IMU Noise Characterization with Allan Variance

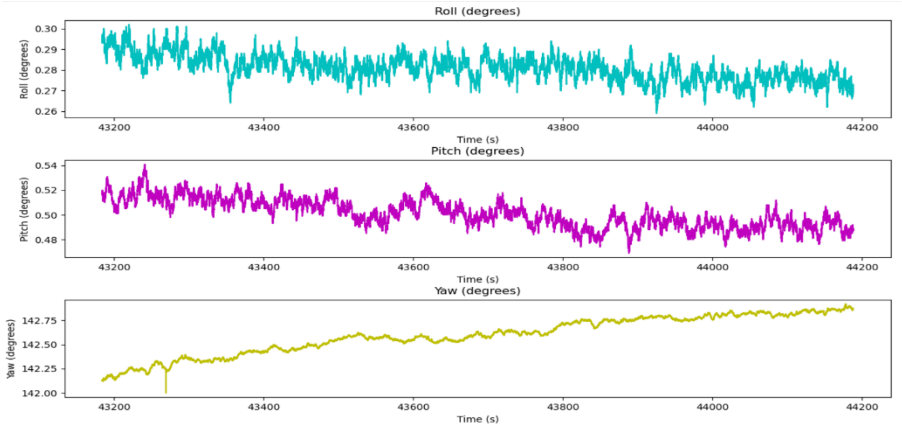
Abstract: The Inertial Measurement Unit (IMU) sensor is used to capture and analyze motion data, such as acceleration, angular velocity, magnetic field, and orientation. The IMU provides measurements in three dimensions (X, Y, Z) for each of the above parameters to study the sensor's characteristics of motion and orientation. A custom driver is developed to serially read the data coming from the IMU and store it in ROS bags. Two sets of data were recorded, one for 15-20 minutes and one for around 5 hours. The 15-20-minute data is visualized by time series plots and histograms for analysis and interpretation. The 5 hours of data are used for Allan variance. IMU can be used in applications like robotics, navigation systems, and motion tracking.

Introduction: Inertial Measurement Unit (IMU) sensors are used to capture motion and orientation data. IMUs are widely used in fields such as robotics, aerospace, and wearable technology to measure linear acceleration, angular velocity, magnetic field strength, and orientation in three-dimensional space. A Vectornav VN-100 IMU sensor is used for this lab which contains multiple sensors to measure its motion and orientation. The aim is to collect and analyze the Euler angles (roll, pitch, yaw), acceleration, angular velocity, and magnetic field of the sensor at a static state. The performance of the sensor can be affected by numerous factors which will be discussed further. The 5-hour data is used to determine the Allan Variance.

Sources of Noise:

- **Mechanical Vibrations:** External mechanical vibrations from the environment (human movement, vehicles, or machines) can introduce noise.
- **Bias Drift (Zero Offset Error):** Over time accelerometers and gyroscopes can experience change in their baseline output leading to bias errors.
- **Inherent Sensor Noise (White Noise):** It refers to the random fluctuations in the output due to the physical and electronic limitations of the sensor and can cause the output to deviate from the true value without any movement.
- **Magnetic Interference:** The magnetometer in IMU is sensitive to external magnetic fields. Nearby electronic devices, magnets, or metallic objects can cause magnetic interference.
- **Alignment and Mounting Issues:** Misalignment of the IMU sensor axes and reference coordinate system or improper mounting can introduce errors.

Graphs and Plots:



A] Orientation

The orientation (Roll, Pitch, Yaw) and the angular velocity of the object are given by the Gyroscope present in the IMU. The gyroscope provides roll, pitch, and yaw which is then converted to quaternions to avoid gimbal lock. Although the graphs are plotted for roll, pitch, and yaw as 4D visualization is not possible.

The data is collected when the sensor is at rest, so ideally there should not be any deviation in the values. But there is some noise introduced which causes the readings to deviate from its true value. The mean deviation can be calculated by:

Mean Deviation from 0= $\frac{1}{\eta}\sum_{i=1}^{n}|x_i|$

n is the number of observations.

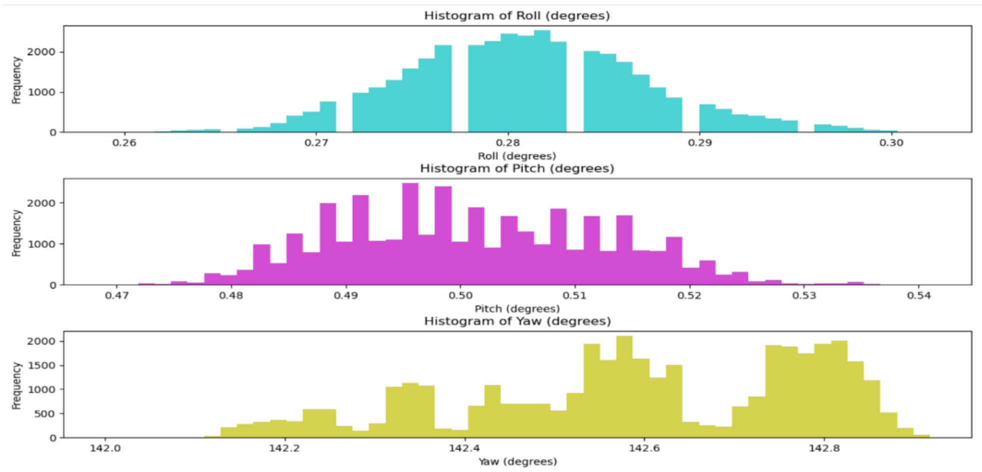
x_i is each observation in the dataset.

