**EECE 5554 Robotics Sensing and Navigation**
**Lab3 IMU Noise Characterization with Allen Variance**
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## Abstract

The goal of this lab assignment is to understand how to characterize and choose IMU sensors for different robotic applications. To better understand IMU, a series of datasets were collected by IMU sensor including 10 minutes stationary data, and a 5-hour data collection for the analysis of Allan Variance.


## Method

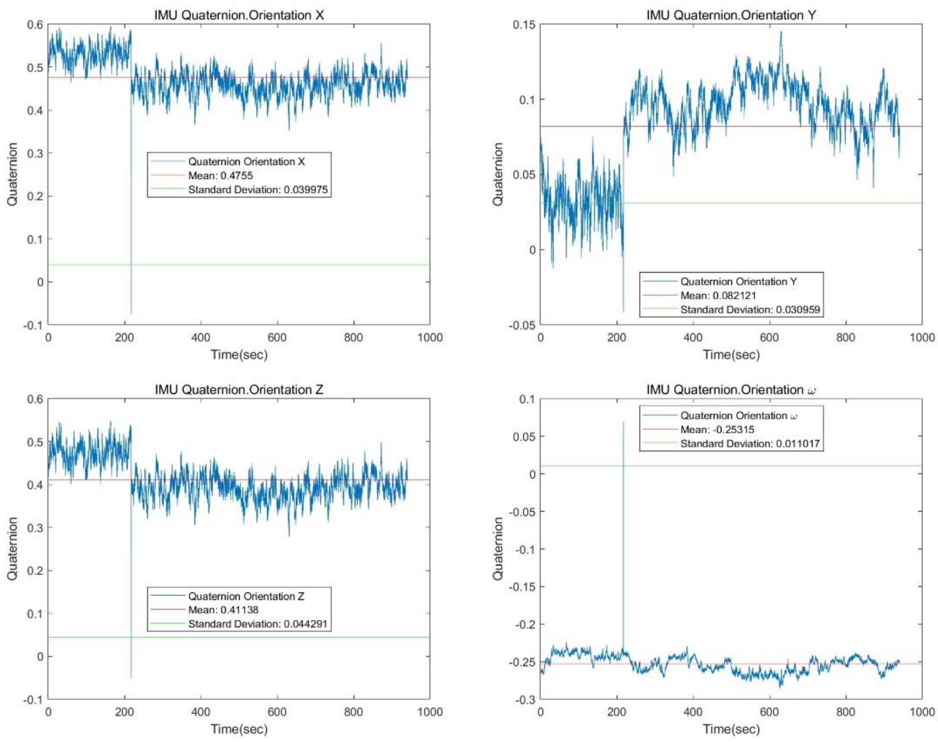
The proper hardware setup has been performed. The correct rule files were created, the USB serial port latency has been set to 1. Furthermore, a driver script has been written to parse the $VNYMR string from IMU. The script first configures the data output frequency of VN-100 sensor to 40Hz, then it will read each element on the $VNYMR string and record them into the corresponding sensor message field. By using the ROS feature, a ROS message that includes IMU and magnetic field coordinates will be published among the topic named “imu”. After passing the lab struct check, a sample dataset has been recorded and verified its correctness.

