AN INVESTIGATION OF NORTH-FINDING

USING A MEMS GYROSCOPE

by

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USING A MEMS GYROSCOPE

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ABSTRACT

Navigational mapping of subsurface holes drilled for oil and gas production is required by law. Currently, mapping a drilled hole requires the use of expensive gyroscopes to determine azimuthal direction (e.g., North, West etc.). However, MEMS (micro-electro-mechanical-systems) gyros are now commercially available and are orders of magnitude less expensive than current downhole spinning mass gyros. Unfortunately, they are not accurate enough to be used for downhole mapping.

Determining the azimuth of a subsurface hole requires a gyro to measure a component of the rotation of the earth. At Fort Worth's latitude, a gyro pointed North would measure a rotation rate of 0.0035 degrees/second; while a gyro pointed East would measure zero degrees/second. Unfortunately, the drift of MEMS gyro-measured rotation rate is much larger than earth's rotation rate. Our experimental work indicates that MEMS gyro signals can be averaged and combined to improve the signal-to-noise ratio and subsequently reduce error.

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INTRODUCTION

The goal of my research project was to continue the research into determining azimuthal north with a micro-electro-mechanical system (MEMS) gyroscope. The application for this research is downhole mapping. Downhole mapping requires point-by-point measurement of depth, inclination, and azimuth. Depth and inclination are relatively easy to measure; measuring azimuth is much more difficult. The determination of azimuthal direction done by a gyroscope is known as gyrocompassing.

Oil and gas companies in Texas are required by the Railroad Commission of Texas to map the subsurface where they are drilling. Companies currently use a variety of different gyroscopes for these applications such as macro-scale fiber optic, ring laser, and quartz hemispherical resonator gyroscopes. These gyroscopes are very large and expensive. MEMS gyroscopes are now being considered for gyrocompassing since they are both cheaper and smaller; however, current MEMS gyroscopes' measurements are considered unreliable. The ultimate goal of our research is to eventually create a procedure for taking data in about a minute that can then be filtered to determine the earth's rotation rate that will allow the tool to determine azimuth.

GYROSCOPES

Gyroscopes measure rotation rates and have a variety of uses. They are often spinning bodies and can be found in toys and cellphones among others. They are even used to balance a moving system such as a Segway. However, I will focus on their use in measuring the rotation rate of the earth. From determining the rotation rate of the earth, the azimuthal direction can be determined through the use of trigonometry. For example, since we know the latitude of Fort Worth, we can determine the y-component of the rotation rate at Fort Worth, rotation rate facing North. $Earth\ Rotation\ Rate = \frac{360°}{24\ hours} * \frac{1\ hour}{3600\ seconds} \cos(32.7574°) = \mathbf{0.0035\ °/sec}$. The current gyroscopes used for this function are very expensive, large spinning mass gyros. Our hope is that we can substitute this kind of gyro with a MEMS gyroscope.

<u>MEMS</u>

MEMS or micro-electro-mechanical systems is a growing area of the electrical sensor industry. MEMS technology has many potential applications in numerous areas. One of the first applications of MEMS technology was in accelerometers in automobiles to detect collisions and thus deploy airbags. MEMS devices often provide an alternative to current technology in a chip form. MEMS gyroscopes are much less expensive and smaller than those currently used. The problem, however, is that MEMS gyroscopes are not as accurate as their counterparts. Through the use of filters, we hope to be able to determine the azimuthal direction that the gyroscope is facing based on the measurement of the rotation rate of the Earth. The two gyroscopes that were used in testing are the Analog Devices AD646 and Sensonor STIM210.

Analog Devices AD646

The AD646 is pictured in Figure 1 and was the less expensive of the two, costing about $135. It measures the rotation rate of the earth through the use of sensors inside of the chip. The chip contains inner sensors that measure displacement due to the force generated by the Coriolis Effect on a rotating system. These inner sensors interact with outer sensors in order

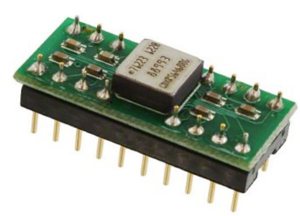


Figure 1: Picture of the Analog Devices AD646 MEMS Gyroscope

to create a capacitive signal proportional to the angular rate based on the Coriolis Effect. The capacitive signal is transferred to an output voltage. This output voltage can then be converted to rotation rate in degrees/second through the use of the 0.009 V/(degrees/second) conversion rate provided by Analog Devices. Analog Devices claims that its gyros are able to eliminate small vibrations as noise. It advertises its ability to have vibration stability as its most important feature. The quad-sensor design contained by the AD6464 allows for this feature. The four sensors are connected in such a way that a new "zero" is created based on the common signal experienced by the four sensors; therefore, the chip can eliminate both linear and angular acceleration resulting in the rejection of shock and vibration. This is an ideal trait for the gyroscope due to the nature of the work it will perform. The gyro will be subject to numerous vibrations during underground measurements; therefore, to be able to filter that noise out and be left with just the rotation rate data is important.