Mean Deviation of Roll: 0.2809°

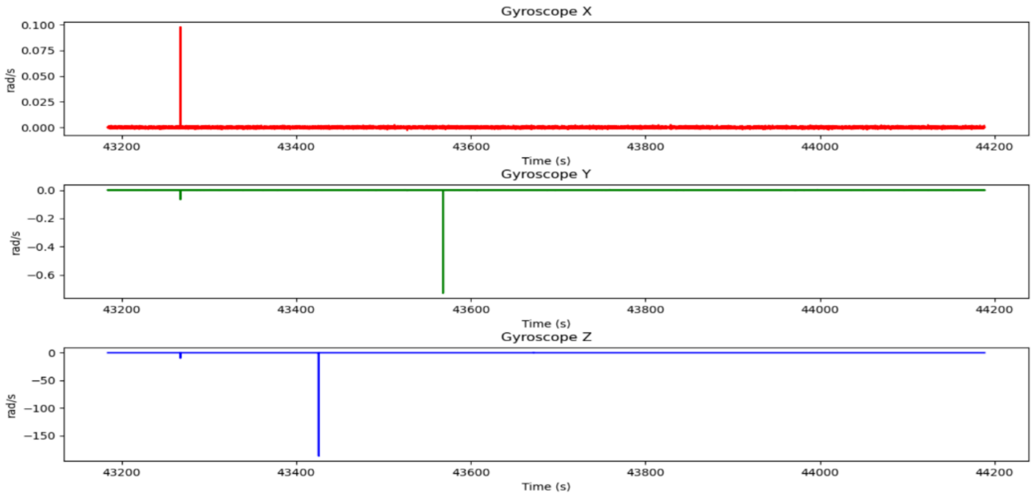
Mean Deviation of Pitch: 0.5011°

Mean Deviation of Yaw: 142.5934°

Distribution Plot:



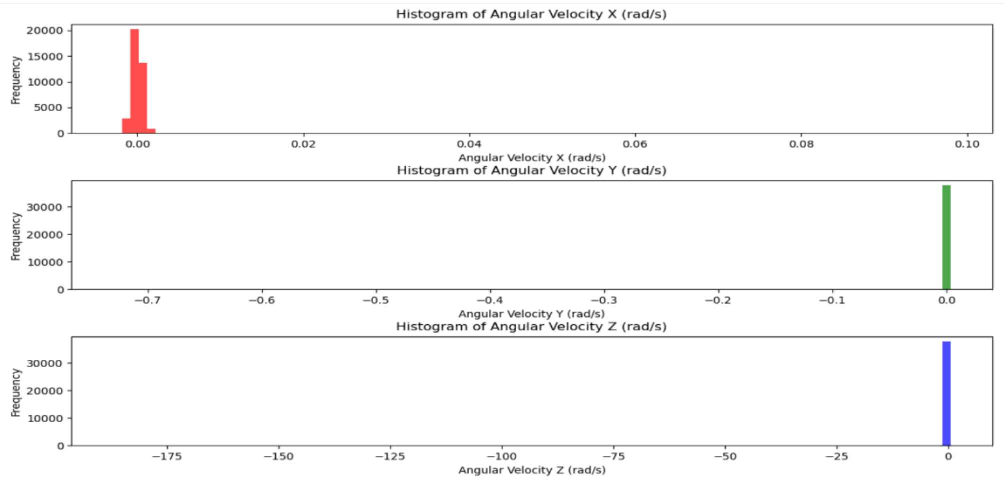
B] Angular Velocity



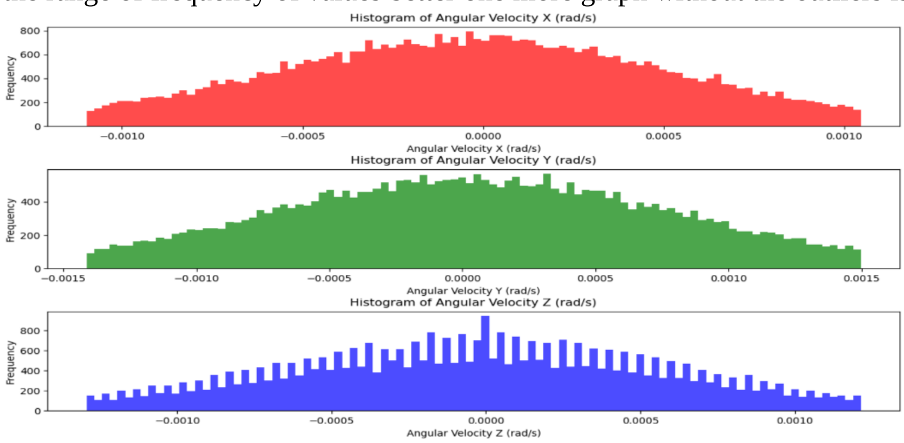
The Angular Velocity is given by the gyroscope which refers to the rate of rotation along the axes of IMU. The data displays spikes or outliers at different and random instances. These spikes can be the result of the noise sources mentioned above.

