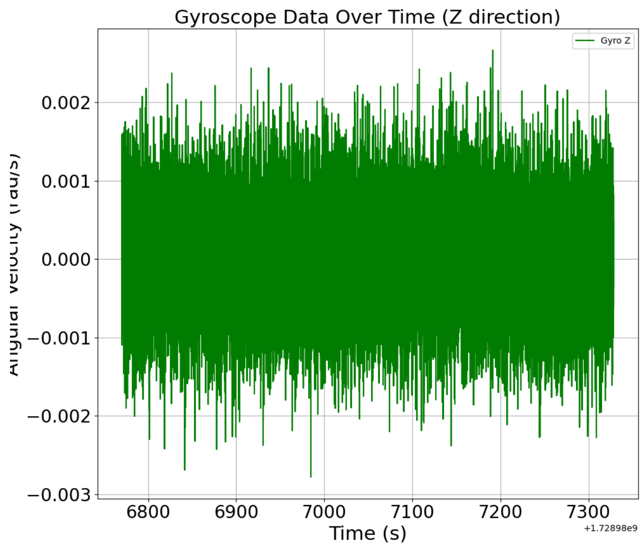
TIME SERIES **HISTOGRAM**

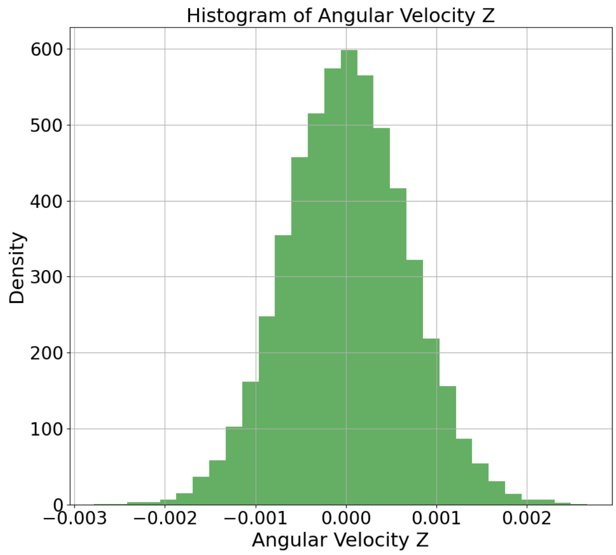








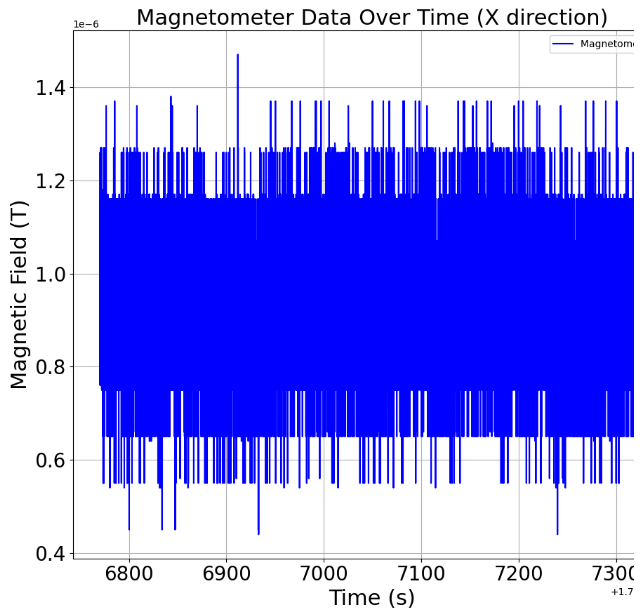


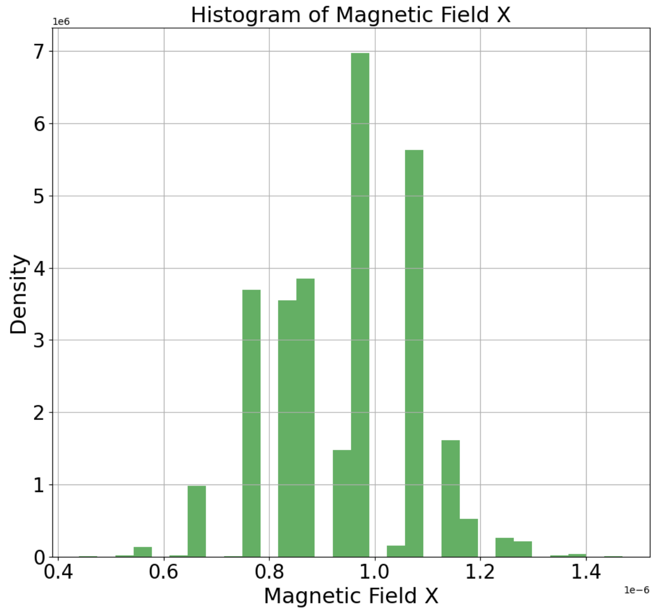


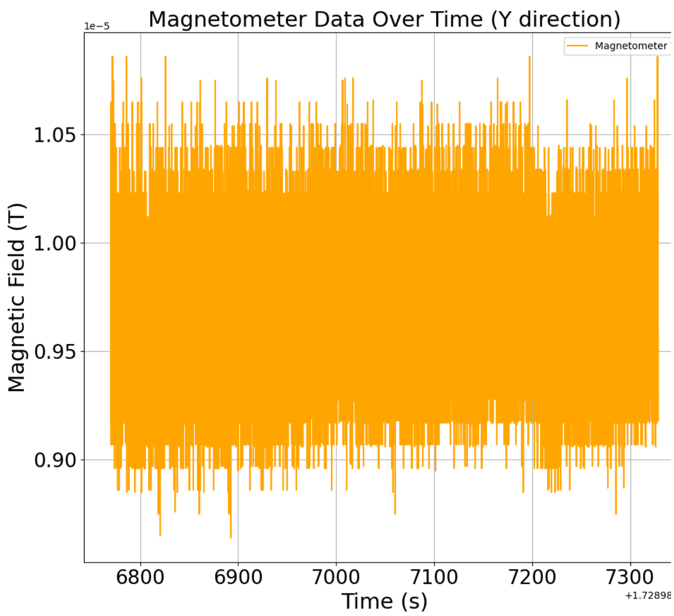
Magnetic Field Analysis

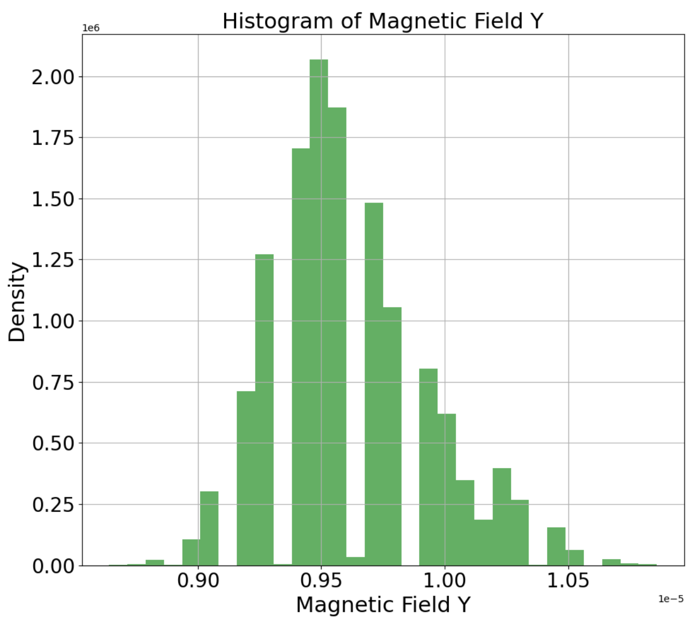
The histograms and time series plot of the Magnetic Field data, show a distribution that closely aligns with a Gaussian profile. This suggests that the measurements are primarily influenced by a consistent magnetic environment. However, noticeable spikes in the data indicate interference from nearby electronic devices, such as laptops and mobile phones. This external electromagnetic noise can introduce variability in the readings, emphasizing the importance of conducting measurements in a controlled environment to minimize such disturbances

