University of Stuttgart
Insititute of Navigation


# GEOENGINE

## Master Thesis

# Temperature Dependency of a Low-cost IMU

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# □ Introduction

# Background

- Navigation plays very important role from past to now on for people.
- Inertial Navigation System is an important modern navigation method.
- MEMS (Micro-Electro-Mechanical-Systems) technology enables IMUs to be manufactured smaller, lighter and cheaper.
- MEMS IMUs have become very widely used.
- MEMS IMUs are still far less accurate than some traditional high accuracy IMUs at present.
- Temperature influences the performance of MEMS IMUs differently from device to device.

# Objectives

Inertial Navigation

Allan Variance

Temperature dependency of MPU-9250

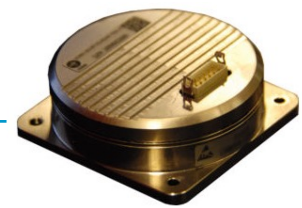
# ☐ Inertial Navigation

# Types of Gyroscope

Gyroscope

Source:[1]

Mechanical



Source:[2]

Optical


Source:[3]

MEMS

# Types of Accelerometer

Accelerometer


Source:[4]

Mechanical


Source:[5]

Optical


Source:[3]

MEMS

# MEMS Inertial Sensor

## Advantages

- Small size
- Low weight
- Rugged construction
- Low power consumption
- Short start-up time
- Inexpensive to produce
- High reliability
- Low maintenance

## Disadvantage

- Less accurate than some conventional high accuracy IMUs at present.

# Growing Market for MEMS Inertial Sensor

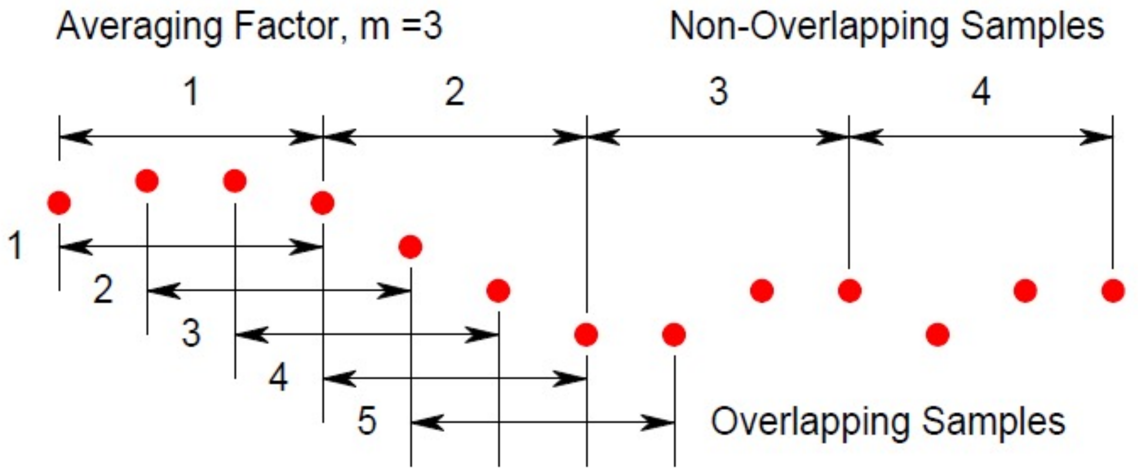

Source:[6]

# ☐ Allan Variance

## Allan Variance

- Allan Variance was proposed by David W. Allan in 1996.
- An important method of analyzing a sequence of data in the time domain.
- One of the most popular methods for identifying and quantifying the different noise terms that exist in inertial sensor data.
- The Allan Variance analysis consists of computing its Allan Deviation and then analyzing the characteristic regions and log-log scale slopes of Allan Deviation curves to identify the different noise terms.

# Allan Variance




Source:[7]

Non-Overlapped Allan Variance: Stride = $\tau$ = averaging period = $m \cdot \tau_0$

$$\sigma_y^2(\tau) = \frac{1}{2(M-1)} \sum_{i=1}^{M-1} (y_{i+1} - y_i)^2$$

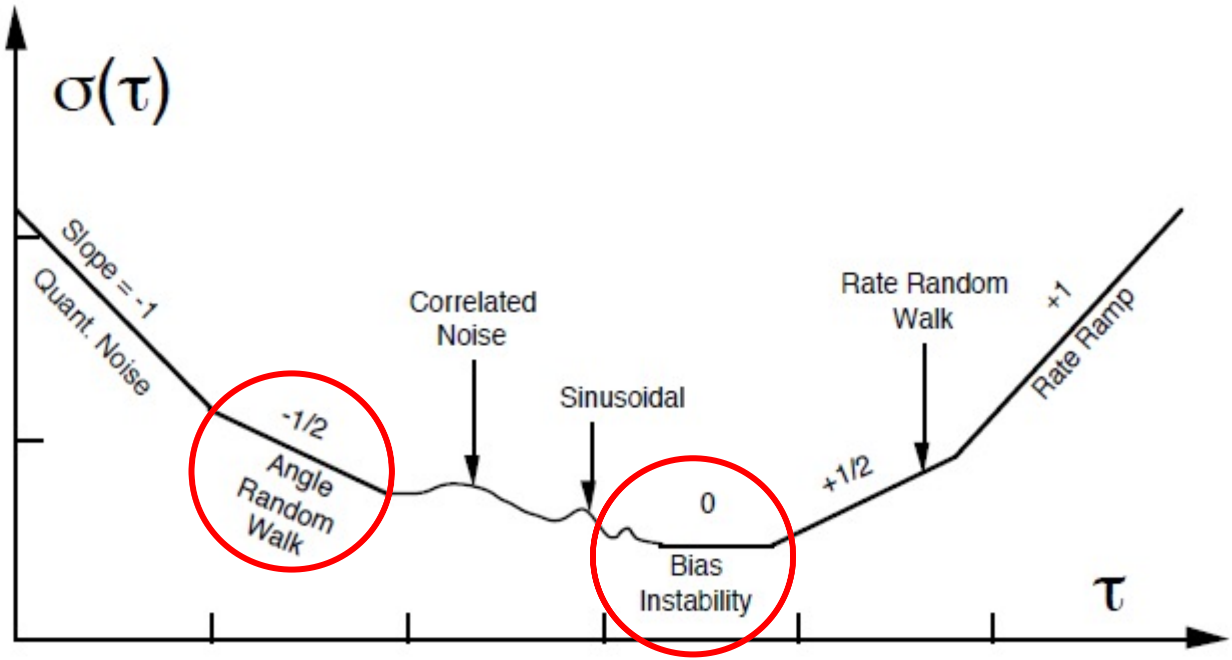
$i$th of $M$ fractional frequency values averaged over $\tau$