A common trait used to characterize the drift performance of gyroscopes is through a parameter called bias instability. Data sheets provide a bias stability for the given gyro that can be defined as lowest bias stability able to be achieved for the gyro. It can be determined for a given gyro by looking at the Allen Variance of the gyro. The lowest bias stability is the optimum parameter for taking data since it is the longest time frame where data averaging reduces error. Analog Devices provides that the bias instability of the AD646 is 12°/hr. This means that over the course of an hour, the gyro's error due to drift is 12°.

The AD646 gyroscope requires a 6 volt power supply ± 0.15 V. Since the output of the AD646 is an analog voltage, the AD646 required a separate data acquisition package called LabJack. The gyro connects to LabJack with a circuit board in order to collect the different output signals such as ground, output voltage, and temperature. The circuit board is also used in order to place an initial low-pass filter through the use of a voltage divider and capacitors. LabJack connects to the computer through the use of an USB port and reads MATLAB scripts. The gyro is mounted on an Aerotech A3200 rotation table, which is also able to be controlled by a Matlab script. Therefore, a single script was created to control both data acquisition and the rate table.

Sensonor STIM210

The Sensonor STIM210 gyro was borrowed for a semester to perform measurements and compare those to the AD646. The STIM210 is a more expensive gyroscope costing $5,780; however, it also has a much higher accuracy as seen by its bias instability of 0.5°/hr. The Sensonor gyro is a three axis self-contained miniature package as seen in Figure 2. In addition to excellent performance in vibration and shock as was true with the AD646, the STIM210 is also compensated for drift due to temperature effects. It is connected to the computer through the use of two USBs, one for power and the other for data collection. Sensonor provides its own software package to handle the data acquisition, which allowed for a simpler setup since no other hardware or software was required to collect data or to power the gyro. The software provided a simple digital interface that allowed the parameters of the testing to be controlled. Matlab was still used in order to control the rotation table when running tests.

Figure 2: Picture of the Sensonor STIM210 MEMS Gyroscope package

CHARACTERIZATION

In order to minimize the amount of error in a gyroscope, it is first important to understand the errors that are prevalent. Ideally a gyro would measure zero when it is not experiencing any rotation; however, this is not true. Some error inducing factors include temperature effects, null bias drift, outside forces, and incorrect characterization among others. Bias drift is the tendency for the gyro to drift over a period of time. To minimize the null bias of a gyro it is important to reduce all of these factors if possible. One of the main reasons that the AD646 was chosen is that it reduces the effect that external vibration has on a rotation measurement. The STIM210 enhances bias error reduction even more by self-compensating for the effects of temperature. Correctly characterizing the gyro is also an important step in order to minimize the amount of error.

Allan Variance

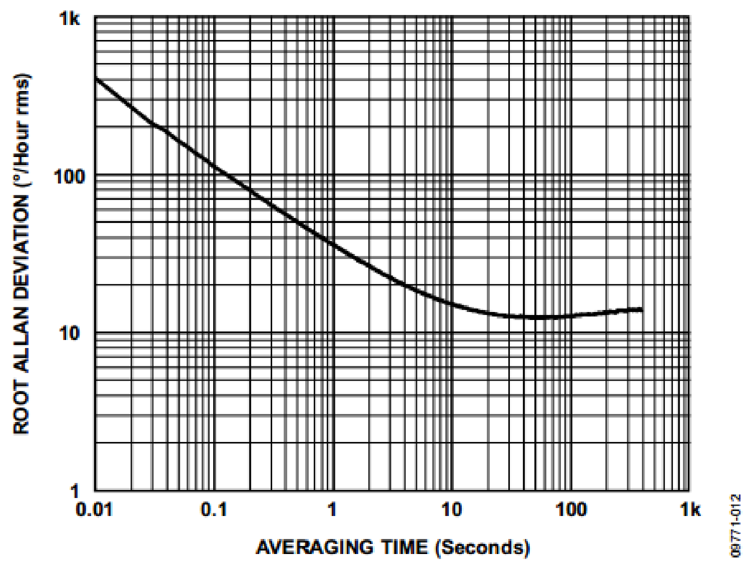
A common method to characterize gyroscopes is through a parameter called Allan Variance or Allan Deviation.