Mean Deviation in X-axis: 0.0000244 rad/s
Mean Deviation in Y-axis: 0.000022 rad/s
Mean Deviation in Z-axis: 0.005234 rad/s

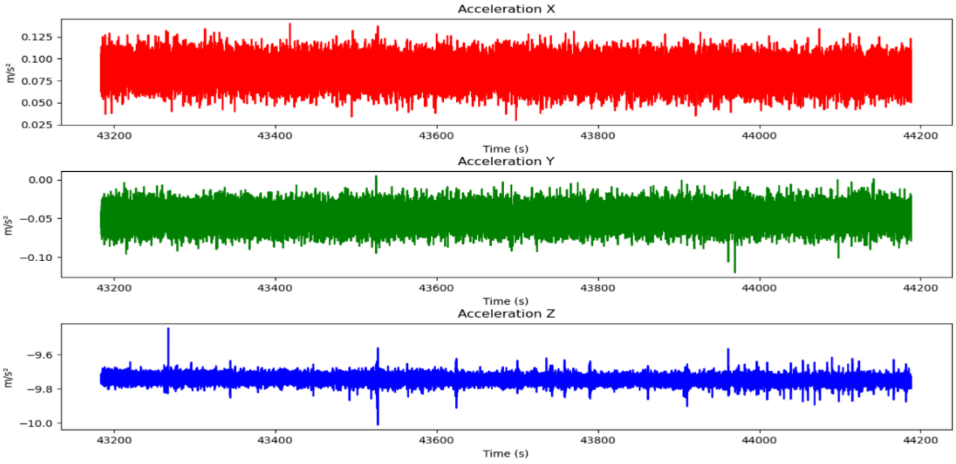
Distribution Plot:



To visualize the range of frequency of values better one more graph without the outliers is provided.



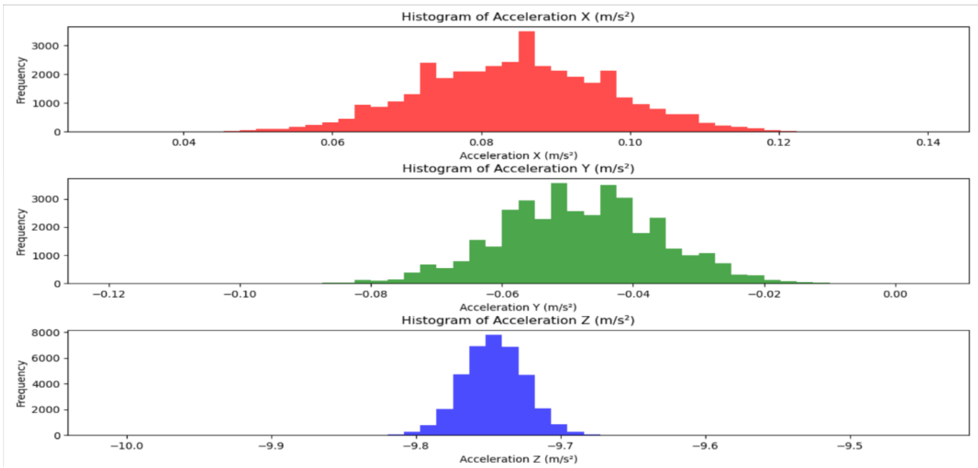
C] Linear Acceleration



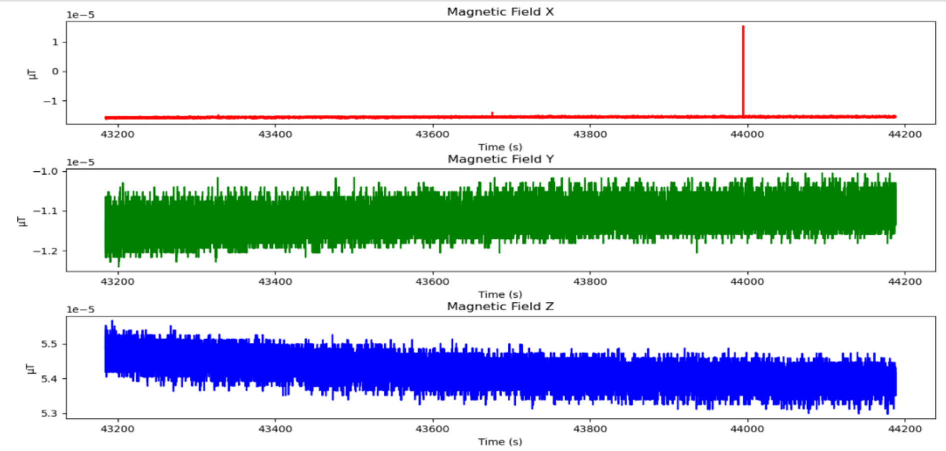
The accelerometers determine the acceleration that the object experiences over time in a straight line. The acceleration can be due to external or internal forces as well as gravity. The mean deviation from 0 for X, Y and Z axes are:

Mean Deviation in X-axis: 0.0845 m/s^2
Mean Deviation in Y-axis: 0.0481 m/s^2
Mean Deviation in Z-axis: 9.7459 m/s^2

Distribution Plot:

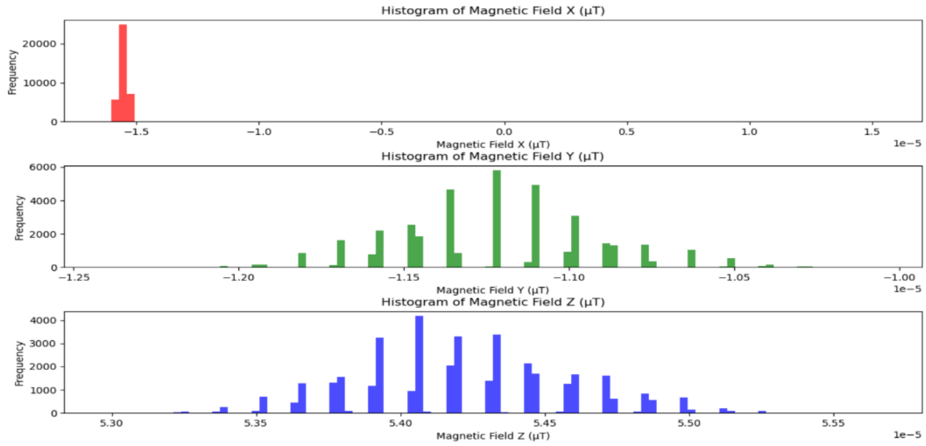


D] Magnetic Field

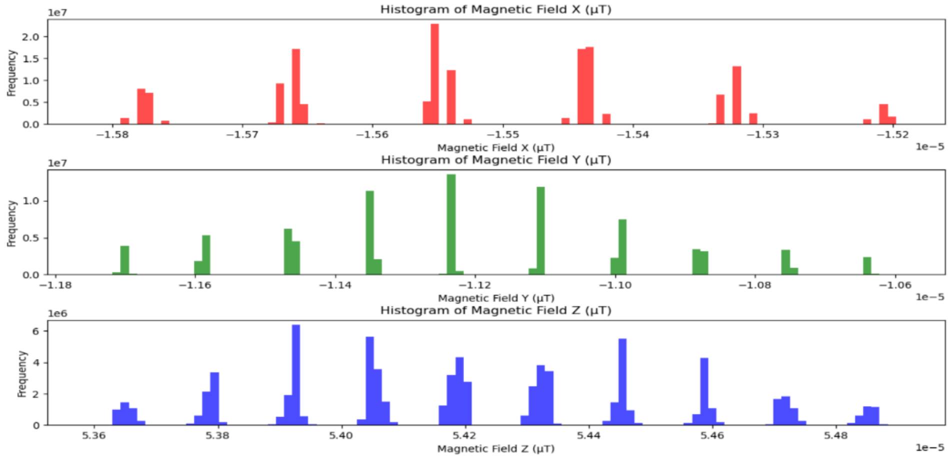


The magnetometer present in the IMU is used to measure the magnetic field. Magnetometers can also be used as a compass to determine the directions. Magnetometers can be used to correct drift errors. There is a spike in the data of the X-axis indicating it was subjected to noise or sudden change in the magnetic field along the X direction. The mean deviation of values from zero is:

Mean Deviation in X-axis: 0.0000155 μT
Mean Deviation in Y-axis: 0.0000112 μT
Mean Deviation in Z-axis: 0.0000542 μT
Distribution Plot:



To visualize the range of frequency of values better one more graph without the outliers is provided.



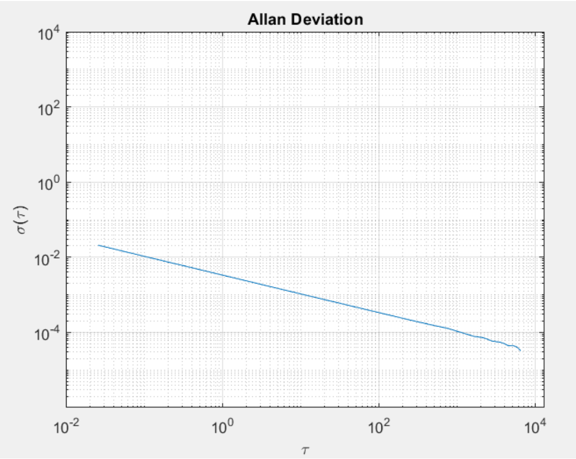
E] Allan Variance

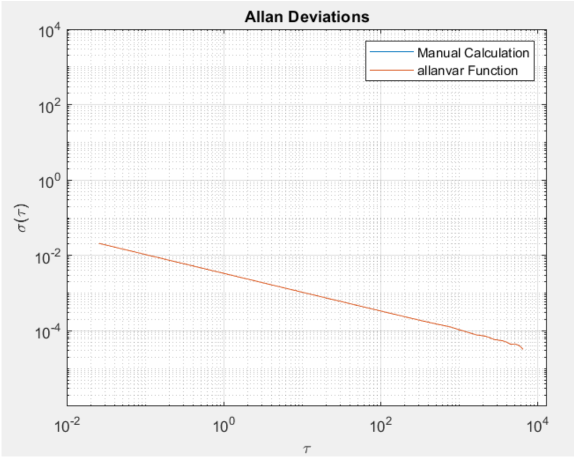
- **What is Allan Variance?**
  Allan Variance is used to analyze frequency stability and noise characteristics of signals, particularly of a time-varying system. It identifies different types of noise sources in sensors, especially in gyroscopes and accelerometers

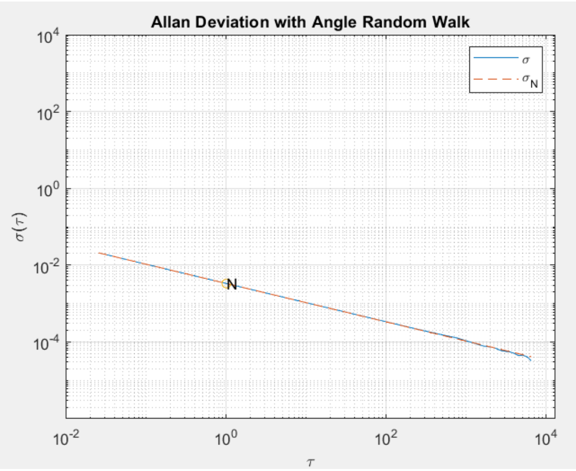
- **What kind of errors/sources of noise are present?**
  Noise sources like:
  Bias Instability: It is a low-frequency noise that causes slow drift in the sensor's output over time.
  Angle Random Walk: It is a high-frequency white noise in gyroscopes, this leads to random fluctuations in angular velocity and causes unbounded angular error over time.
  Rate Random Walk: A random drift in the rate output due to accumulated noise, showing as a positive slope in the Allan variance plot.
  Flicker Noise: It is a low-frequency noise source that affects the sensor's stability over intermediate timescales, often related to electronic component imperfections.