The information about stationary data

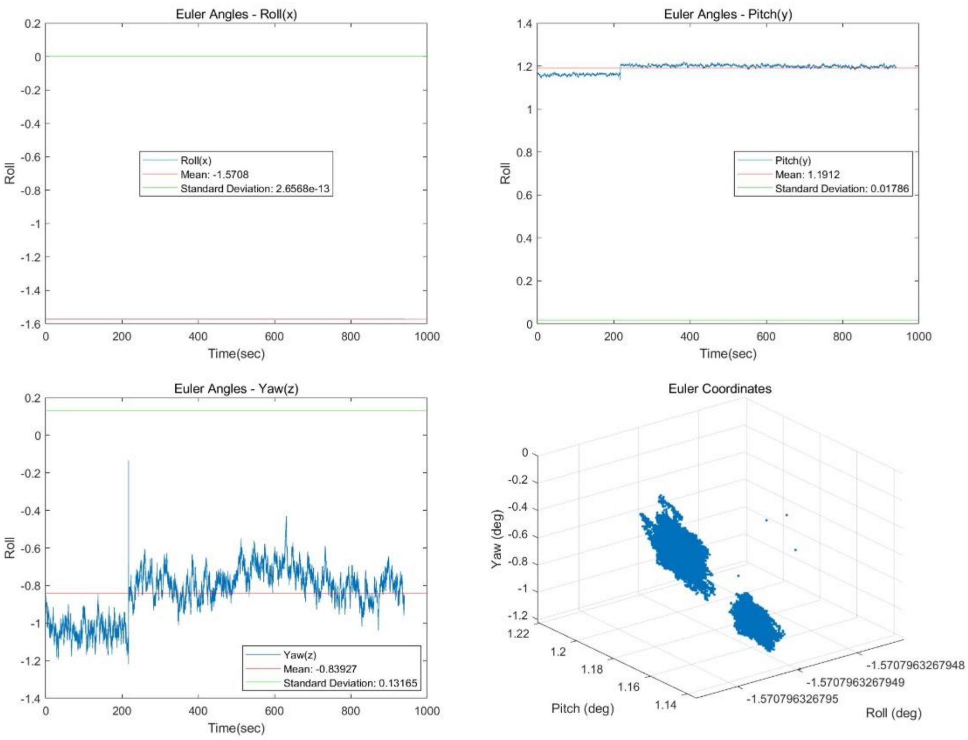
| Time Duration | Sample Size | Location |
|---|---|---|
| ~15 minutes<br>940.47 seconds | 37616 messages | Study lounge at the first floor of apartment |

Data plot with time series are displayed below:

**IMU Quaternion and Euler Angles Data**



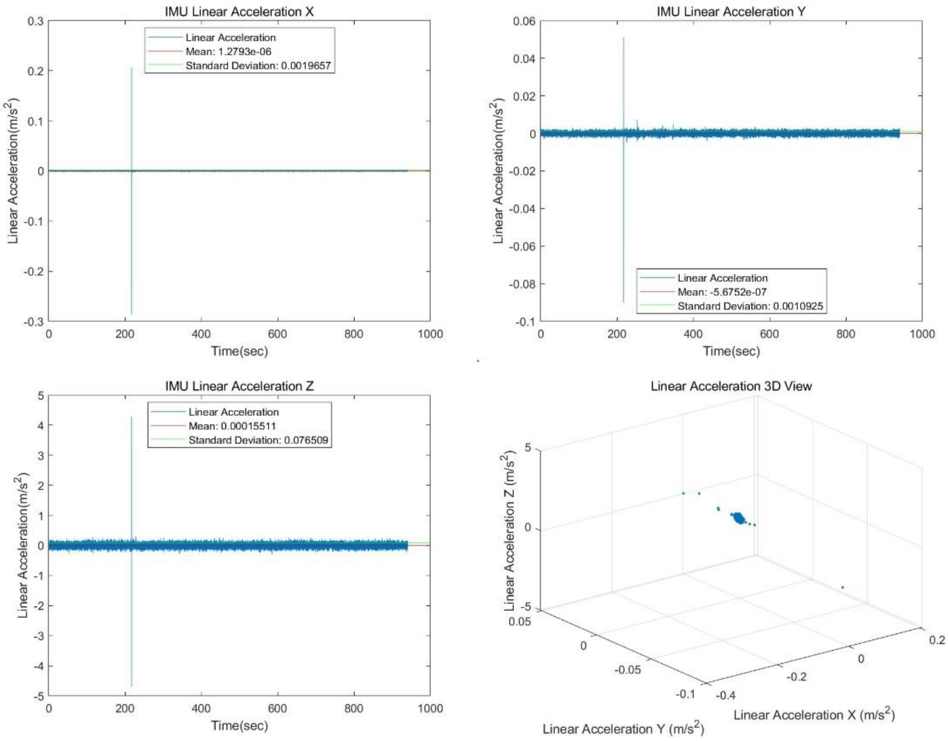
Because the 4-dimensional is not visible. Therefore, to see the 3-dimensional view, the Quaternion coordinates has been converted back to Euler coordinates.




