Initial Setup

In the selection of sensors for robotic applications, it is important to characterize the sensor's inherent stochastic properties that need to be considered for future data acquisition and analysis. For this lab, a Vectornav VN-100 IMU was provided that combines a 3-axis accelerometer, gyroscope, and magnetometer. An IMU driver was created in Python to parse the $VNYMR output ASCII string into linear acceleration (X, Y, and Z), angular velocity (X, Y, and Z), magnetic field intensity (X, Y, and Z), and orientation (yaw, pitch, and rol, converted to quaternions). Lastly, an emulator was used to spoof IMU serial data to verify driver functionality.

Before connecting the hardware, it is important to note that Linux systems are not designed for real-time data acquisition, and can only guarantee data within 16 milliseconds. However, using udev rules and including custom ".rules" files, the latency response of the sensor can be reconfigured for more predictable data acquisition. For the purposes of this lab, the IMU was configured to output data at 40Hz, despite being capable of outputting 800Hz. This is because 40Hz is the maximum output available for outputting ASCII data. At higher frequencies we would have to work with binary data.

Data Collection

Two sets of data were captured: a short dataset of 10-15 minutes, and a long dataset of around 5 hours. The 5-hour dataset was performed in the basement of an apartment building to minimize the external vibrations and taped to the floor for extra security. With the goal of analyzing the sensor's stochastic characteristics by Allan Variance, it is important for data acquisition to be in a zero-input situation so that any sensor output is due to noise arising from the sensor itself. All data can be found attached to the end of this document.

Attached to the end of this document are the plots for IMU data with the corresponding mean and standard deviation noise measurements in the legend. In the **magnetometer data**, it can be seen that the mean values (in Teslas) are on the same order of magnitude compared to the Earth's magnetic field, which is approximately $5.8 \times 10^{15} [T]$ in Boston. In the **accelerometer data**, the X and Y accelerations are not exactly zero because the ground on which it was taped was not completely flat, so gravity plays a small role. Comparatively, the Z acceleration does hover around the expected gravitational acceleration of -9.8 m/s^2. The slightly larger standard deviations are likely due to the location of the sensor, which was taped to a hardwood floor. In this situation any nearby footsteps will result in a propagation of vibrations that will result in slightly more variability in data. In the **gyroscopic data**, the angular velocity remained constant around 0 rad/s for all measurements with a very small standard deviation. In the **orientation data**, stored as a quaternion, there does appear to be bias in the measurements, seen clearly in the sloping trends seen particularly well in Z and Omega plots.

Allan Variance Analysis

The types of errors visualized in the typical Allan Deviation plot can be broken down into three regions: an area of near-linear decrease in variance, followed by a global minimum, and concluding with a noisy increase in variance as averaging time increases. At short observation (averaging) time τ, the Allan deviation is high because of **gaussian (white) noise**. As τ is increased, the noise begins to average out and the variance decreases. This is because averaging gaussian noise is known to reduce the error by $\sqrt{n}$. This decrease in variance and the presence of white noise can be characterized by the presence of a slope of -0.5 on the log-log plot. Integrating this white noise produces a **random walk**, which is found by fitting a straight line through this slope and squaring its value at $\tau = 1$. The variance transitions into an area of **flicker (pink) noise** and approaches a trough that represents the **In-Run Bias Stability**, which describes how the bias will drift during operation over time and gives the best accuracy that can be expected to estimate the sensor's bias. At even longer τ, the deviation begins to increase and is characterized by **brownian (red) noise**. This highlights the presence of other internal noise characteristics that may be caused by temperature variation or component aging. Fitting a line with a slope of 0.5 to this noise, the **rate random walk** coefficient can be found by reading the value at $\tau = 3$. These sources of error (Gaussian Noise, Flicker Noise, and Brownian Noise) are present in most MEMS sensors, so the Allan Deviation plot is a useful tool for visualizing the timescales on which they take effect, in this case, for both the IMU accelerometer and gyroscope.

Using the "Inertial Sensor Noise Analysis Using Allan Variance" Matlab walkthrough, Allan Deviation plots were generated for the 3-axis accelerometer and gyroscope with the resulting values for the random walk coefficient, N, rate random walk coefficient, K, and bias instability coefficient B. These values can be found in Table 1 and Table 2 below.