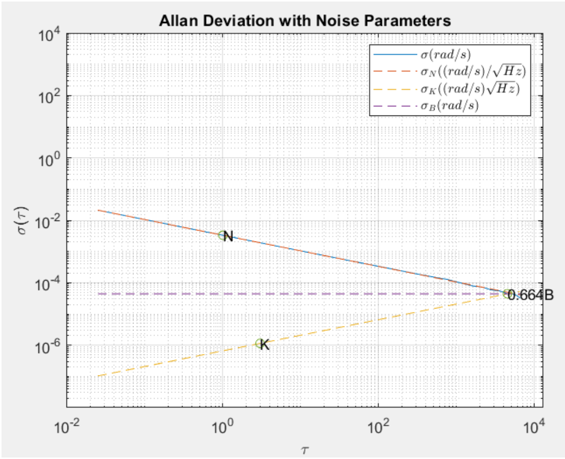
- **How do we model them? Where do we measure them? Can you relate your measurements to the datasheet for the VN100?**
  Bias Instability appears as a flat region in the Allan Variance plot. It is measured at the lowest point of the Allan Variance curve.
  Angle Random Walk causes angular errors and appears as a descending slope ($\tau^{-0.5}$) in the Allan Variance plot.
  Rate Random Walk is the drift in the rate output which is an ascending slope ($\tau^{0.5}$) in the Allan Variance Plot.
  Flicker Noise (1/f) affects the sensor's output stability and is observed as a flat line in the Allan Variance plot.

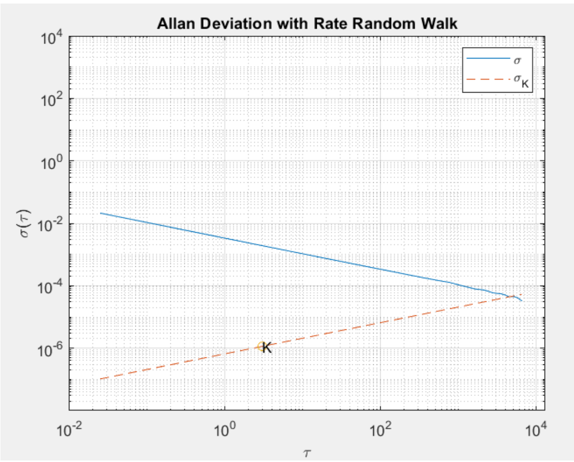
Plot for Allan Variance in Angular Velocity in X-axis