For IMU Quaternion data, the overall mean and standard deviation are shown below

| Coordinate | Mean | Standard Deviation |
|---|---|---|
| **Quaternion-X** | 0.4755 | 0.039975 |
| **Quaternion-Y** | 0.0821 | 0.030959 |
| **Quaternion-Z** | 0.4113 | 0.044291 |
| **Quaternion-ω** | -0.2531 | 0.011017 |
| **Euler-Roll (x)** | -1.5708 | 2.6568e-13 |
| **Euler-Pitch (y)** | 1.1912 | 0.01786 |
| **Euler-Yaw (z)** | -0.83927 | 0.13165 |

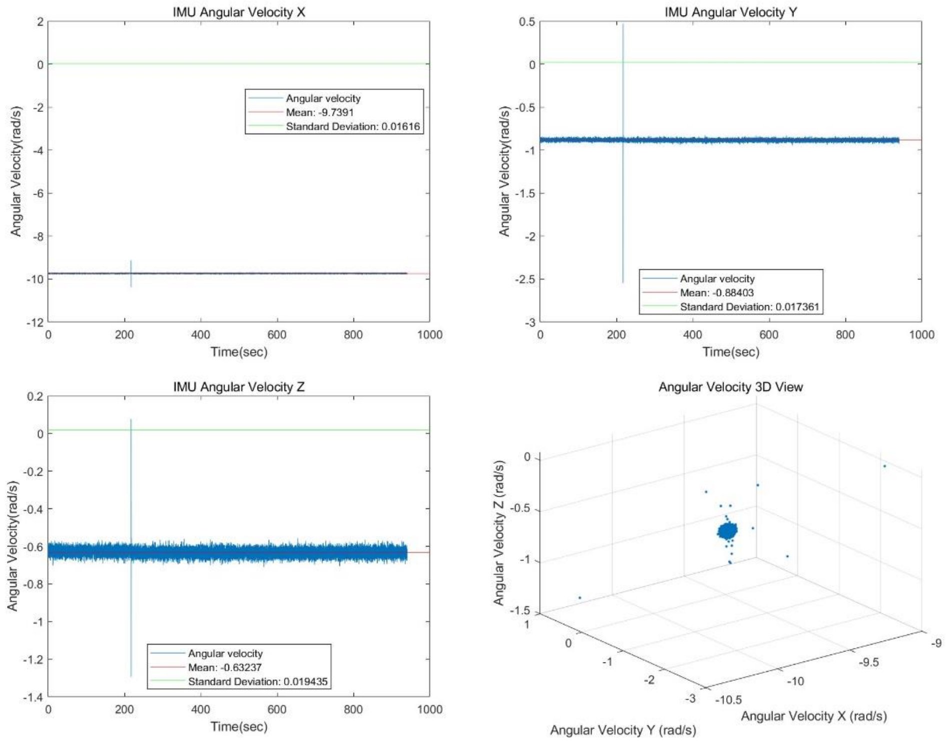
## IMU Linear Acceleration Data




For IMU linear acceleration, the overall mean and standard deviation are shown below

| Linear Acceleration | Mean ($m/s^2$) | Standard Deviation |
|---|---|---|
| X | 1.2793e-06 | 0.0019657 |
| Y | -5.6752e-07 | 0.0010925 |
| Z | 0.00015511 | 0.076509 |