$$AVAR(\tau) = \frac{1}{2 * (n-1)} \sum_i (a(\tau)_{i+1} - a(\tau)_i)^2$$

A graph of the square root of AVAR vs τ on a log-log plot can be analyzed in order to determine the optimum parameter to collect data. The y-axis of Allan deviation is the bias stability of the gyro; consequently, the minimum point on the y-axis corresponds with the ideal duration for taking data in the x-axis.

Analog Devices provides the Allan Deviation plot in Figure 3 in the data sheet for the AD646. By looking at the plot, it can be determined that the minimum root Allan Deviation or bias stability is 12°/hr corresponding to an average time between thirty and

Figure 3: Typical Root Allan Deviation at 25°C vs Averaging Time for the AD646



forty seconds. Although Analog Devices characterizes each of the gyros, it is also important to characterize the gyros that will be used for testing. To characterize the gyro we used, data was collected for a period of time such as one hour while the gyro remained in the same direction. This data was placed in either a script that we created in Matlab to calculate the Allan Variance and produce a plot or a program called Alavar 5.2, which returned similar information. The output plot of the Matlab script for the AD646 is pictured in Figure 4. As is seen by the plot, the minimum Allan Variance occurs at 34.5 seconds. The parameter that we determined through our own characterization appears to match fairly closely to the plot from the data sheet.

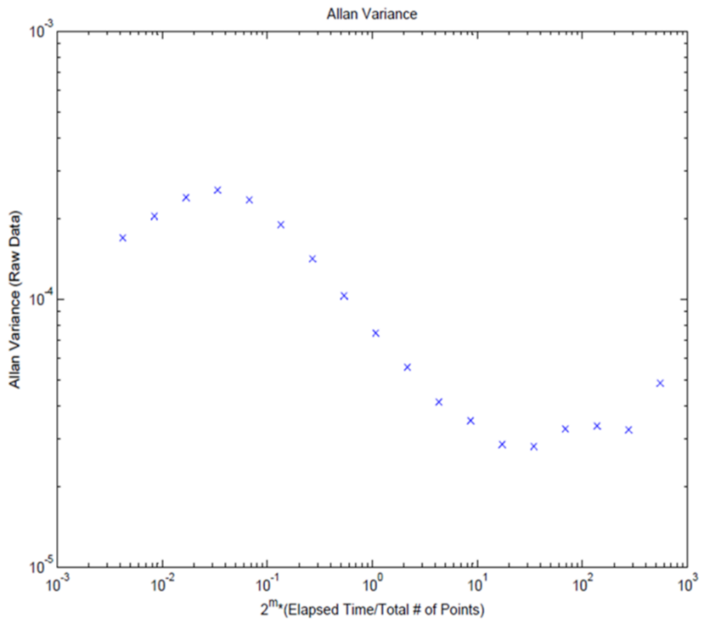


Figure 4: Allan Variance Plot generated with the Matlab script for the AD646. Plot of Allan Variance vs Averaging Time

Sensonor provides a similar plot for root Allan Variance in their data sheet for the STIM210 as seen in Figure 5. The minimum point of bias stability occurs at a considerably longer duration for the STIM210, as the averaging time is about 1000 seconds for all three of the axes. Figure 6 depicts a plot of the Allan Variance for the STIM210 that was created using Alavar 5.2. The minimum point occurs at a time constant, τ, of 32,768 which translates to about 4.4 minutes with a bias stability of about 0.7 °/hr. However, 4.4 minutes is too great of a period to collect data, so we looked at the point when the time constant was 2,048 and its duration was 16.4 seconds which provided an error of 1.6°/hr. This point allowed a large tradeoff in time without sacrificing the bias stability too greatly. These two characterization tests provided the starting durations that were used in creating a procedure for data acquisition for each of the gyroscopes.