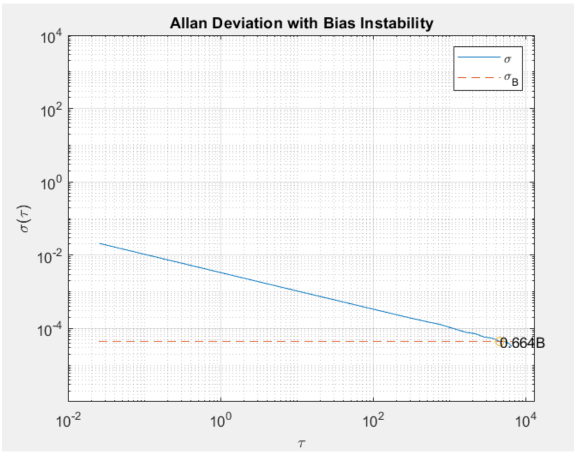




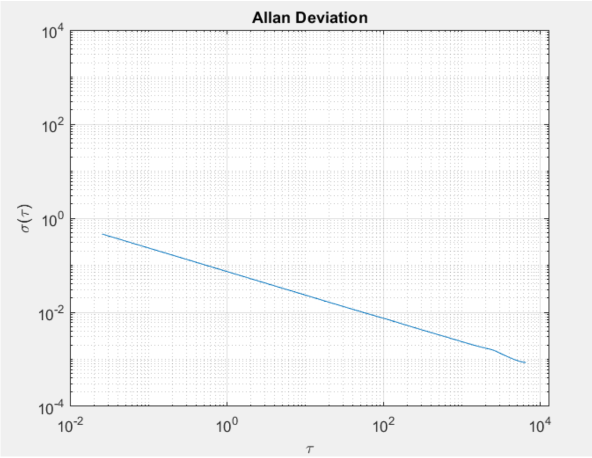


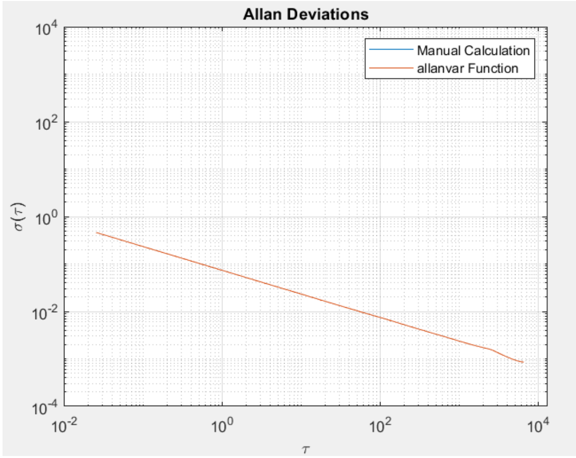


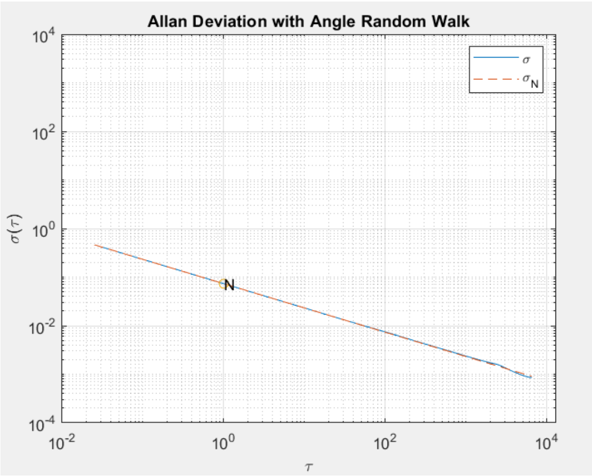


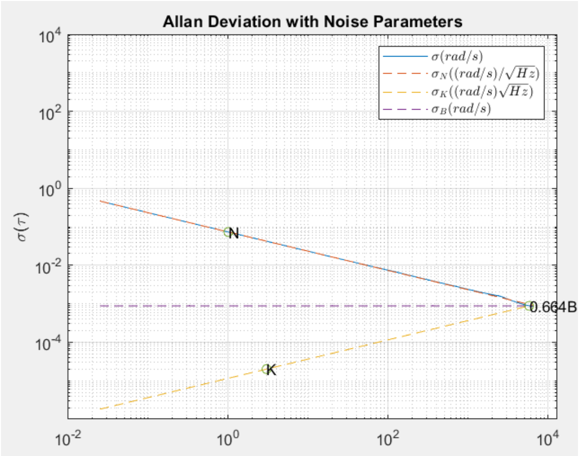


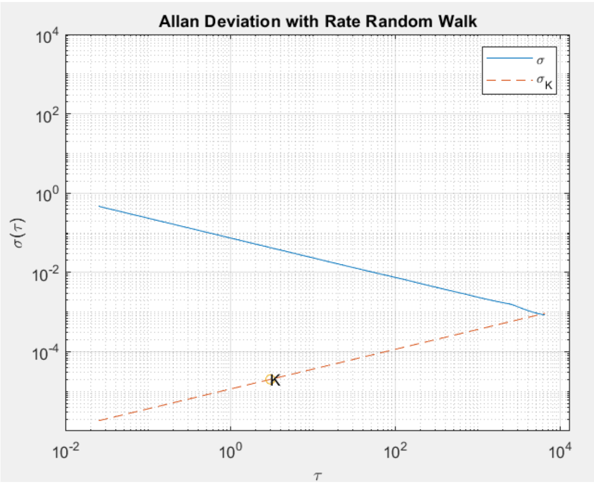
Plot for Allan Variance in Angular Velocity in Y-axis