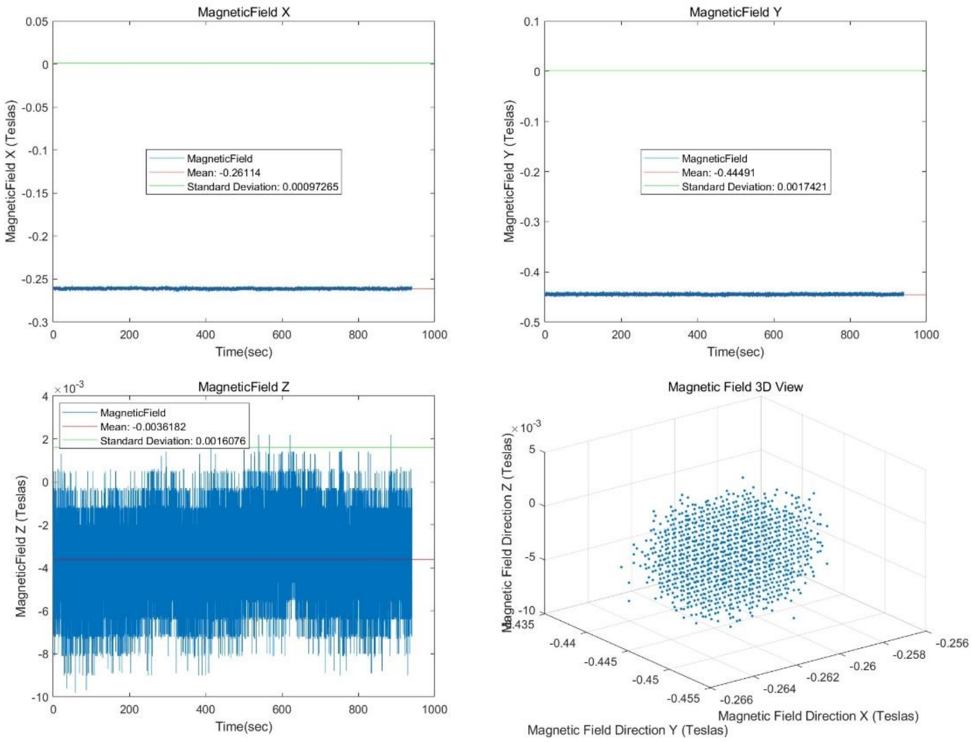
## IMU Angular Velocity Data



For IMU angular velocity, the overall mean and standard deviation are shown below

| Angular Velocity | Mean ($rad/s$) | Standard Deviation |
|---|---|---|
| X | -9.7391 | 0.01616 |
| Y | -0.884.3 | 0.017361 |
| Z | -0.63237 | 0.019435 |

**Magnetic Field Data**




For magnetic field, the overall mean and standard deviation are shown below

| Magnetic Field | Mean ($Tesla$) | Standard Deviation |
|---|---|---|
| X | -0.26114 | 0.00097265 |
| Y | -0.44491 | 0.0017421 |
| Z | -0.0036182 | 0.0016076 |

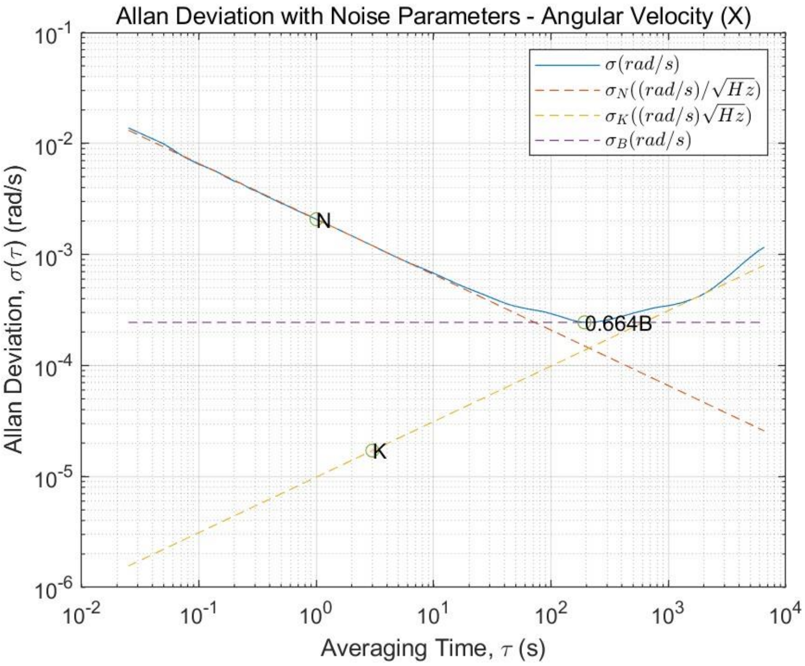
This dataset has been recorded in stationary environment. The VN-100 IMU sensor is fixed in one position. Therefore, the 3-dimensional view for linear acceleration and angular velocity is distributed like a dot. That is because, stationary means no linear acceleration nor angular velocity. The magnetic field data is distributed around a center. From the magnetic field plot, although magnetic field in z direction looks like it has a large fluctuation. That is because the number in the y-axis is very small, the data however, is distributed on the mean value, and has low standard deviation.