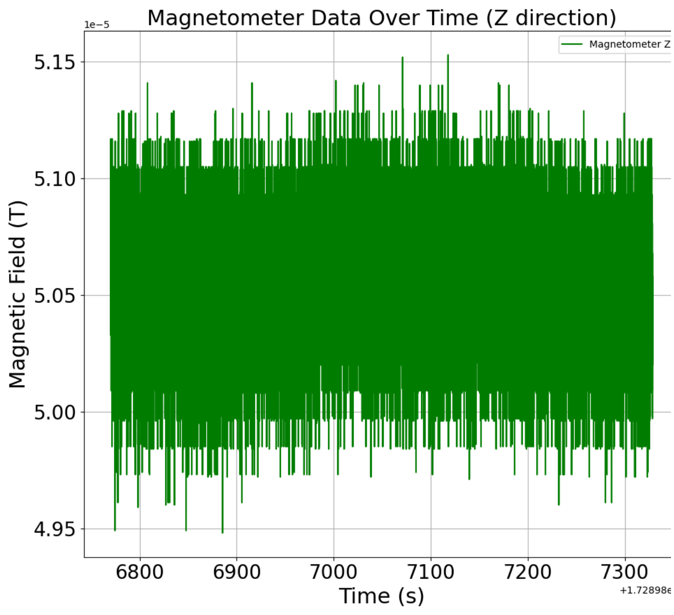
TIME SERIES | **HISTOGRAM**

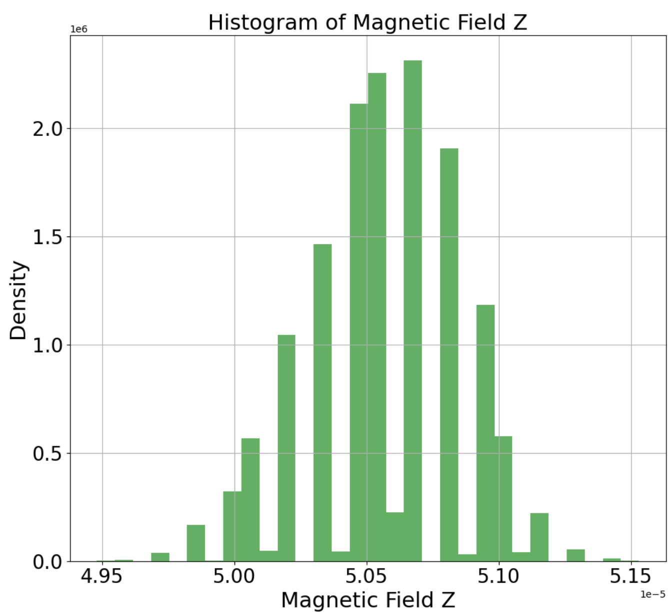












Allan Variance Data Collection and Analysis

For the Allan Variance analysis, our group collected 5 hours of stationary IMU data in a low-vibration environment (basement) to minimize external disturbances. Using MATLAB's Allan variance functions, we analyzed the IMU's noise characteristics for each sensor axis (accelerometers and gyroscopes).

Types of Noise Present: The analysis revealed several types of noise:

- **Angle Random Walk (ARW):** Represented by a slope of -0.5 in the Allan deviation plot, this noise is due to the random variation in the rate measurements and can be modeled as a white noise process in the gyroscope data.
- **Rate Random Walk (RRW):** Shown by a slope of 0.5, this noise describes random drift in the rate measurements over time, typically originating from external factors like temperature changes.
- **Bias Instability:** Occurs at the flat portion of the Allan deviation curve and represents low-frequency noise in the gyroscope and accelerometer data. It is often modeled using a random constant offset.

Modeling Noise and Measurement:

- **Modeling**:
  - **Allan Variance**: This method is used to analyze the noise characteristics of the gyroscopes and accelerometers. It helps to quantify the white noise, bias instability, and random walk components by examining how the noise scales with different averaging times (tau).
  - **Kalman Filter**: A mathematical model that can be used to estimate the true state of the system while filtering out noise, especially in applications involving inertial sensors.
  -
- **Angle Random Walk** is measured in units of (rad/s)/Hz(rad/s)/\sqrt{Hz}(rad/s)/Hz
- **Rate Random Walk** is modeled by random drift over time, measured in (rad/s)Hz(rad/s)\sqrt{Hz}(rad/s)Hz
- **Bias Instability** is typically the minimum point of the Allan deviation plot. For the VN100, this noise characteristic is crucial as it impacts long-term accuracy, and its values can be related to those found in the IMU datasheet.