Table 1: Angular Velocity Allan Deviation IMU Parameters

	Angular Velocity (X)	Angular Velocity (Y)	Angular Velocity (Z)	VN-100 Datasheet
N $[°/s/\sqrt{Hz}]$	0.0057	0.0065	0.0083	0.0035
K $[°/s * \sqrt{Hz}]$	--	--	--	Not Provided
B $[°/s]$	--	--	11.5137	< 10 (5-7 typ)

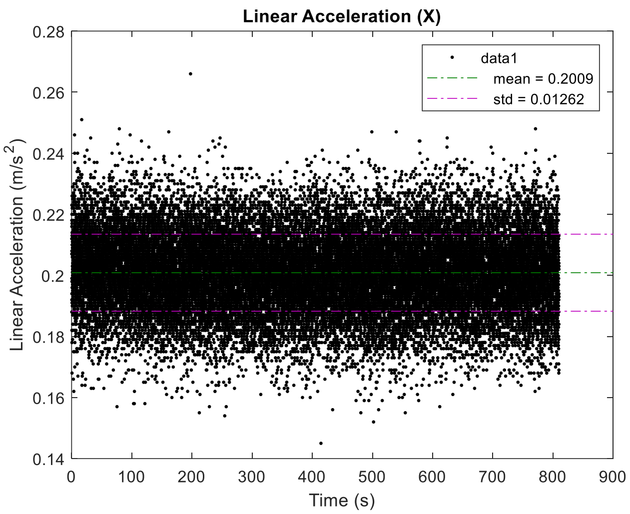
Table 2: Linear Acceleration Allan Deviation IMU Parameters

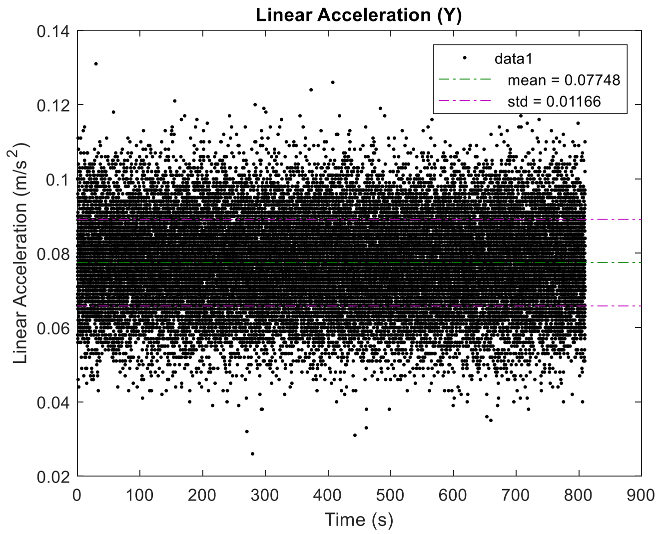
	Linear Acceleration (X)	Linear Acceleration (Y)	Linear Acceleration (Z)	VN-100 Datasheet
N $[mg/\sqrt{Hz}]$	0.2039	0.1835	0.2753	0.14
K $[mg * \sqrt{Hz}]$	0.0058	0.0136	0.0062	Not Provided
B $[mg]$	0.0496	0.0520	0.0767	< 0.04

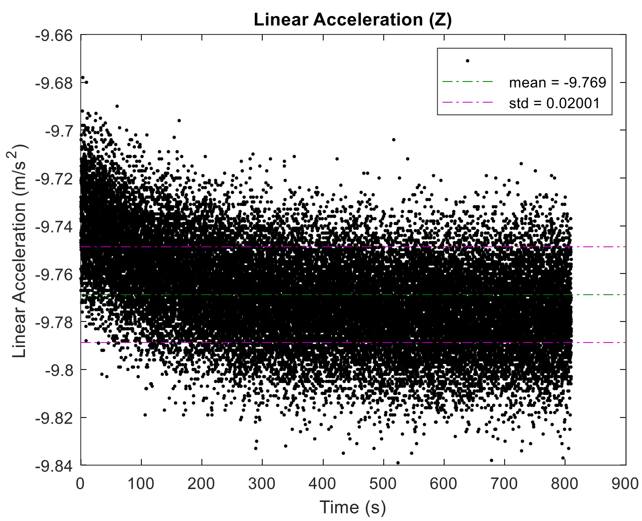
For all six Allan Deviation plots, white noise was verified by the initial linear region fitting the slope of -0.5, as discussed above, and a value for the gyroscope's angle random walk (ARW) and the accelerometer's velocity random walk (VRW) were found and converted to match the units in the VN-100 datasheet. For all ARW and VRW values, the measurements are up to double the value expected in the datasheet. Similarly, the Bias Instability values are well above the supposed maximum values proposed in the datasheet. These discrepancies are likely the result of our 40Hz sampling frequency, which is extremely slow for this IMU considering it is capable of up to 800 Hz.