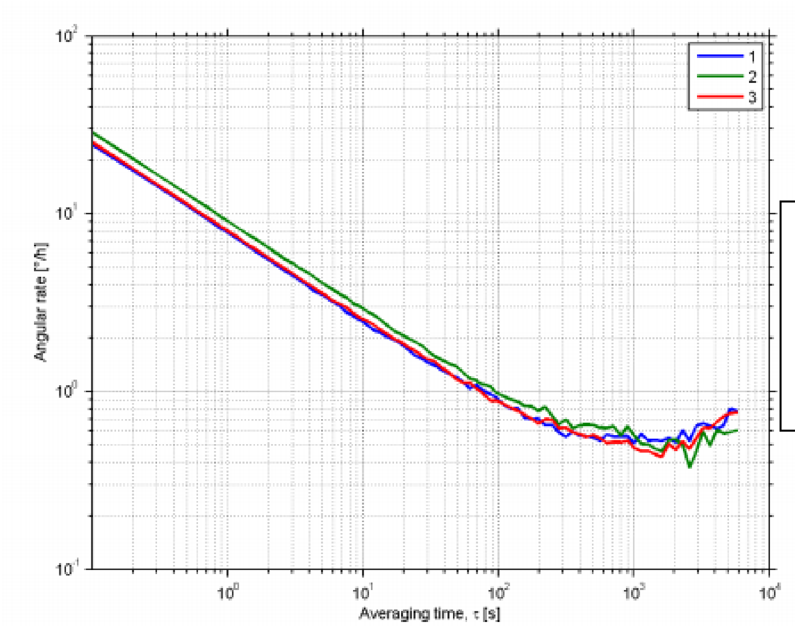


Figure 5: Typical Root Allan Deviation vs Averaging Time for the three axes of the STIM210

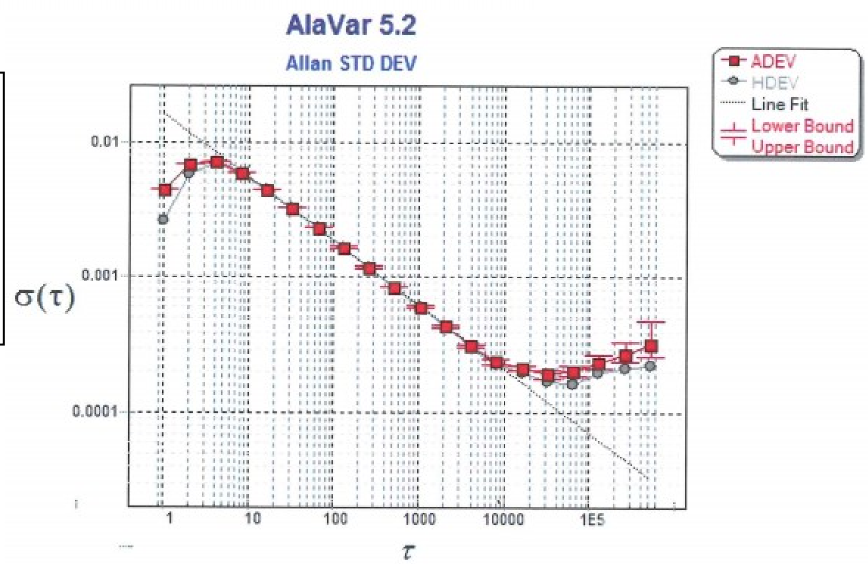


Figure 6: Allan Deviation vs Time Constant for the STIM210 generated using Alavar 5.2

COLLECTING DATA

After the characterizing each gyro, a procedure for collecting data for azimuthal measurements was created. The Earth's rotation rate can be measured using static and dynamic methods. Static methods involve taking data while the gyro remains stationary, while dynamic methods take data while the gyro is moving.

Maytagging

For most of our testing, we used a static method called "maytagging." This process gets its name from the motion of a washing machine. This procedure is done by facing the gyro in a given direction while collecting data for the desired interval. The gyro then rotates 180° and remains there for the same interval, then returning to the original position by rotating -180 degrees. This procedure is repeated ten times for a single data set; therefore, measurements are taken during twenty intervals. Since Allan Variance characterization should minimize error for 32 seconds averaging time, that was the interval used for the AD646. Maytagging was chosen as the primary means of measuring the Earth's rotation rate since it allows for some cancellation of error when calculating the rotation rate. When taking the average of the adjacent signals, some of the bias error is removed as seen in the equation. A majority of the error is removed, but

$$\frac{Rotation\ Rate}{Conversion\ Factor} = \frac{(+North\ Signal + Error) - (-South\ Signal + Error)}{2}$$

due to the nature of instability in the bias error significant error remains. In addition to the two-point maytagging described, we also looked at four-point maytagging.