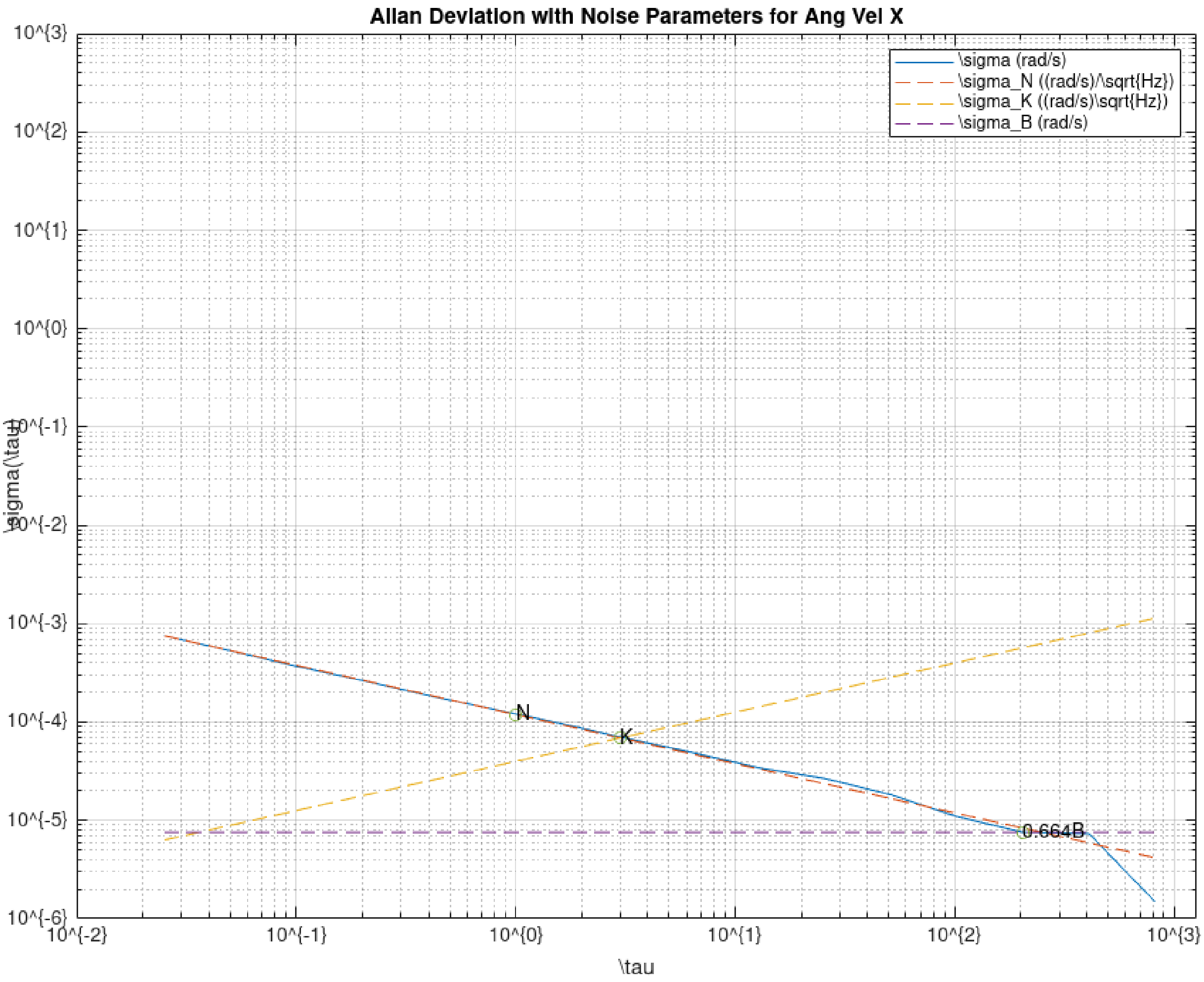
Gaussian white noise

Gaussian White Noise can be assessed using an Allan deviation plot for the gyroscope data. If the sensor exhibits Gaussian white noise, the left side of the plot should display a slope of -0.5. A line with a slope of -0.5 to the X-gyro Allan deviation plots, which aligns well with the observed data. This indicates that the sensor exhibits Gaussian white noise, which is crucial to confirm since many sensor fusion algorithms, like Kalman Filters, assume that measurements are subject to Gaussian white noise.