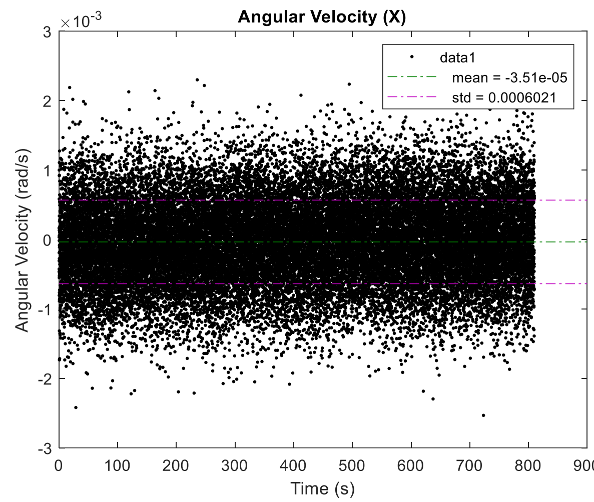
While the Linear Acceleration Allan Deviation plots follow the expected trends detailed at the beginning of this section, the Angular Velocity plots do not, as the variance continues to decrease with increased time-averaging, making the rate random walk and bias instability indeterminate. This inferrs that there is no long-term drift in the angular velocity measurements for the 5-hour time period used here. Further data collection would be necessary to fully characterize these effects by taking longer measurements on the scale of days rather than hours.