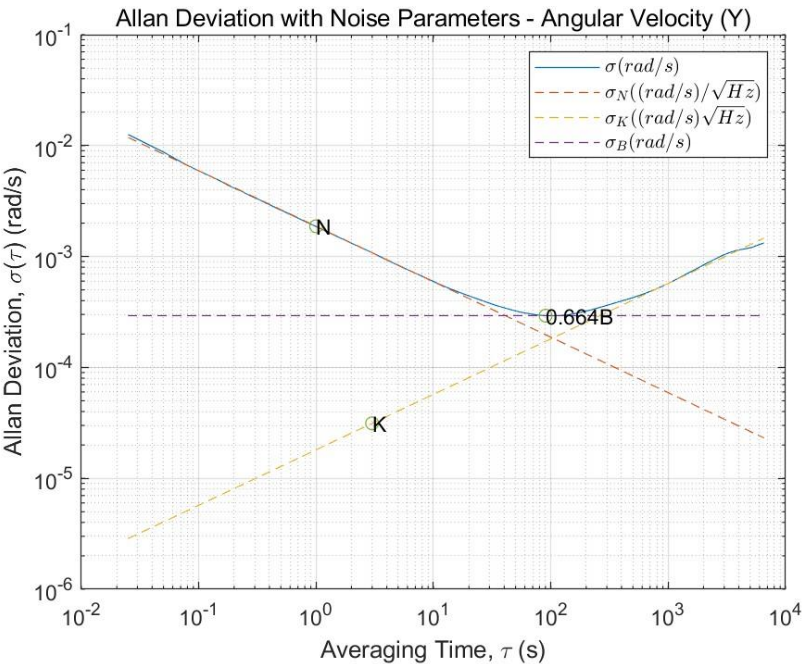
**Allan Variance**

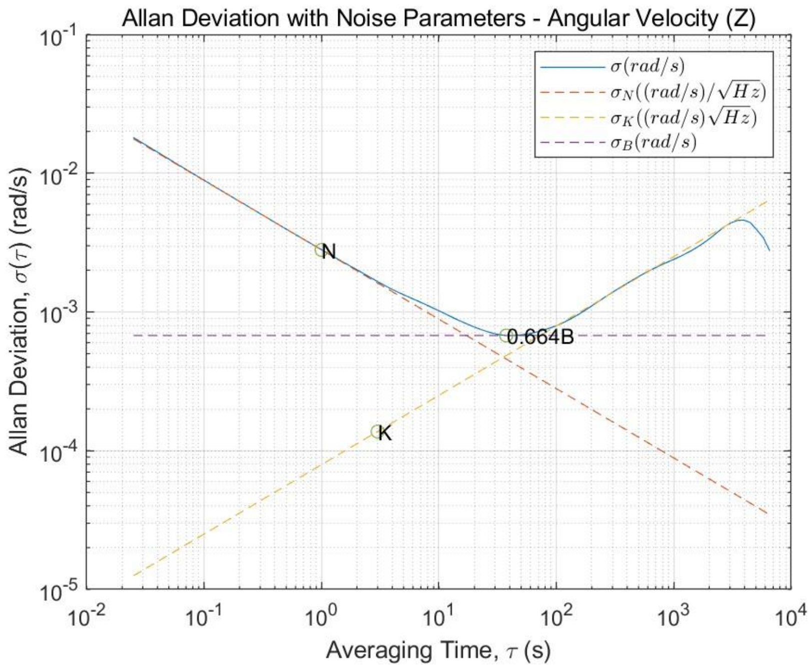
Information about data collection for Allan Variance

| Time Duration | Sample Size | Location |
|---|---|---|
| ~5hours 02seconds | 720309 messages | Study lounge |

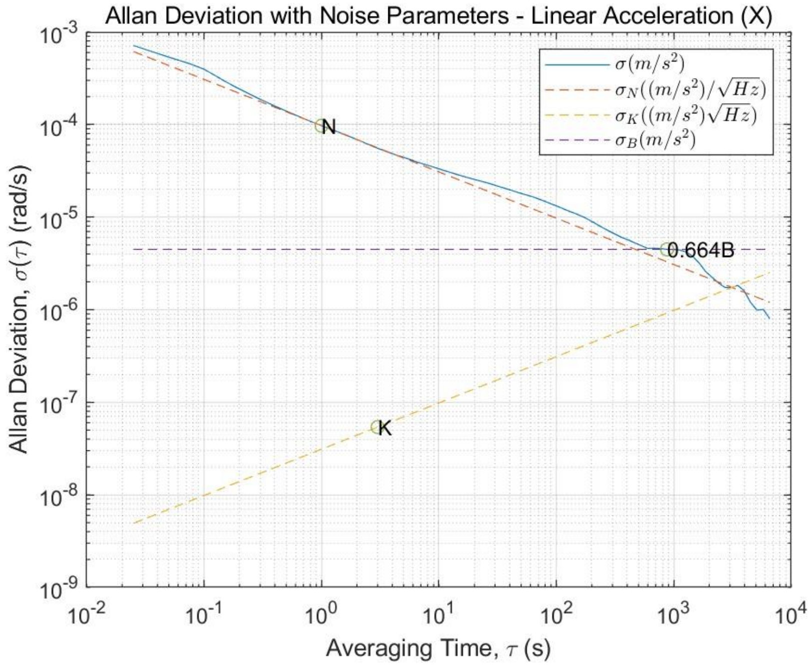
According to the *MATLAB Inertial Sensor Noise Analysis Using Allan Variance.* The result plots are generated below