Overlapped Allan Variance: Stride = $\tau_0$ = sample period

$$\sigma_y^2(\tau) = \frac{1}{2m^2(M-2m+1)} \sum_{j=1}^{M-2m+1} \sum_{i=j}^{j+m-1} (y_{i+m} - y_i)^2$$

Number of samples

# Noise Characterization

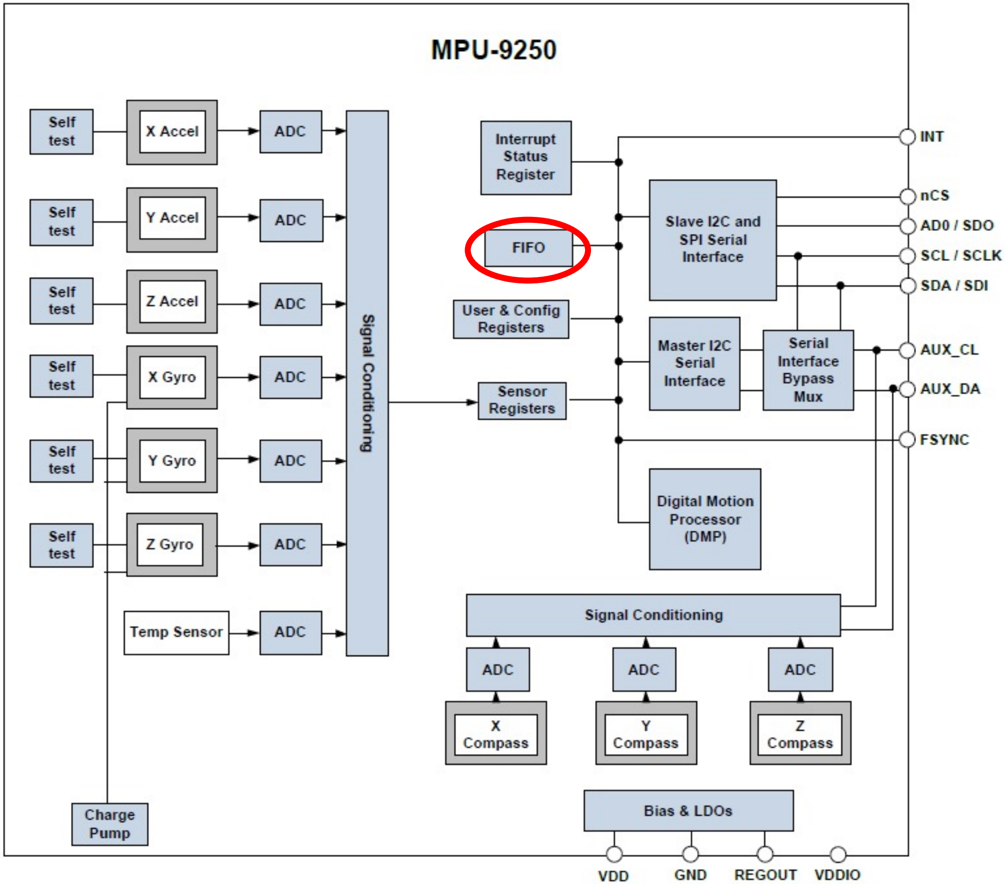



Source: [8]

- **ARW/VRW** (Angle/Velocity Random Walk) describes the average deviation or error that will occur when integrating the signal.
- **BI** (Bias Instability) can be defined as how much deviation or drift the sensor has from its mean value of the output rate.

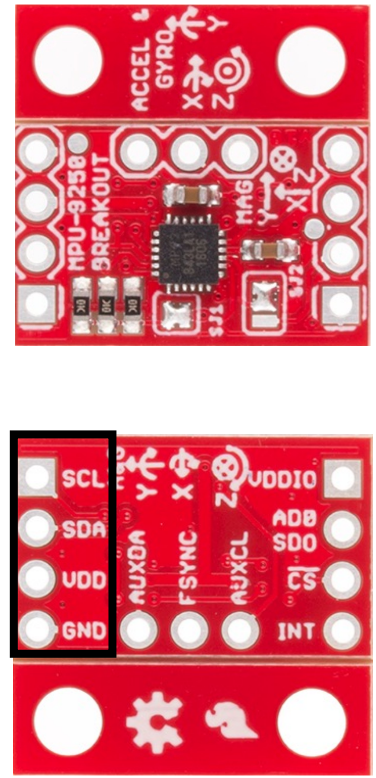
- Hardware Implementation

# MEMS IMU




Block Diagram

Source: [10]