IMU Data from Accelerometer, Gyroscope, Magnetometer, and Orientation

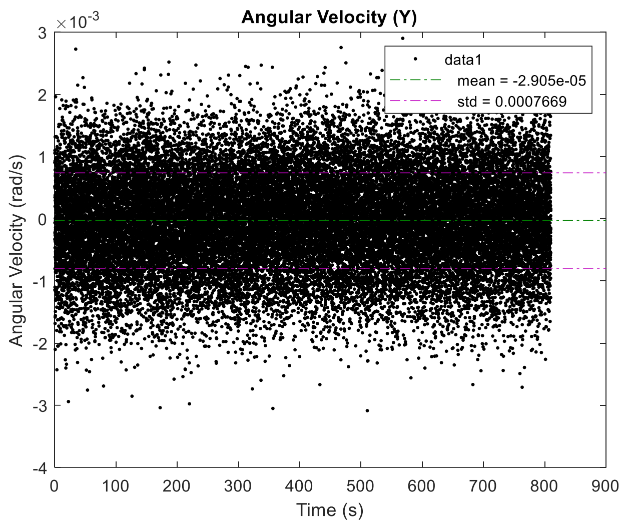


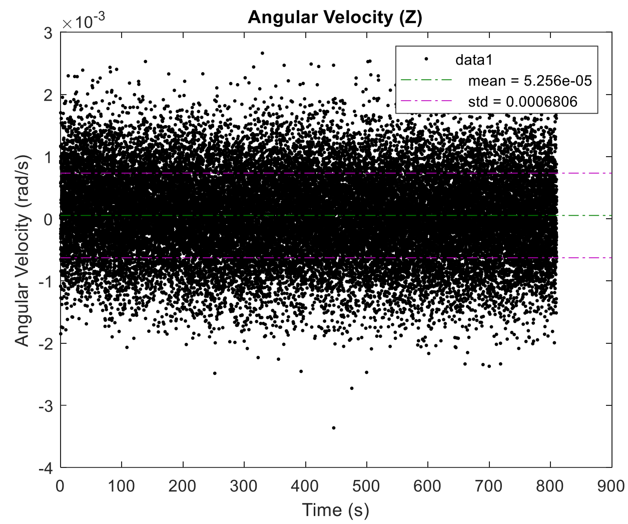


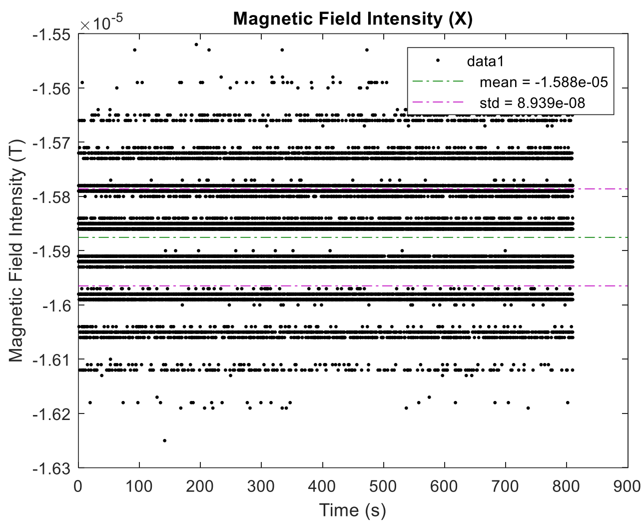


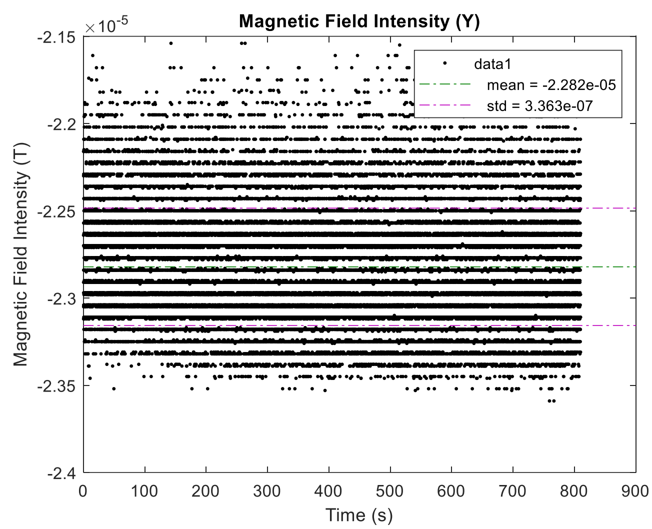


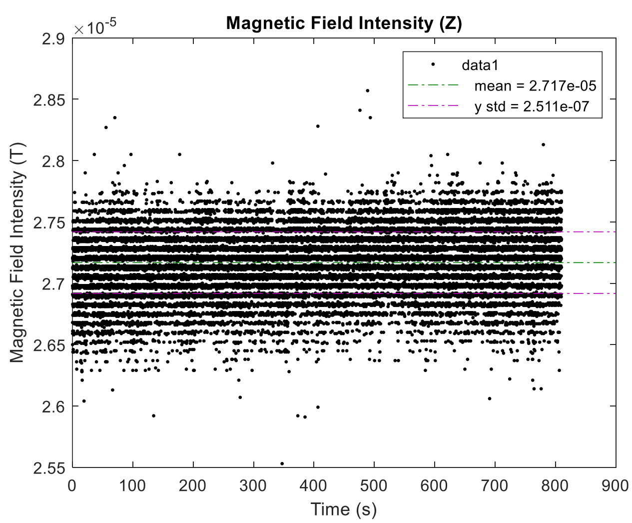
Matthew Euliano EECE5554 Lab 3 Analysis

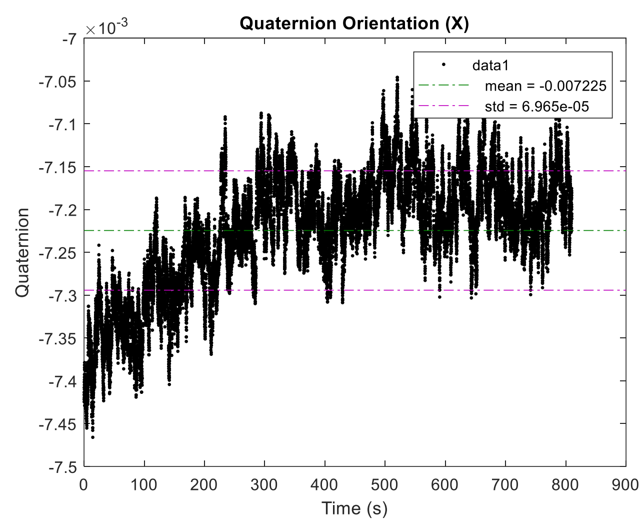


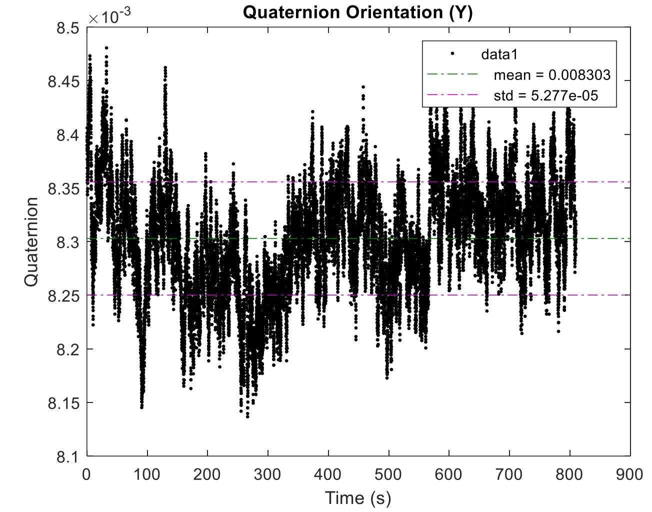