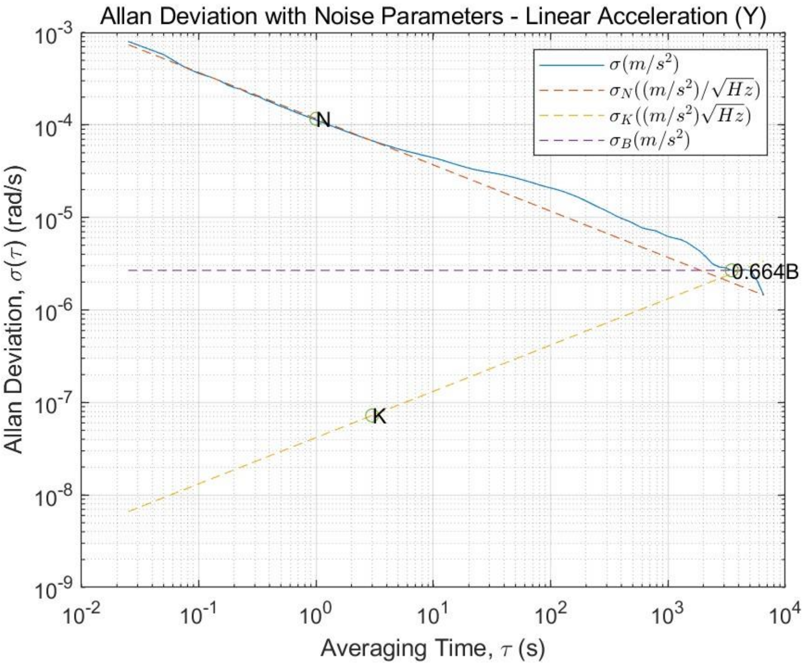



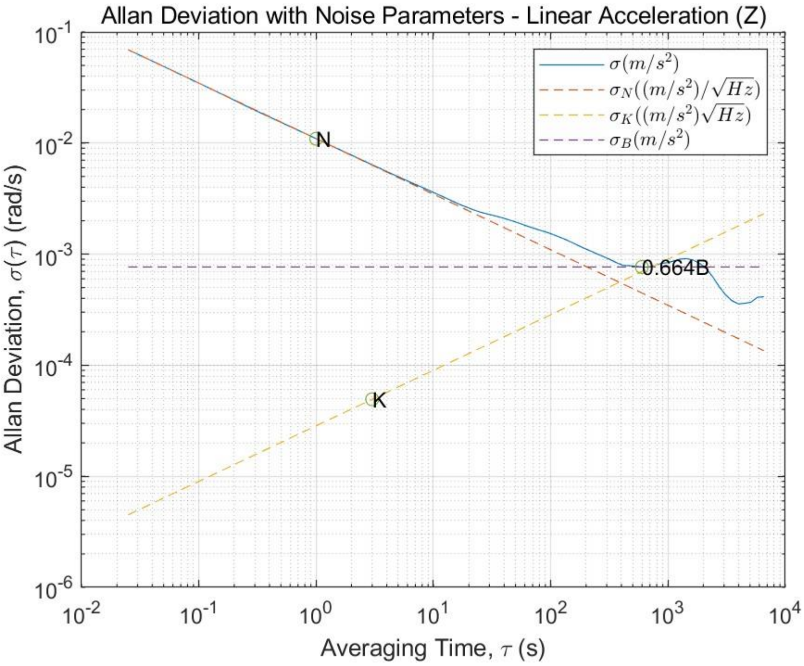


Allan Deviation with Noise Parameters - Angular Velocity (Z)
$\sigma(rad/s)$
$\sigma_N((rad/s)/\sqrt{Hz})$
$\sigma_K((rad/s)\sqrt{Hz})$
$\sigma_B(rad/s)$
N
0.664B
K
Allan Deviation, $\sigma(\tau)$ (rad/s)
Averaging Time, $\tau$ (s)