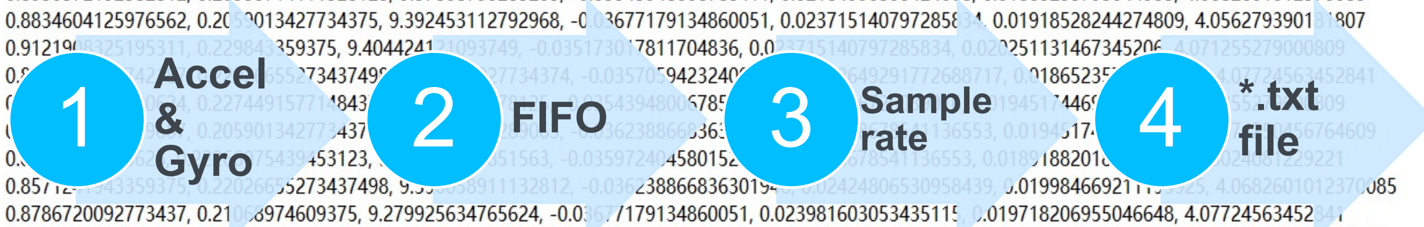

Source: [9]

# Single Board Computer

- Raspberry Pi 3 Model B+
  - ✓ Broadcom BCM2837B0, Cortex-A53 (ARMv8) 64-bit SoC @ 1.4GHz
  - ✓ 5V/2.5A DC power input
  - ✓ 1GB LPDDR2 SDRAM
  - ✓ Raspbian OS (Linux core)