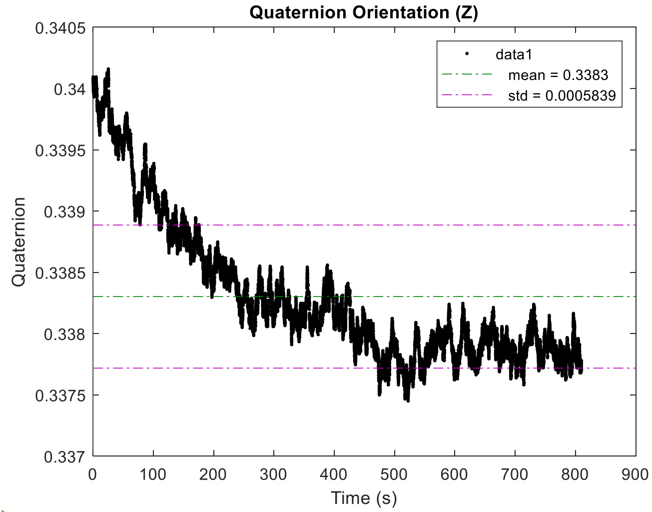


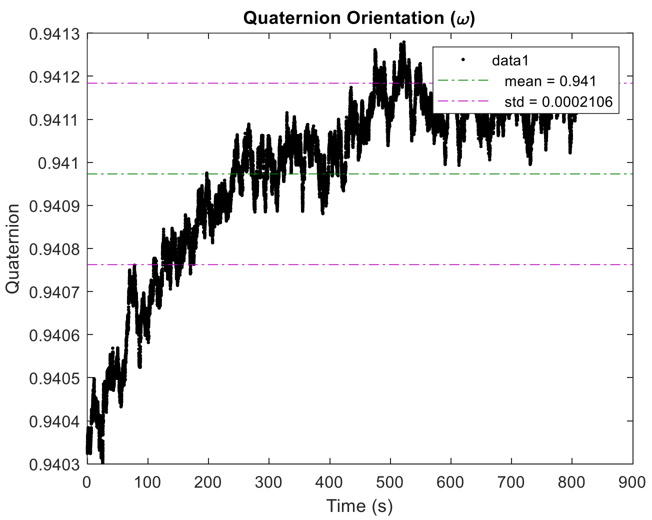







Quaternion Orientation (Y)
$\times10^{-3}$
data1
mean = 0.008303
std = 5.277e-05
Quaternion
Time (s)


Quaternion Orientation (Z)
data1
mean = 0.3383
std = 0.0005839
Quaternion
Time (s)

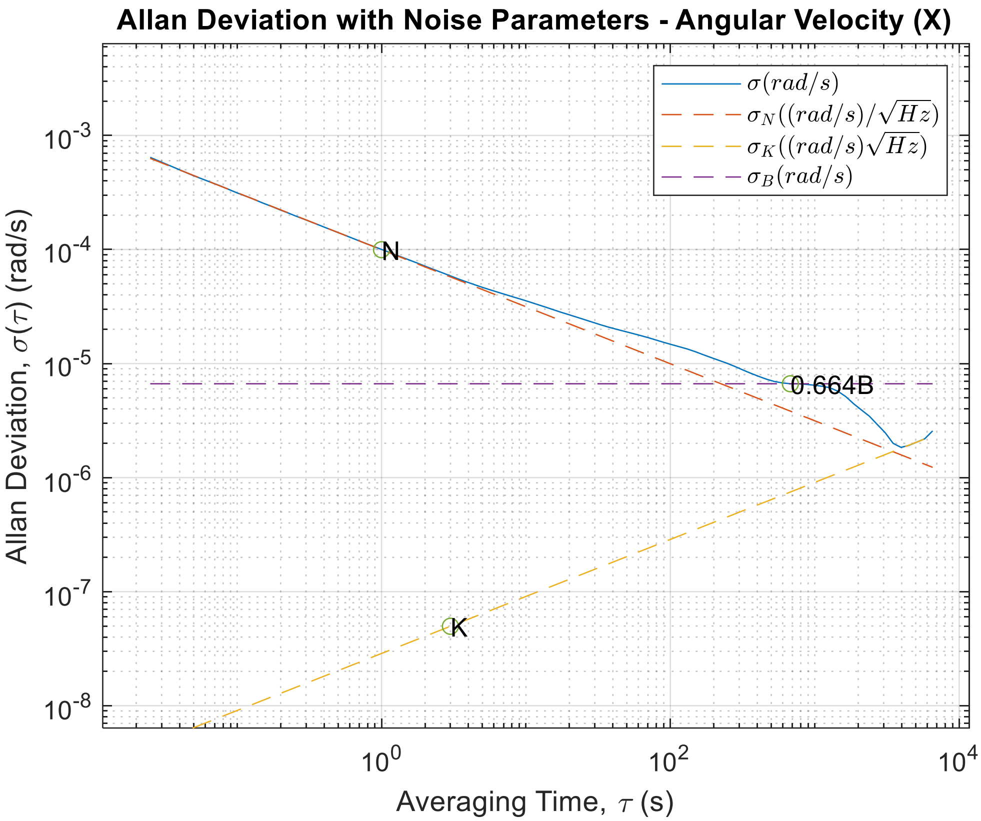

Quaternion Orientation (ω)
data1
mean = 0.941
std = 0.0002106
Quaternion
Time (s)