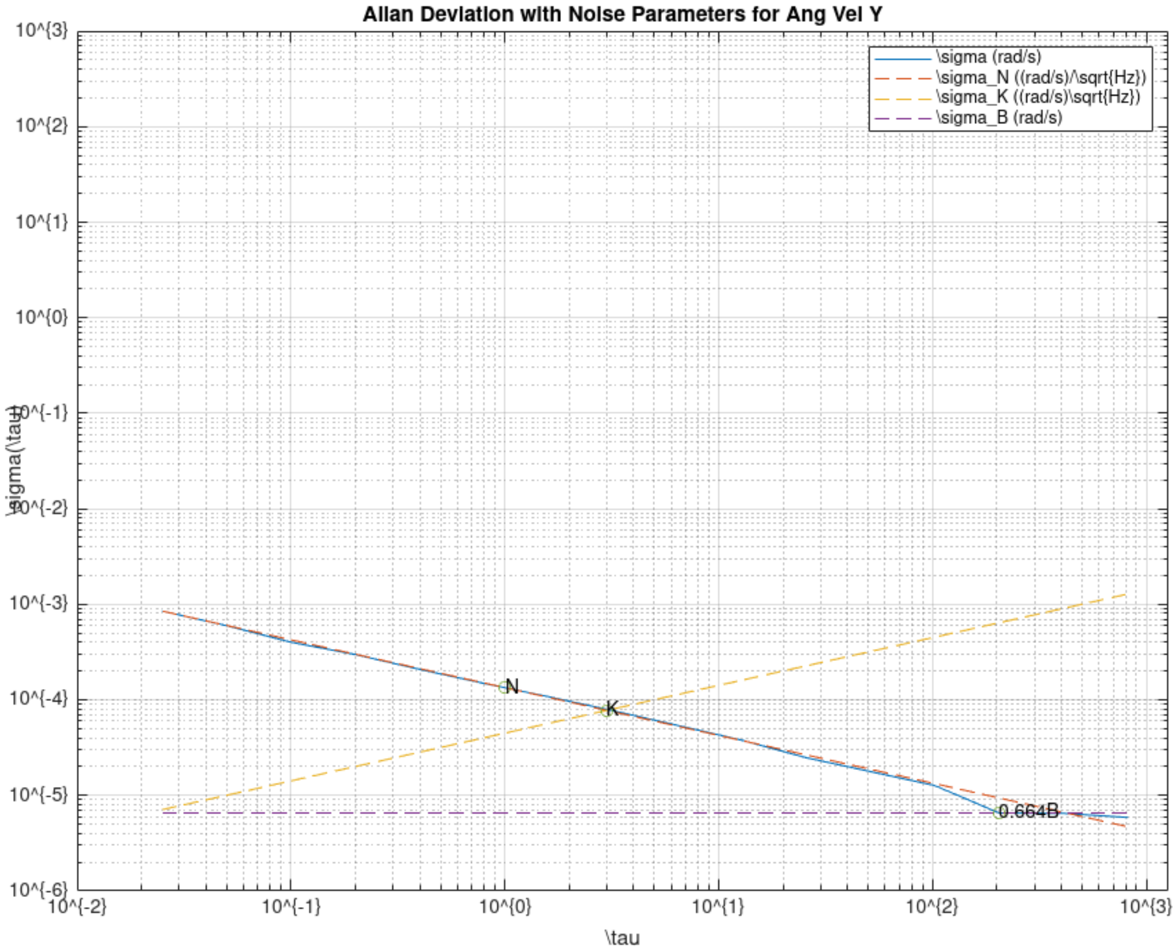
Gyroscope Noise Analysis

- **Angular Velocity X**
  - ARW: 0.00011924 (rad/s/√Hz)
  - RRW: 6.8842e-05 (rad/s√Hz)
  - BI: 1.1367e-05 (rad/s)
- **Angular Velocity Y**
  - ARW: 0.00013413 (rad/s/√Hz)
  - RRW: 7.7438e-05 (rad/s√Hz)
  - BI: 9.8231e-06 (rad/s)
- **Angular Velocity Z**
  - ARW: 0.00011018 (rad/s/√Hz)
  - RRW: 6.3611e-05 (rad/s√Hz)
  - BI: 1.671e-05 (rad/s)

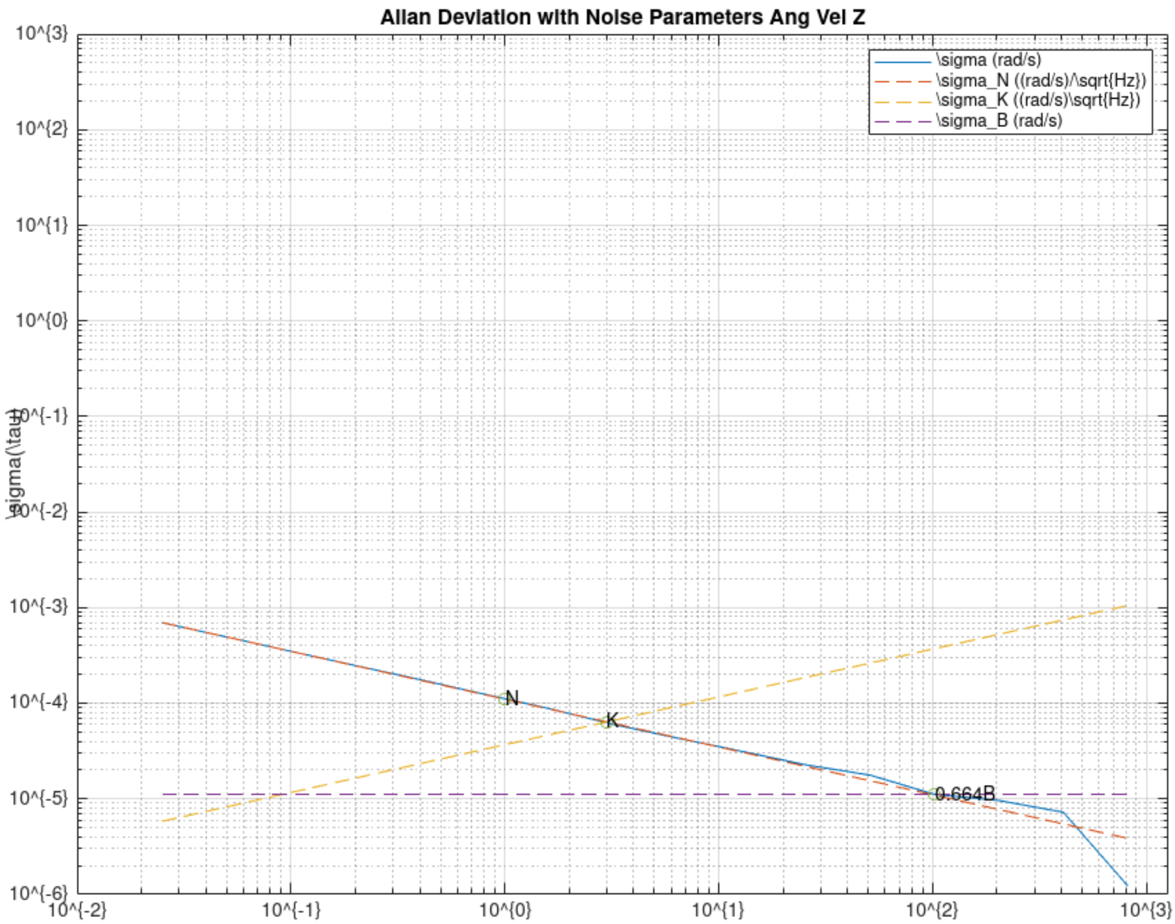
Allan Deviation With Noise Parameters for Angular velocity x