  - ✓ Extended 40-pin GPIO header
  - ✓ Support I²C and SPI communication
  - ✓ Cost: ≤40€


Source: [11]

# Software Design

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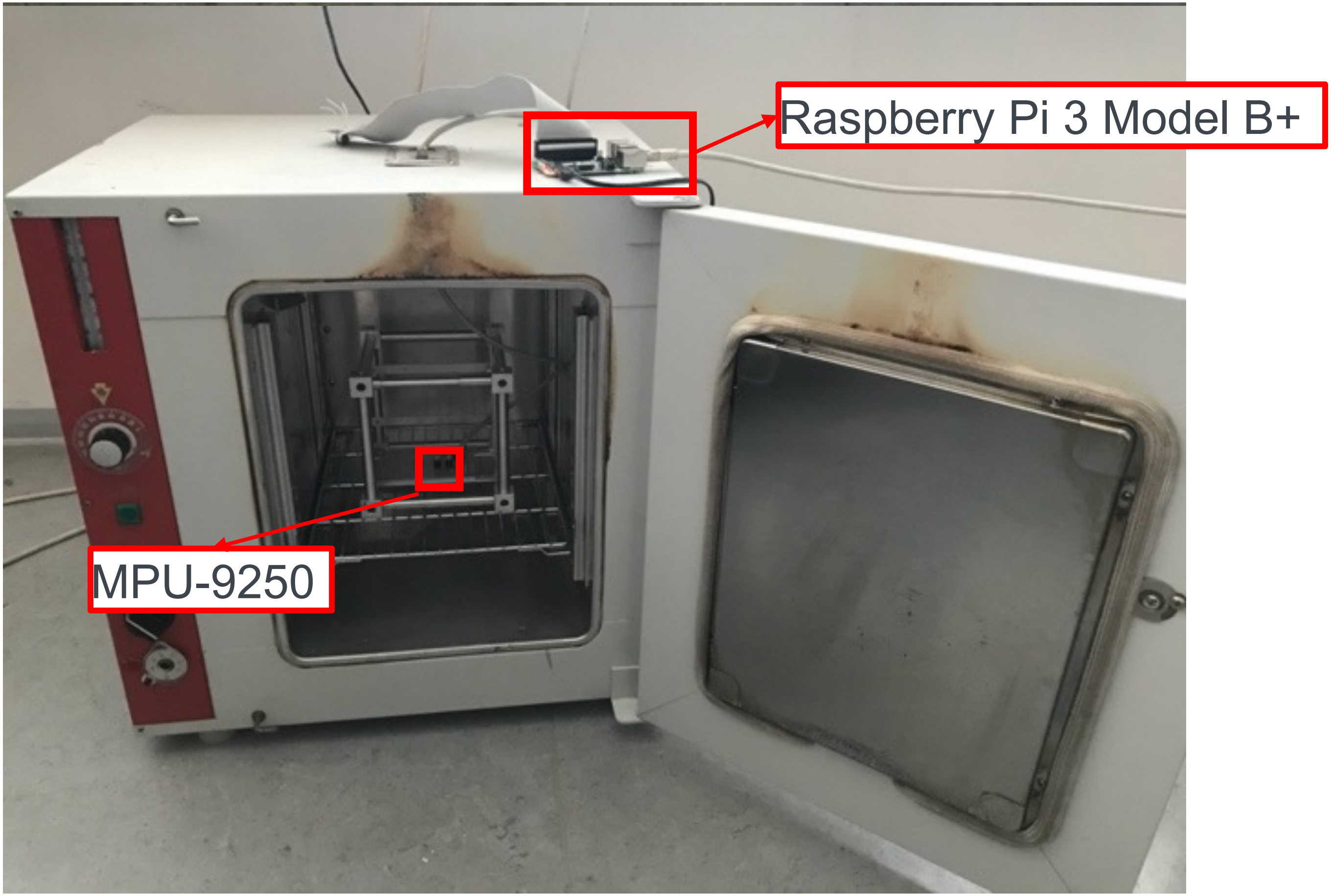
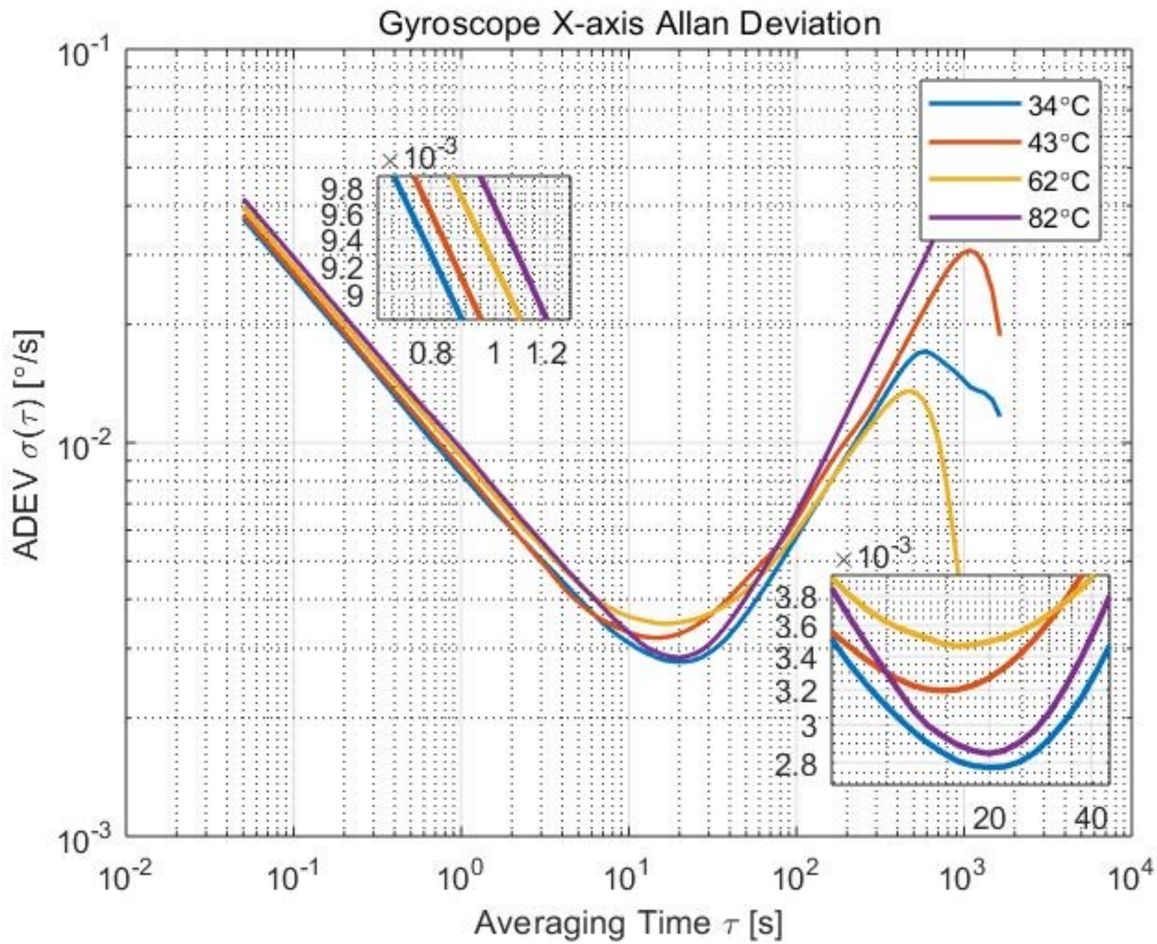
- Python 3.7
- Linux