Allan Deviation Plots for Gyroscope and Accelerometer

N - Angle Random Walk Coefficient

K - Rate Random Walk Coefficient

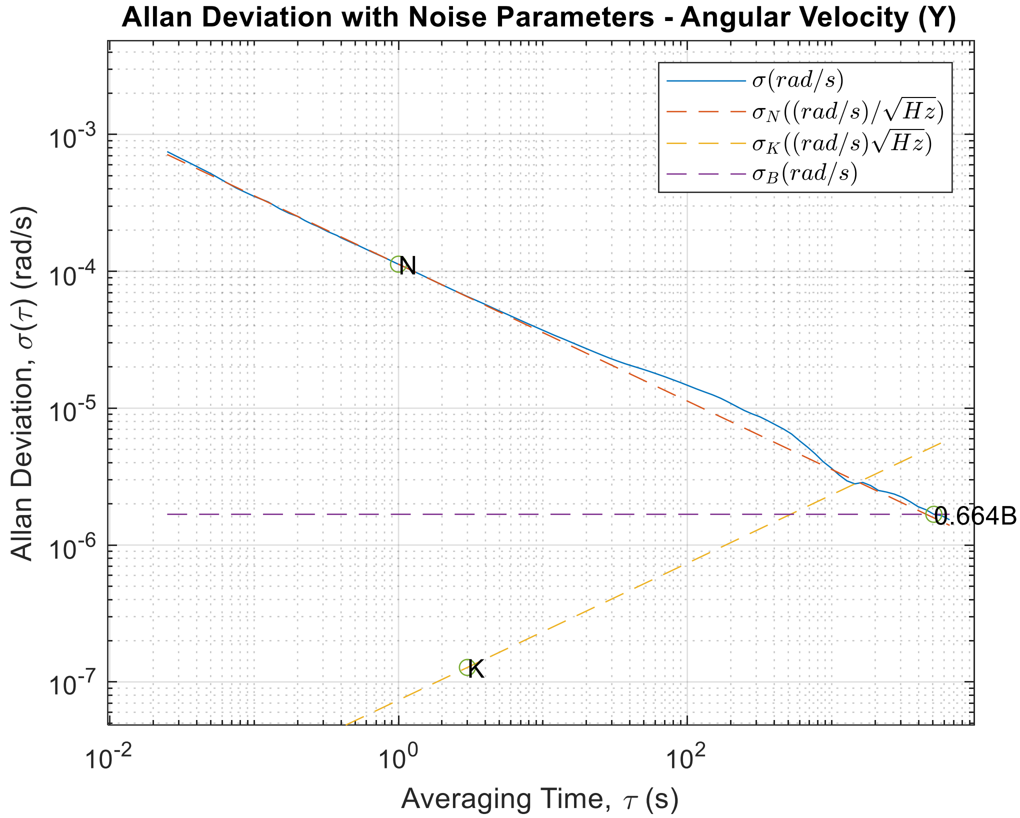
B - Bias Instability Coefficient



N = 9.9612e-05 rad/s/sqrt(Hz) = 0.0057 deg/s/sqrt(Hz)

K = 4.9734e-08 → Not Useful

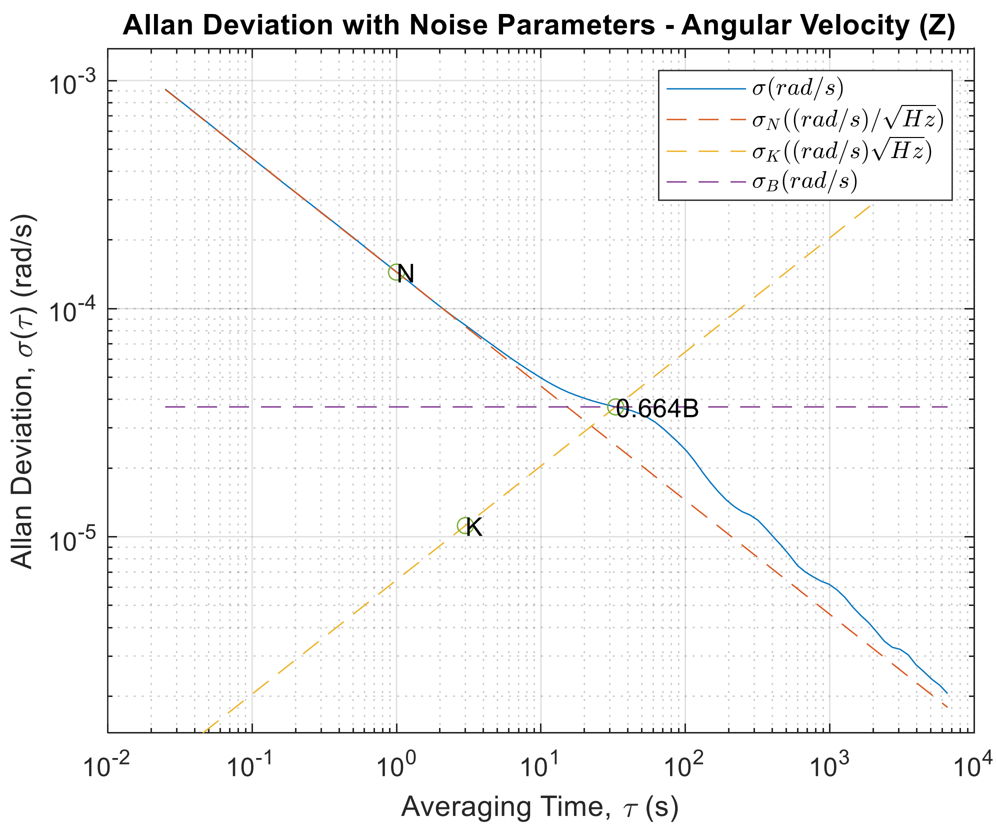
B = 1.0015e-05 → Not Useful



N = 1.1274e-04 rad/s/sqrt(Hz) = 0.0065 deg/s/sqrt(Hz)