Allan Deviation With Noise Parameters for Angular velocity Y



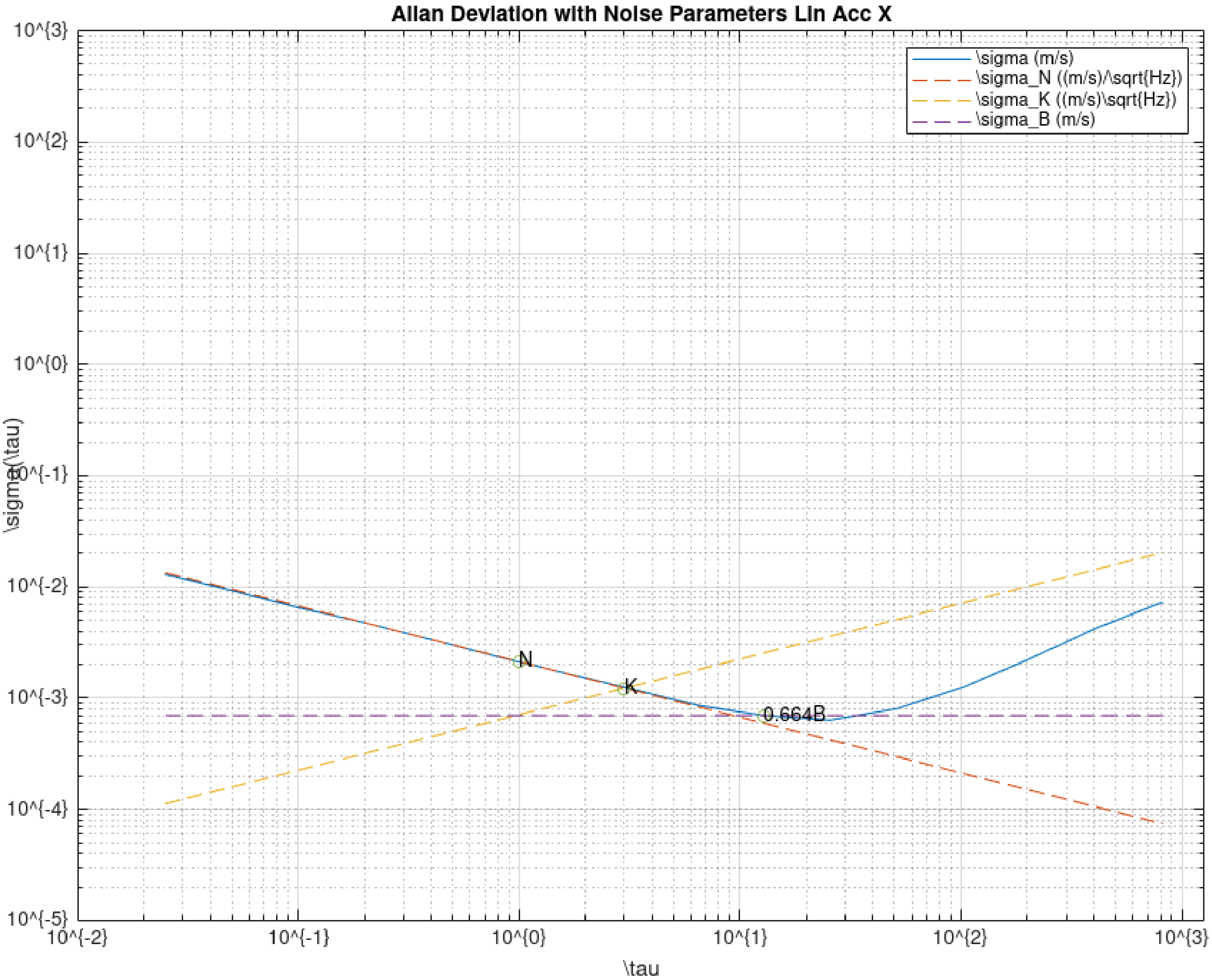
Allan Deviation With Noise Parameters for Angular velocity Z



Accelerometer Noise Analysis

The analysis of the accelerometer data provided insights into the noise characteristics of the IMU. The following noise parameters were calculated for the accelerometer readings, expressed in linear acceleration units:

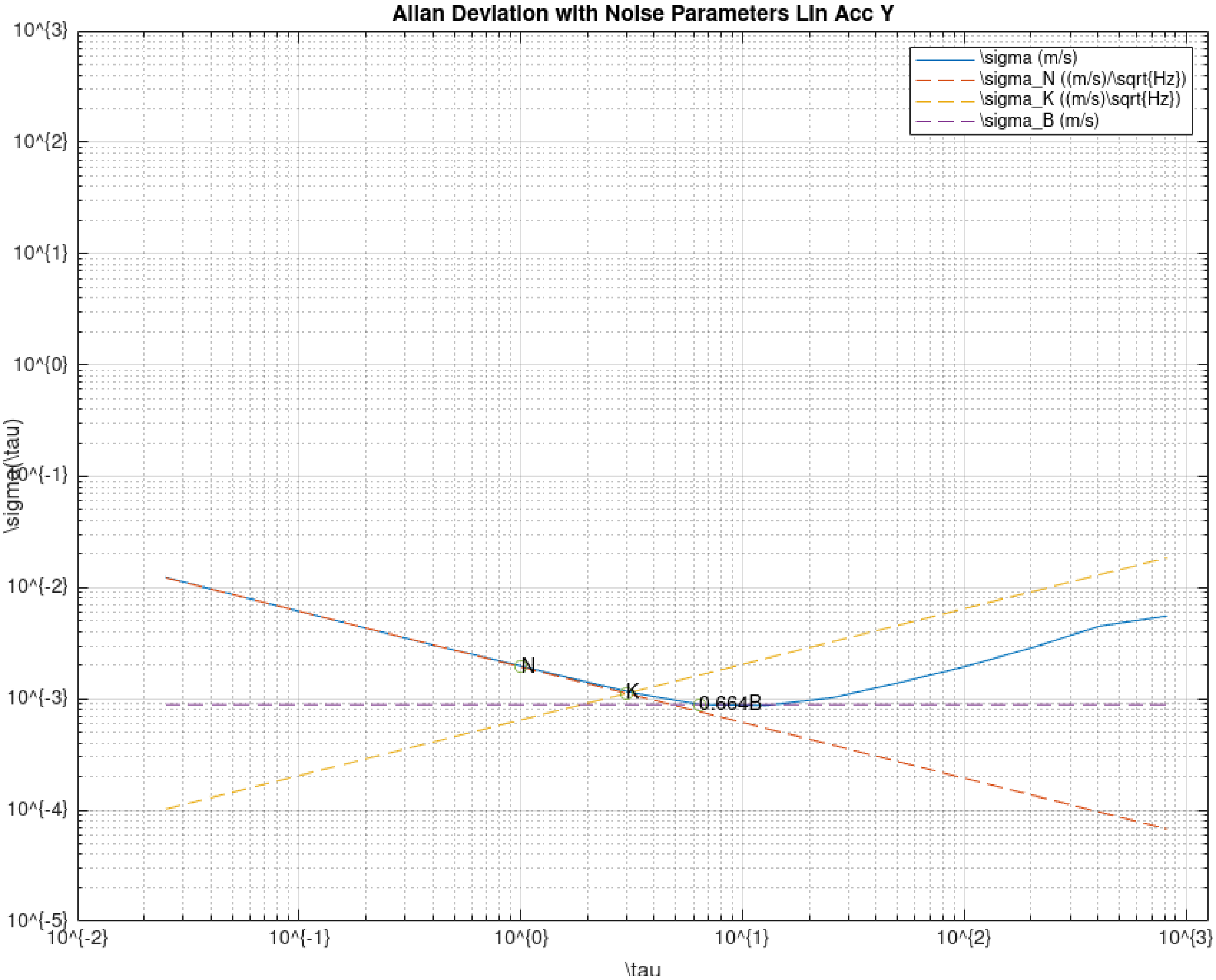
Allan Deviation With Noise Parameters for Linear Acceleration X



Accelerometer X

- **Angle Random Walk (ARW):** 0.0021298 ($m/s^2/\sqrt{Hz}$)
- **Rate Random Walk (RRW):** 0.0012297 ($m/s^2\sqrt{Hz}$)
- **Bias Instability (BI):** 0.0010493 (m/s^2)
- **Tau Parameters:** [1.0000, 3.0000, 12.8000]