# Experimental Setup

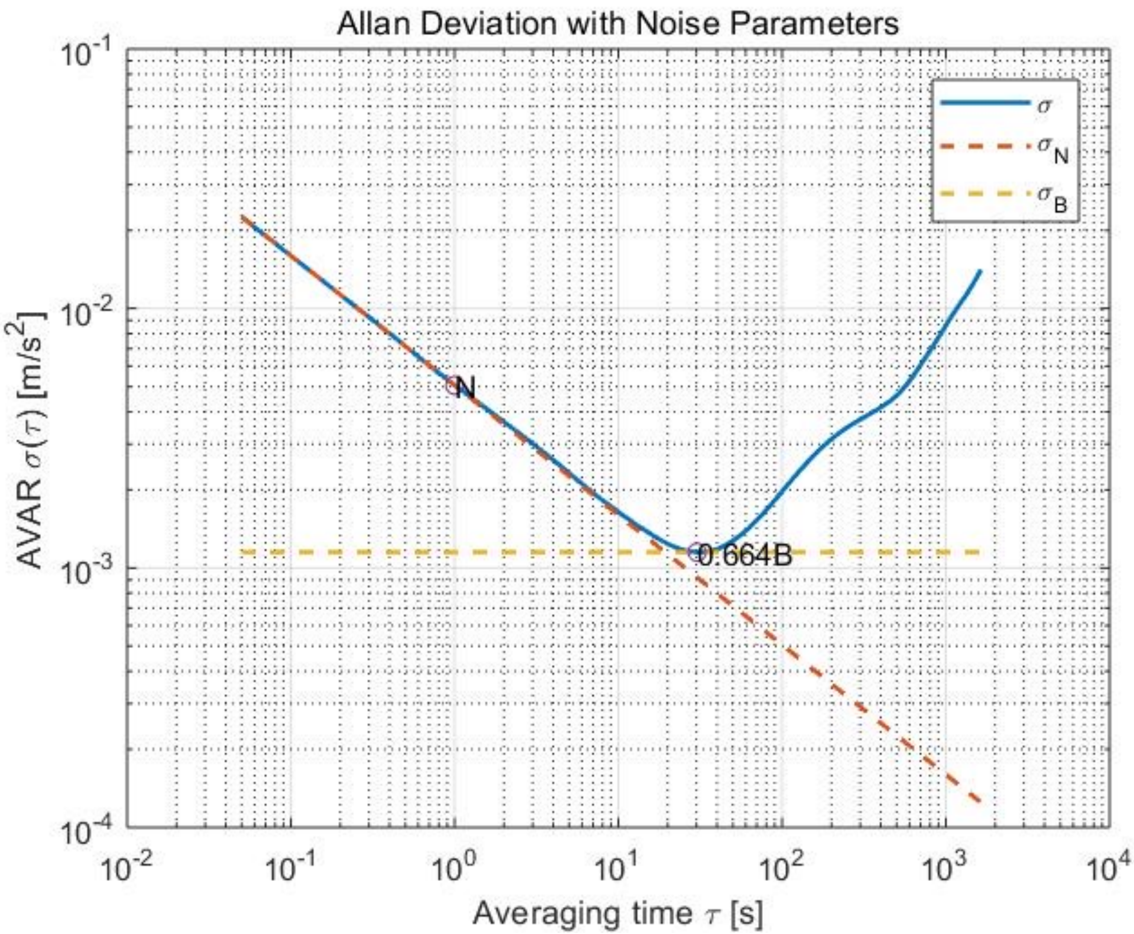


# Result

# Allan Deviation Plot



# Noise Parameters



# Accelerometer Noise Parameters

| Velocity Random Walk ($m/s^2/\sqrt{s}$) | | | | |
|---|---|---|---|---|
| | 34°C | 43°C | 62°C | 82°C |
| **Accel X** | 0.0046 | 0.0049 | 0.0049 | 0.0051 |
| **Accel Y** | 0.0045 | 0.0049 | 0.0049 | 0.0050 |
| **Accel Z** | 0.0072 | 0.0076 | 0.0078 | 0.0083 |

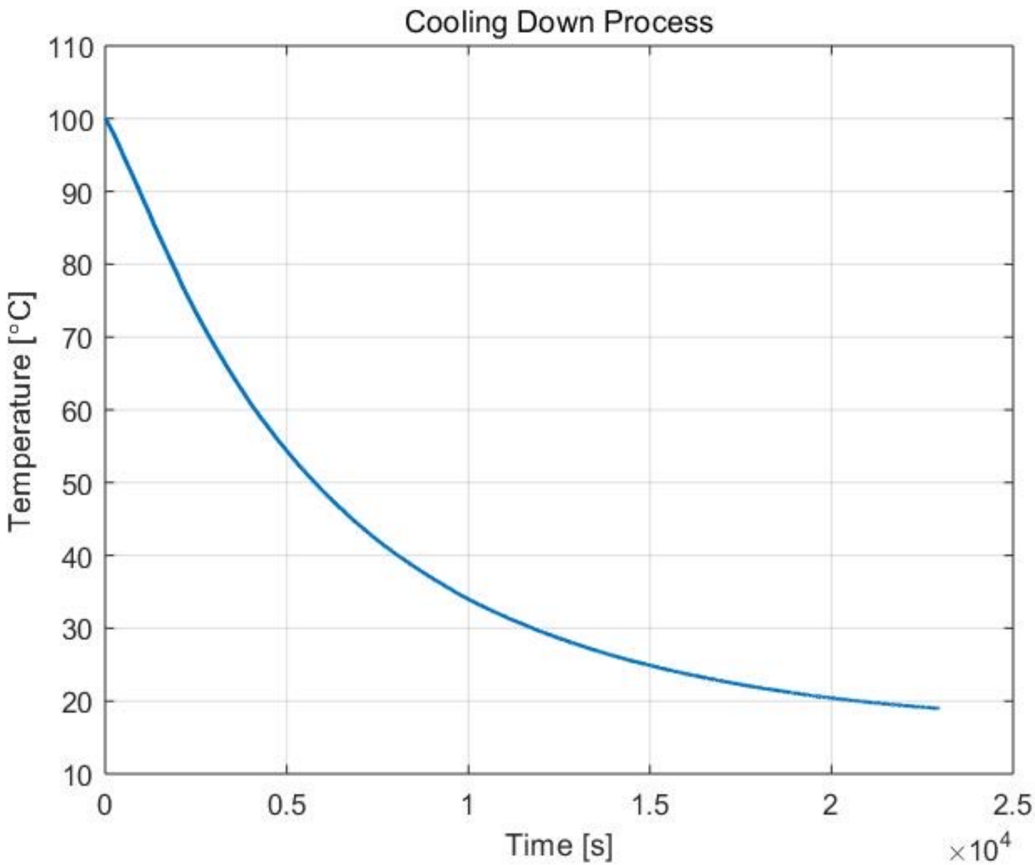
| Accel Bias Instability ($m/s^2$) | | | | |
|---|---|---|---|---|
| | 34°C | 43°C | 62°C | 82°C |
| **Accel X** | 0.0016 (at 46.1s) | 0.0018 (at 37.4s) | 0.0020 (at 24.6s) | 0.0017 (at 30.3s) |
| **Accel Y** | 0.0015 (at 37.4s) | 0.0018 (at 30.3s) | 0.0018 (at 41.6s) | 0.0017 (at 46.1s) |
| **Accel Z** | 0.0016 (at 86.6s) | 0.0017 (at 96.2s) | 0.0024 (at 33.7s) | 0.0023 (at 41.6s) |