K = 1.2758e-07 → Not useful

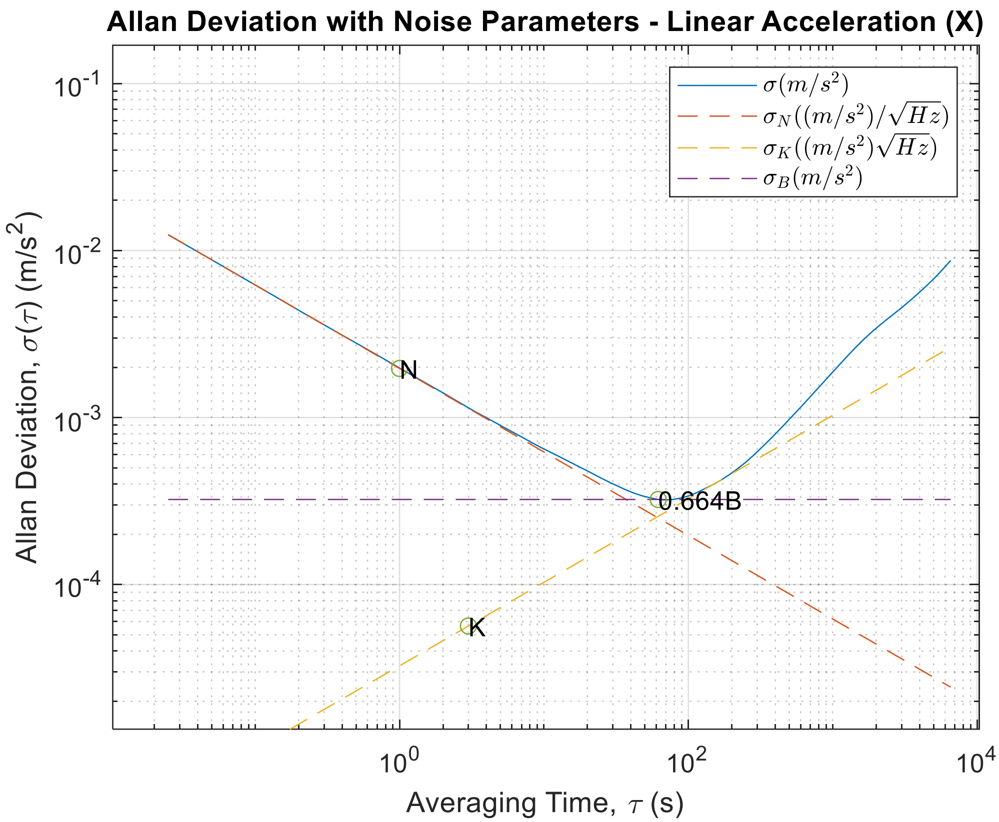
B = 2.5256e-06 → Not useful



N = 1.4454e-04 rad/s/sqrt(Hz) = 0.0083 deg/s/sqrt(Hz)