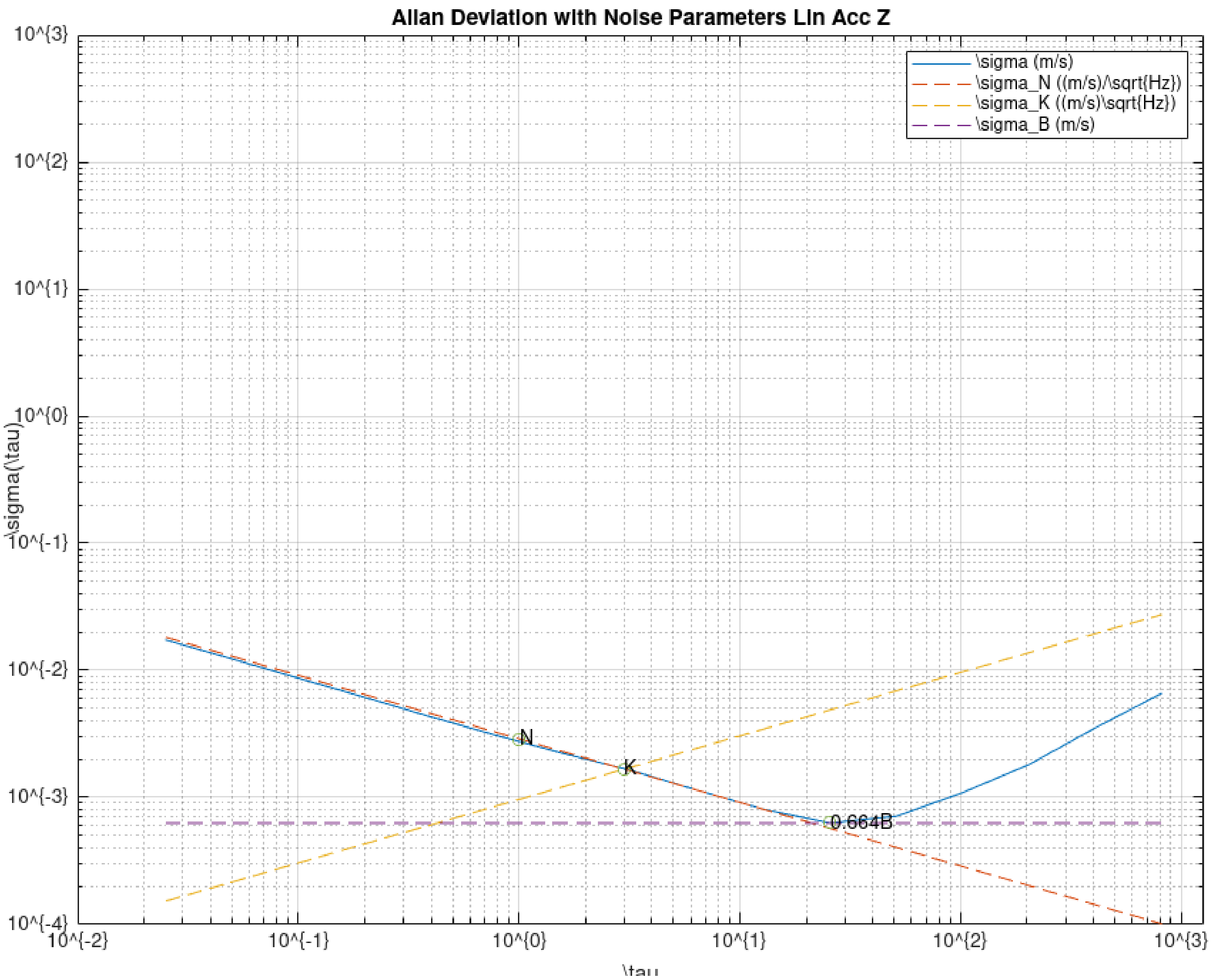
Allan Deviation With Noise Parameters for Linear Acceleration Y



Accelerometer Y

- **Angle Random Walk (ARW):** 0.0019364 (m/s²/√Hz)
- **Rate Random Walk (RRW):** 0.001118 (m/s²√Hz)
- **Bias Instability (BI):** 0.0013371 (m/s²)
- **Tau Parameters:** [1.0000, 3.0000, 6.4000]

Allan Deviation With Noise Parameters for Linear Acceleration Z



Accelerometer Z

- **Angle Random Walk (ARW):** 0.0028802 ($m/s^2/\sqrt{Hz}$)
- **Rate Random Walk (RRW):** 0.0016629 ($m/s^2\sqrt{Hz}$)
- **Bias Instability (BI):** 0.00094316 (m/s^2)
- **Tau Parameters:** [1.0000, 3.0000, 25.6000]

Conclusion

Allan Variance (AVAR) is primarily applied to gyroscopes and accelerometers rather than magnetometers due to

Measurement Characteristics:

- **Gyroscopes and Accelerometers**: These sensors continuously measure motion and orientation (angular velocity and linear acceleration), with noise primarily from ***random processes***. This makes them suitable for Allan Variance (AVAR) analysis to assess stability and performance.
- **Magnetometers**: They measure magnetic field strength and direction but are ***affected by external factors*** like nearby ferromagnetic materials and environmental noise, complicating the isolation of intrinsic sensor noise.

Noise Types:

- **Inertial Sensors**: Gyroscopes and accelerometers show well-defined noise characteristics (white noise, bias instability, random walk) that AVAR can quantitatively assess.
- **Magnetometers**: Their noise is often dominated by external interference and artifacts, making AVAR less effective for performance characterization.

In this analysis of the VN-100 IMU, we investigated the noise characteristics of the gyroscopes and accelerometers through Allan Variance (AVAR) analysis, while recognizing the limitations of applying AVAR to magnetometer data due to external interference and intrinsic noise complexities.

The measurements from 10-15 minute stationary data and the 5-hour data collection highlighted the typical noise behaviors, revealing critical parameters such as Angle Random Walk (ARW), Rate Random Walk (RRW), and Bias Instability for each sensor.