# Gyroscope Noise Parameters

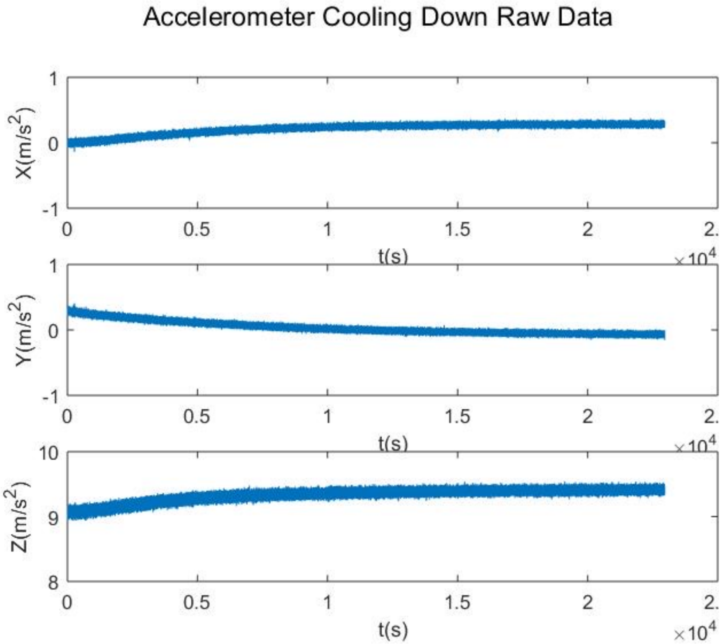
| Angle Random Walk ($°/\sqrt{s}$) | | | | |
|---|---|---|---|---|
| | 34°C | 43°C | 62°C | 82°C |
| **Gyro X** | 0.0084 | 0.0086 | 0.0092 | 0.0097 |
| **Gyro Y** | 0.0087 | 0.0087 | 0.0090 | 0.0096 |
| **Gyro Z** | 0.0088 | 0.0094 | 0.0096 | 0.0100 |

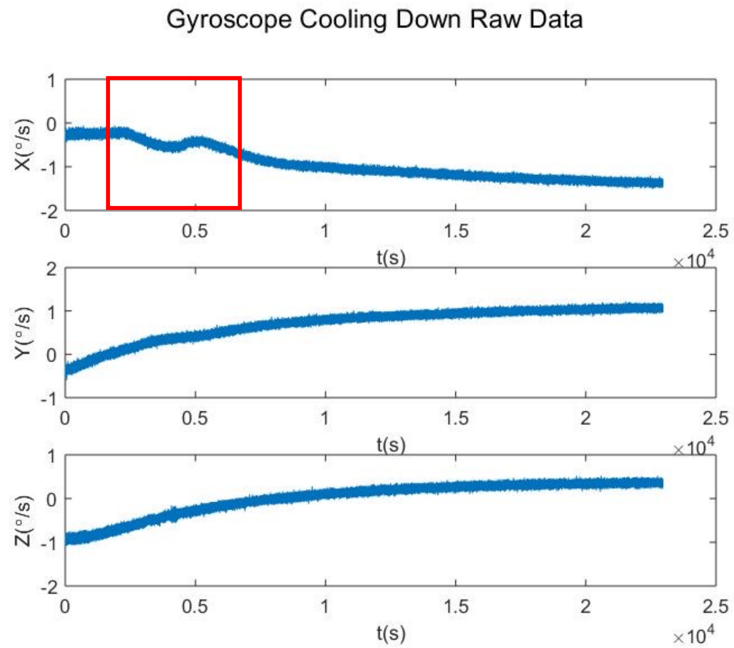
| Bias Instability (°/s) | | | | |
|---|---|---|---|---|
| | 34°C | 43°C | 62°C | 82°C |
| **Gyro X** | 0.0042 (at 19.9s) | 0.0048 (at 14.6s) | 0.0052 (at 16.2s) | 0.0043 (at 19.9s) |
| **Gyro Y** | 0.0036 (at 33.7s) | 0.0037 (at 22.1s) | 0.0049 (at 18.0s) | 0.0047 (at 18.0s) |
| **Gyro Z** | 0.0041 (at 27.3s) | 0.0042 (at 22.1s) | 0.0049 (at 14.6s) | 0.0051 (at 19.9s) |