K = 1.1189e-05 → Not Useful

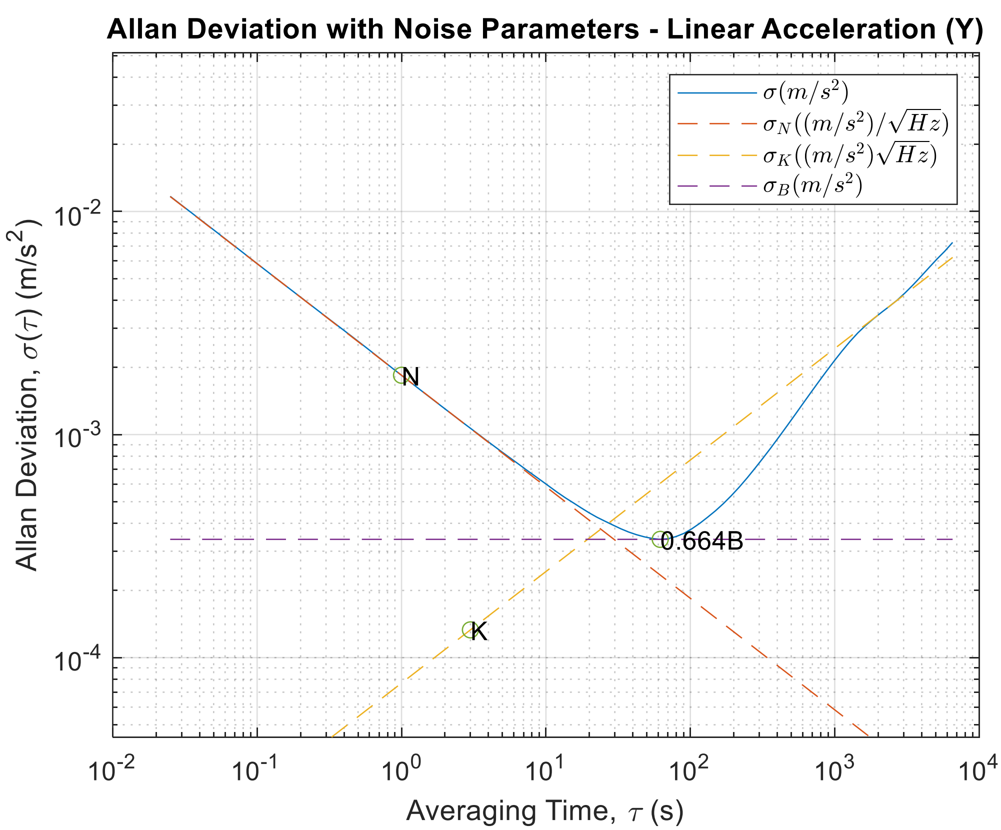
B = 5.5820e-05 rad/s = 11.5137 deg/hr



N = 0.0020 m/s^2/sqrt(Hz) = 0.2039 mg/sqrt(Hz)

K = 5.6485e-05 = 0.0058 mg*sqrt(Hz)

B = 4.8646e-04 = 0.0496 mg

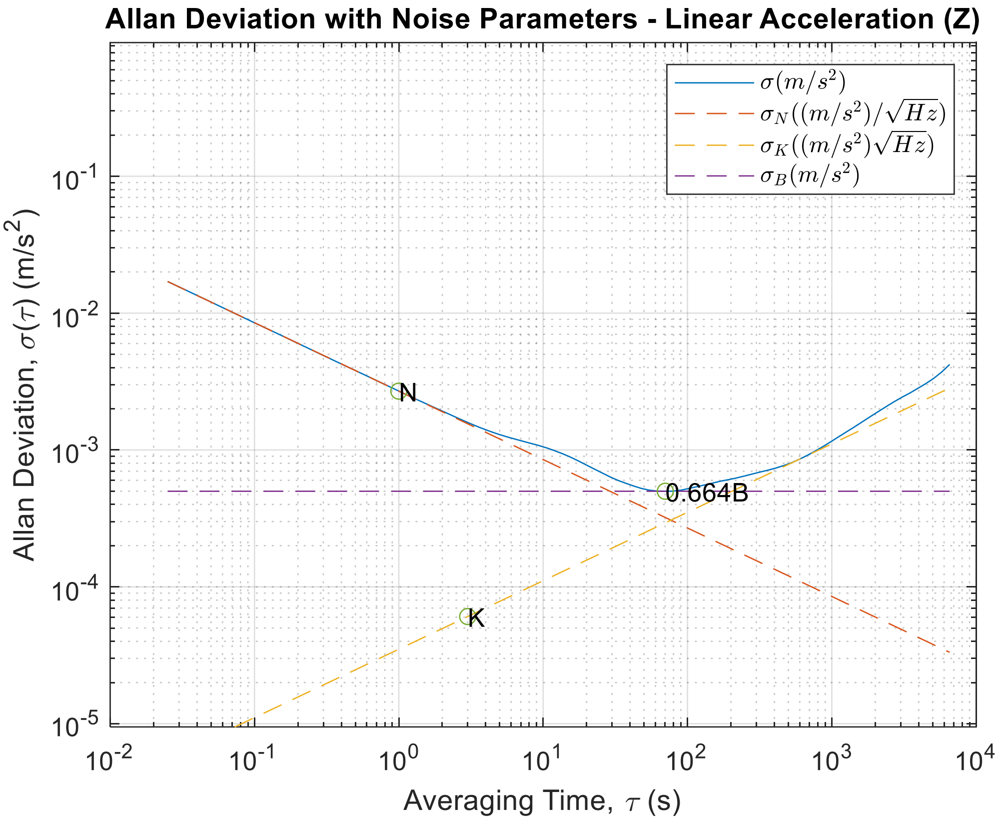


Matthew Euliano EECE5554 Lab 3 Analysis

N = 0.0018 = 0.1835 mg/sqrt(Hz)

K = 1.3316e-04 = 0.0136 mg*sqrt(Hz)

B = 5.1021e-04 = 0.0520 mg



N = 0.0027 = 0.2753 mg/sqrt(Hz)

K = 6.0700e-05 = 0.0062 mg*sqrt(Hz)

B = 7.5183e-04 = 0.0767 mg