East-Seeking

Maytagging was our most successful method for measuring the rotation rate of the Earth, but we also experimented with another static method which we called East-Seeking. The East-Seeking algorithm builds on maytagging to find East. It involves orienting the gyro in a random direction, and then begins maytagging at that point. After the gyro gets a reading of its direction, it tries to correct itself based on the rotation rate that was measured. This process is repeated until the gyro correctly measures East. Based on the amount the gyro adjusted, we can determine which direction it was originally facing. This script provided some promising results with the AD646 at first; however, it was determined that the gyro was not stable enough in order to further investigate the script in the current setup.

Carouselling

One dynamic method we used was "carouselling." Carouselling involves taking data as the gyro continually spins. The results of this test should produce a sine wave, which can then be examined to locate specific points on the wave. The peaks would be North and South, while the intercepts are East and West. Due to the bias noise of the gyro, the signal was indistinguishable and was quickly deemed useless with the AD646.

Optimum Parameters

Although we determined the optimum averaging duration for each gyro, we also experimented with various durations and column lengths. For each of the gyros, we took data at half and double the parameter determined from Allan Variance. For the AD646, we took data with durations of 16, 34, and 68 seconds at maytagging stops. After comparisons between data sets, it was determined that the better results occurred at the 34 second duration. Since the STIM210 had a different characterization, we used durations of 8, 16, and 32 seconds. The idea for taking various lengths originally started by thinking that the Allan Variance time is actually the time for one complete cycle compared to just one stop.

In addition to changing the duration of each stop, we also looked at the number of columns or stops in a data set. The standard set of data originally consisted of ten complete cycles of maytagging or twenty stops for both gyros. This was chosen arbitrarily because a complete cycle was not too lengthy and it allowed the rotation rate to be calculated as an average of ten rotation rates. We were uncertain as to whether the number of columns was significant. We wanted to be able to somewhat definitively state what the optimum number of columns should be as we did with the duration. To figure out the number of columns chosen per data set for the AD646, we came up with the idea of taking the Allan variance for all of the calculated rotation rates for a given set of data. To do this, we took a data set of 108 columns which would give us an Allan variance graph with six points (1,2,4,8,16,32). The Allan Variances for these runs were calculated using Alamath 5.2. We determined that the 32 columns points had too great of an error bar and should not be used even though they usually were the lowest value. Therefore, we were left with the 16 columns point. This means that the optimum number of columns per data set should be around the 16 – 20 columns per data set.

When comparing the amount of columns to the rotation rates they provided, we saw that the rotation rate did not always improve by that much from 20 columns to 108 columns for the AD646. In fact, sometimes it got worse. Therefore, we concluded that collecting 20 columns was better than 108 for data, especially due to the time difference between the two. In the future, we decided to take 18 columns per data set since it is in the middle of the range. The other common data set for the STIM210 contained 100 complete cycles. These large data sets were done to be more versatile. Although the long data sets did not work well for the AD646, it worked really well for the STIM210. We could look at the data set as a whole or break it into ten sets of ten rotation rates. This also allowed for easier testing in that the gyro could be left unattended for an extended period of time.

Variables

Table

Throughout the course of my research, we experimented with a number of different experimental variables. The first major variable that was adjusted was the table on which data was taken. The table used for the lab is an optics table. Optics tables are designed to minimize vibrations experienced by the table. This is done by having the legs of the table fill up with air creating an air cushion between the ground and workspace. Optics work is very sensitive, so these tables help nullify any vibrations that would normally be transferred through the ground. Initially, all of our testing was done with the table "floating." It was suggested that we try to take data when the table rested on the actual legs with the air removed. I performed a comparison of five data sets with each variable. Overall, when the table was resting on its legs the percent error was less than the percent error when the table was floating, 10.9% and 16.6% respectively. Therefore, all future testing was done while the table was resting on its legs.

Circuit Board

Another variable that was adjusted for the AD646 was the elimination of the circuit board or breadboard. A breadboard was originally needed as a voltage divider and in order to place a preliminary filter on the signal. The idea was that the extra wiring required for the breadboard created extra noise, so we sought to remove it from the system in order to compare results. To do this, we simply added the capacitors and wiring directly into the LabJack ports. However, no noticeable result was achieved after removing the breadboard.