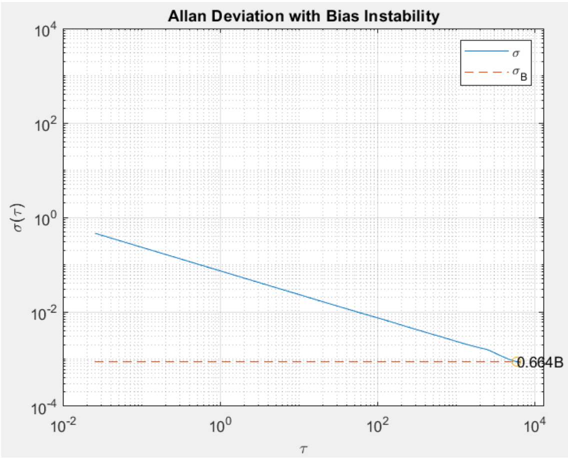




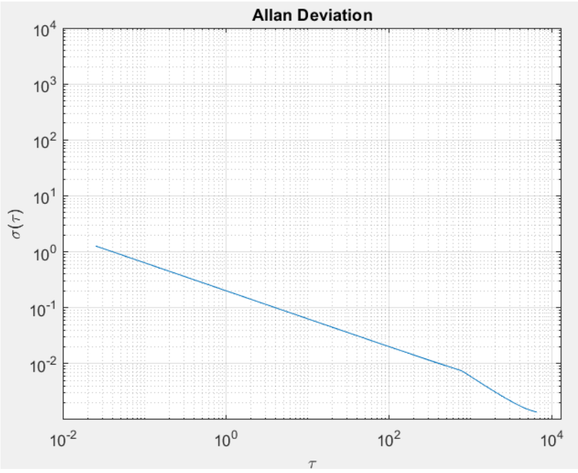


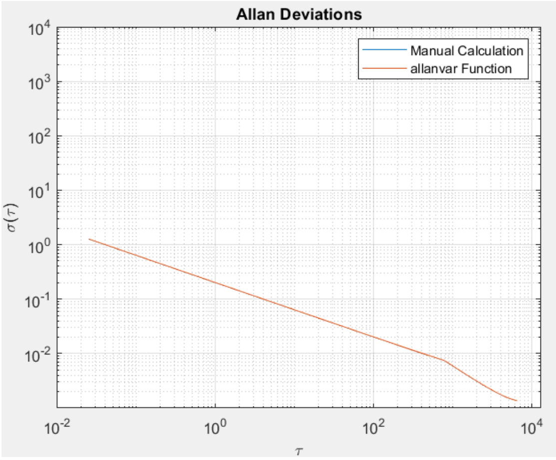


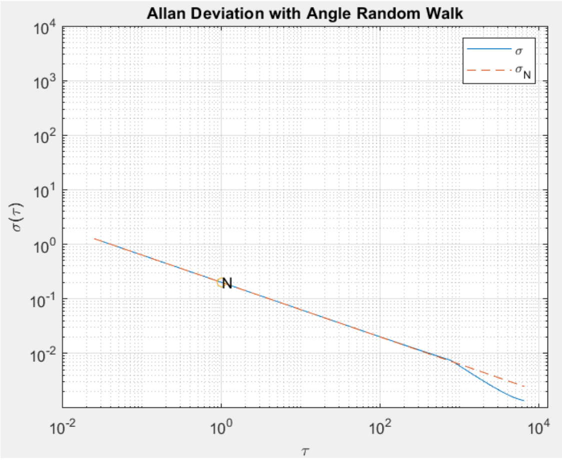


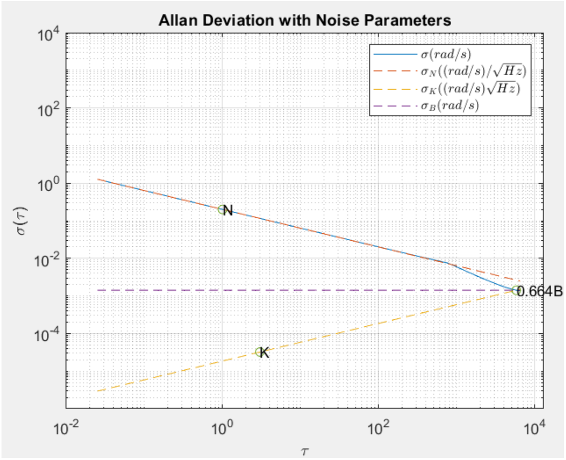


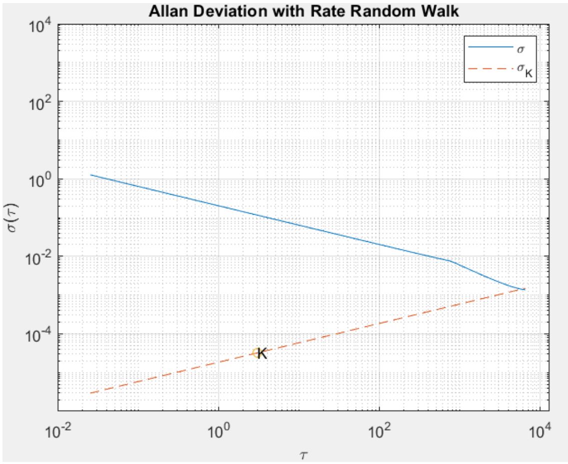
Plot for Allan Variance in Angular Velocity in Z-axis

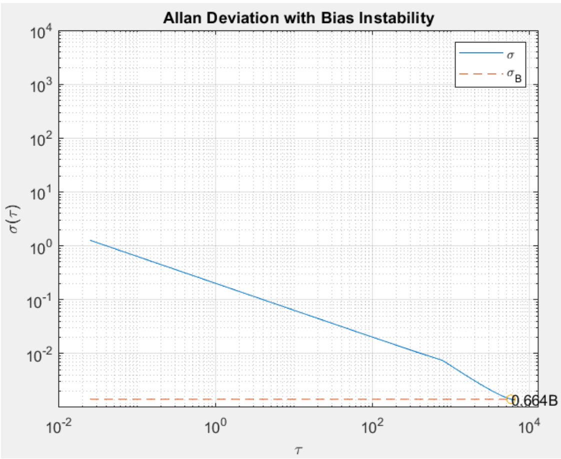




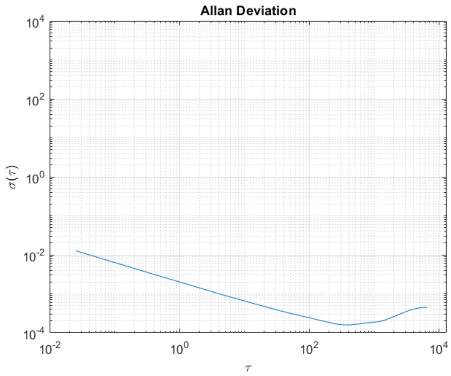


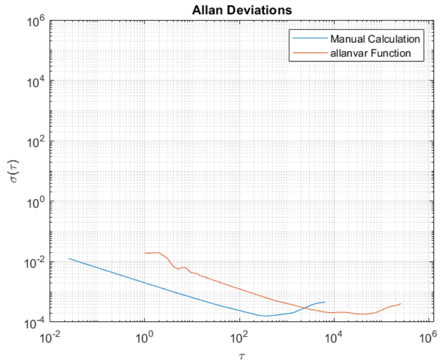


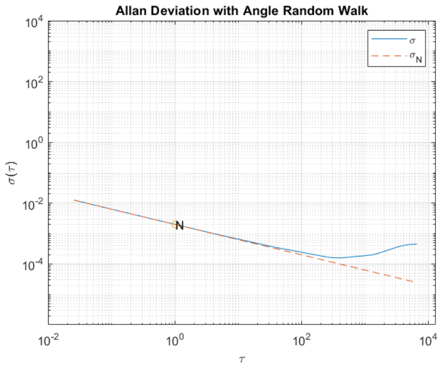


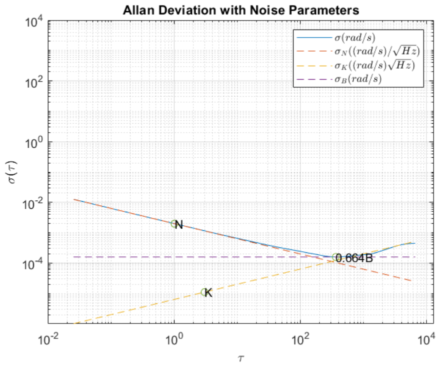


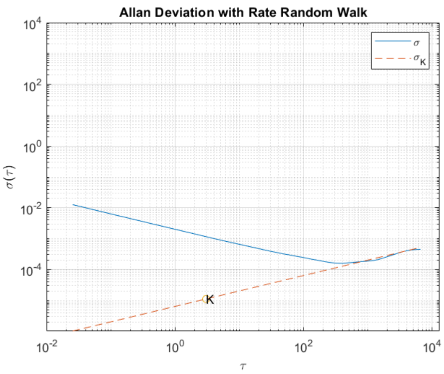
Plot for Allan Variance in Linear Acceleration in X-axis