# Cooling Down Process Temperature Change

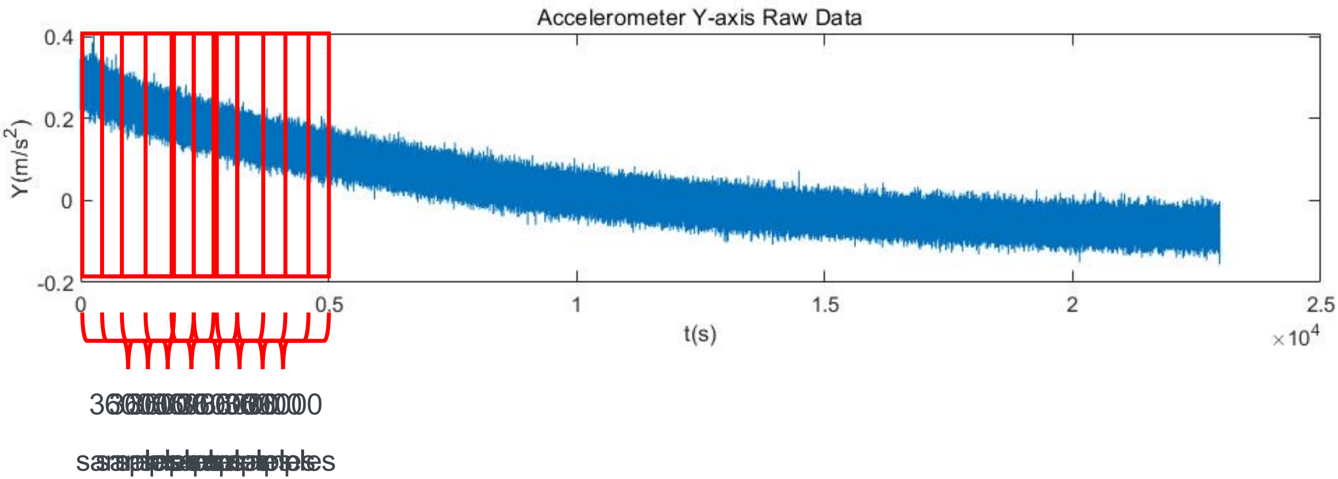


# Cooling Down Process Raw Data

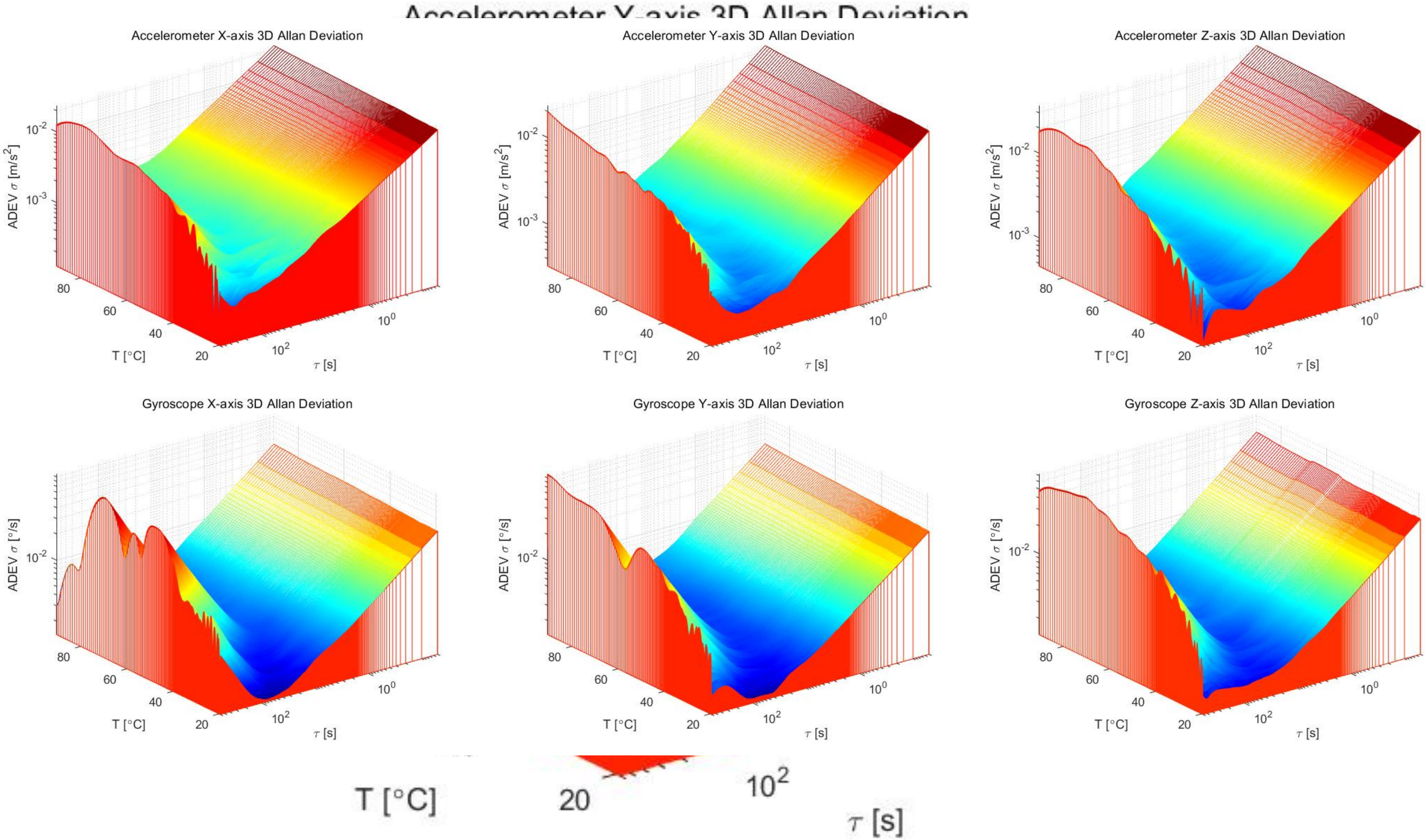


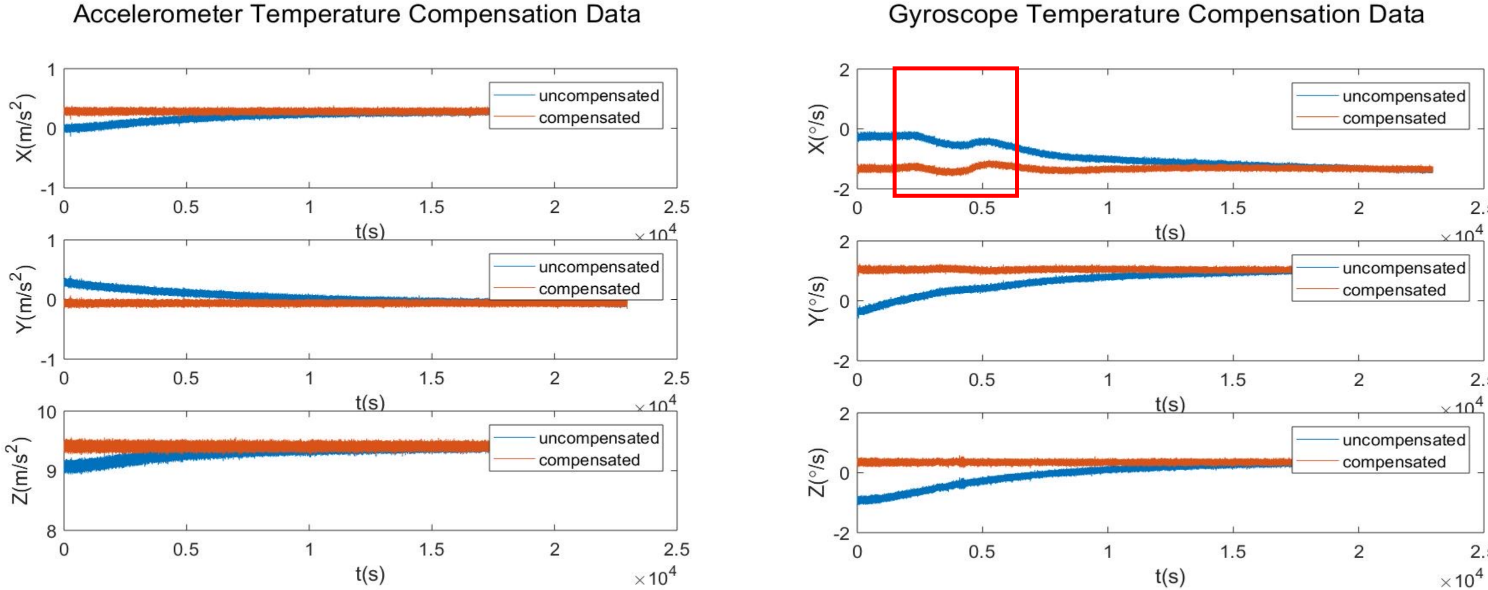
# Cooling Down Process 3D ADEV Plot



# Cooling Down Process 3D ADEV Analysis



# Temperature Compensation Test




Polynomial coefficients

nth order polynomial

Temperature has no bias

```
p = double(polyfit(temp,x,n));
x_comp = x - (polyval(p,temp)-polyval(p,T_NB));
```

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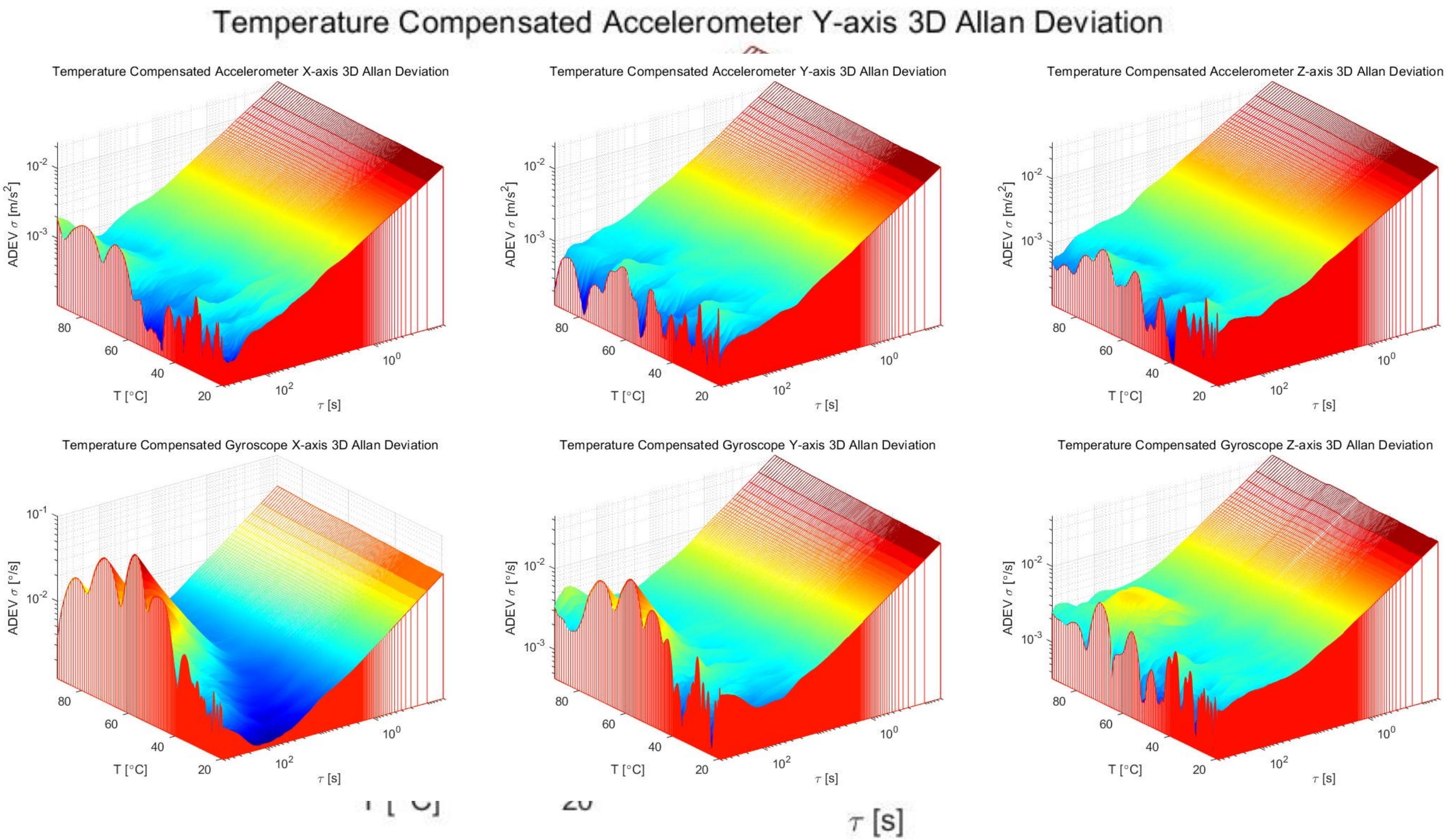
# Temperature Compensation 3D ADEV Analysis



#  Conclusion

# Conclusion and Further Study

## Conclusion

- Temperature influences the performance of MPU-9250.
- Among four 1h temperature datasets, the performance at 34℃ is the best.
- In the cooling down process, 3D ADEV plots show that the noises decrease as the temperature goes down from 100℃ to 20℃.
- Polynomial temperature compensation model can reduce the noises for the high temperature part.

## Further study

- Try out better temperature controller and evaluate at lower temperature.
- Find out better temperature compensation model for MPU-9250.

# References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# Thank you!

# Any Questions?