Allan Deviation with Noise Parameters - Linear Acceleration (X)
$\sigma(m/s^2)$
$\sigma_N((m/s^2)/\sqrt{Hz})$
$\sigma_K((m/s^2)\sqrt{Hz})$
$\sigma_B(m/s^2)$
N
0.664B
K
Allan Deviation, $\sigma(\tau)$ (rad/s)
Averaging Time, $\tau$ (s)




The Allan Variance is designed to measure the frequency stability of some high precision oscillators. It is also designed to identify various noise sources present in the stationary gyroscope measurements. The first source of noise is **Angle Random Walk**, where Angle Random Walk can be characterized by the **white Gaussian noise** spectrum of the gyroscope output. Where N is the coefficient of angle random walk. The second source of noise is **Rate Random Walk**, where Rate Random Walk can be characterized as the **red noise** also known as **Brownian noise**. Where K is the rate random walk coefficient. The third source of noise is **Bias Instability**, where Bias Instability can be characterized as the **pink noise** also known as **Flicker noise**. The coefficient of bias instability is B. Each coefficient of noise is calculated by the script from MATLAB, the raw result is showed in the table below.

| | Angle Random Walk (N) | Rate Random Walk (K) | Bias Instability (B) |
|---|---|---|---|
| Angular Velocity X | 0.0021 | 1.7101e-5 | 3.6795e-4 |
| Angular Velocity Y | 0.0019 | 3.1332e-5 | 4.4077e-4 |
| Angular Velocity Z | 0.0028 | 1.3749e-4 | 0.0010 |
| | Angle Random Walk (N) | Rate Random Walk (K) | Bias Instability (B) |
| Linear Acceleration X | 9.7157e-5 | 5.3941e-8 | 6.7460e-6 |
| Linear Acceleration Y | 1.1671e-4 | 7.2358e-8 | 4.0315e-6 |
| Linear Acceleration Z | 0.0109 | 4.9336e-5 | 0.0012 |

From the datasheet of VN-100 IMU, it has specifications with

| IMU Specifications | ACCELEROMETER | GYROSCOPE | MAGNETOMETER | BAROMETER |
|---|---|---|---|---|
| Range | ±16 g | ±2,000°/s | ±2.5 Gauss | 10 to 1200 mbar |
| In-Run Bias Stability (Allan Variance) | < 0.04 mg | < 10°/hr (5-7°/hr typ.) | - | - |
| Noise Density | 0.14 mg/√Hz | 0.0035 °/s /√Hz | 140 μGauss/√Hz | - |
| Bandwidth | 260 Hz | 256 Hz | 200 Hz | 200 Hz |
| Cross-Axis Sensitivity | ±0.05 ° | < 0.05 ° | ±0.05 ° | - |

Figure 1. VN-100 IMU Specifications

The unit conversion is performed in order to match the unit in the datasheet. The result is shown below

| | Angle Random Walk (N) $[^{\circ}/_{s}/\sqrt{Hz}]$ | Bias Instability (B) $[^{\circ}/_{s}]$ |
|---|---|---|
| Angular Velocity X | 0.12 | 75.8951 |
| Angular Velocity Y | 0.1088 | 90.9153 |
| Angular Velocity Z | 0.1604 | 206.26 |

| | Angle Random Walk (N) $[mg/\sqrt{Hz}]$ | Bias Instability (B) $[mg]$ |
|---|---|---|
| Linear Acceleration X | 0.009907 | 0.00674 |
| Linear Acceleration Y | 0.0119 | 0.00403 |
| Linear Acceleration Z | 0.111149 | 0.12 |

According to the VN-100 datasheet. The Rate Random Walk is not provided in the datasheet. Some results are way out of expectation. One explanation is that the study lounge is not an ideal place to collect the data. Because during the recording, there were people talking, people leaving the room with door slapping that can cause the unwanted factor that may influence the analysis of Allan Variance. Some other factors are, the IMU is running at 40Hz data output rate. Which is extremely low frequency compared to the full capacity of 800Hz. This may influence the bias instability. Also, 5-hour recording time may not be enough to fully analyze the Allan Variance. Long time measurement with larger sample size in the future analysis is necessary to characterize these effects.

**Appendix**

[1] MathWorks, Inertial Sensor Noise Analysis Using Allan Variance
https://www.mathworks.com/help/fusion/ug/inertial-sensor-noise-analysis-using-allan-variance.html

[2] vn-100-datasheet-rev2

[3] vn-100-user-manual-rev_2-45