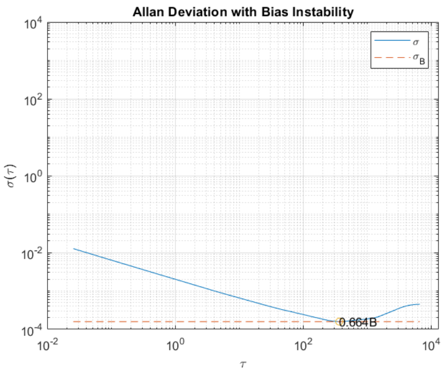




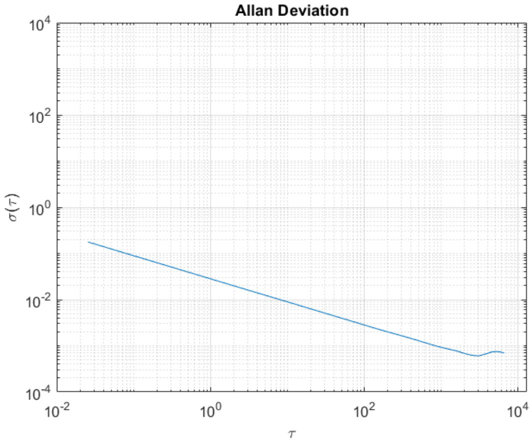


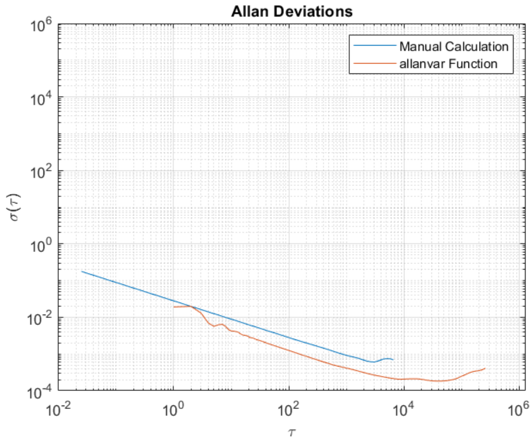


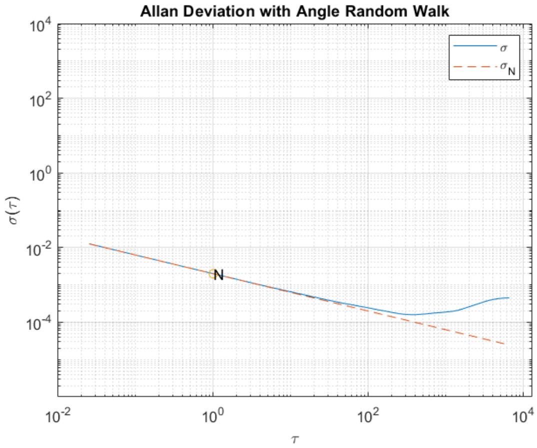


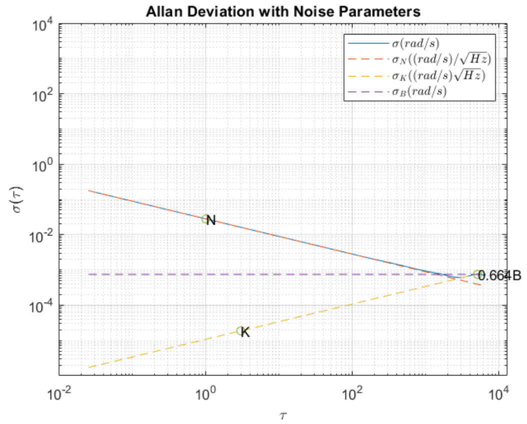


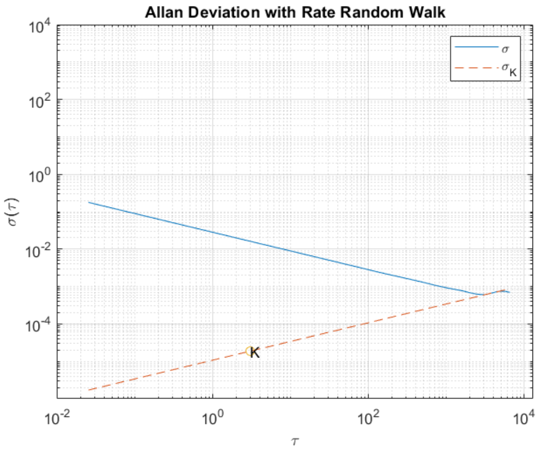
Plot for Allan Variance in Linear Acceleration in Y-axis

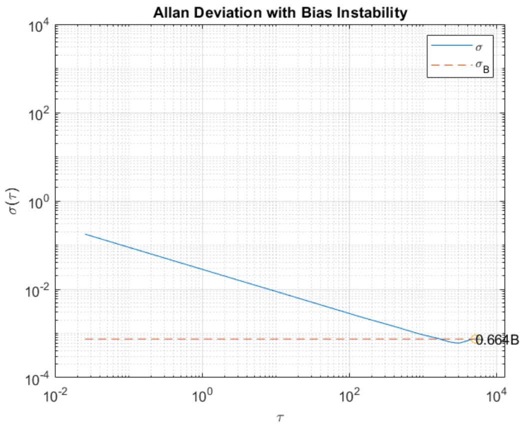












Plot for Allan Variance in Linear Acceleration in Z-axis