Power Source

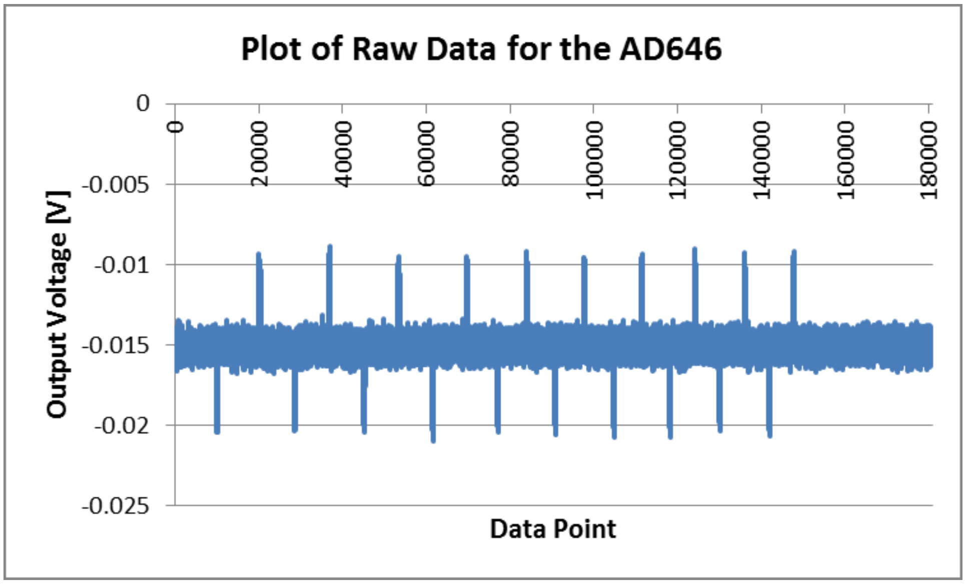
As mentioned previously, the AD646 required a 6 V power source. For most of our testing we used an Agilent 6614C for this power source. It occurred to us that this source may be noisy; therefore we looked to replacing this with 4 AA batteries. AA batteries have a voltage of 1.5V each, so four of them should equal 6 V. However, this was not the case. The four fully charged batteries resulted in a voltage of 6.18 V. Connecting the four batteries to the gyro resulted in frying the AD646 chip. Although we thought about trying the batteries as a source again after they have been drained to 6 V, we never replaced the power source.

Slip Rings

Based on our efforts to reduce noise in the system, we also looked at using the slip rings in the rate table. This would allow us to use shorter wires in addition to removing the movement of the wires while the rate table is spinning. The wires were soldered into the input at the top of the rate table. The signals then move through the rate table through the use of slip rings. The LabJack can then be soldered to the output of the slip rings at the back of the rate table completing the circuit once again. We tested the viability of this option through the use of an oscilloscope. By hooking up a power source to the input and an oscilloscope to the output, we were able to determine that the slip rings did not seem to add measurable noise. The slip rings were used in all subsequent testing.

FILTERS

Once the data was taken, we could then begin the filtering process in order to determine the rotation rate measured by the gyroscope. My research with this project originally began creating a filter for the measured data in Matlab. With our original setup, data was taken by a laptop while the rate table was controlled by another desktop. Therefore, data was taken continuously resulting in a large data set that contained a minimum and maximum bump in the signal for each change in direction. A plot of unfiltered data is seen in Figure 7.



Original Filter

The goal of my filter was to go through and divide this large set into each stop and remove the extrema through the use of a Matlab script. In order for the script to do this, it breaks up the raw data into manually set increments and locates the minimum or maximum point depending on the direction the gyro was facing for that increment. Once the extrema are located, a set number of points on each side of it are tossed out and vectors of the data are created. Therefore, the raw data plot above would result in twenty vectors of data with ten pointed at North and ten at South. The script could then calculate the mean, standard deviation, and variance of each vector as well as plot it to assure the entire extrema was removed. The 21 resultant means are calculated by taking the difference of each North mean and each of its neighbors, which are South means, and then dividing by two. As mentioned when talking about maytagging, this is to help reduce the offset error. This process results in twenty voltage difference values with units of mV which can then be converted the component of the rotation rate of the earth parallel to the Earth's axis of rotation according to the gyro with the conversion factor of 9mV/(°/sec) to obtain 20 rotation rates. The twenty rotation rates in °/second are plotted versus the mean of the values and the accepted value of -0.0035 degrees/second which is the rotation rate of the earth when facing North/South for Fort Worth which is depicted in Figure 8.

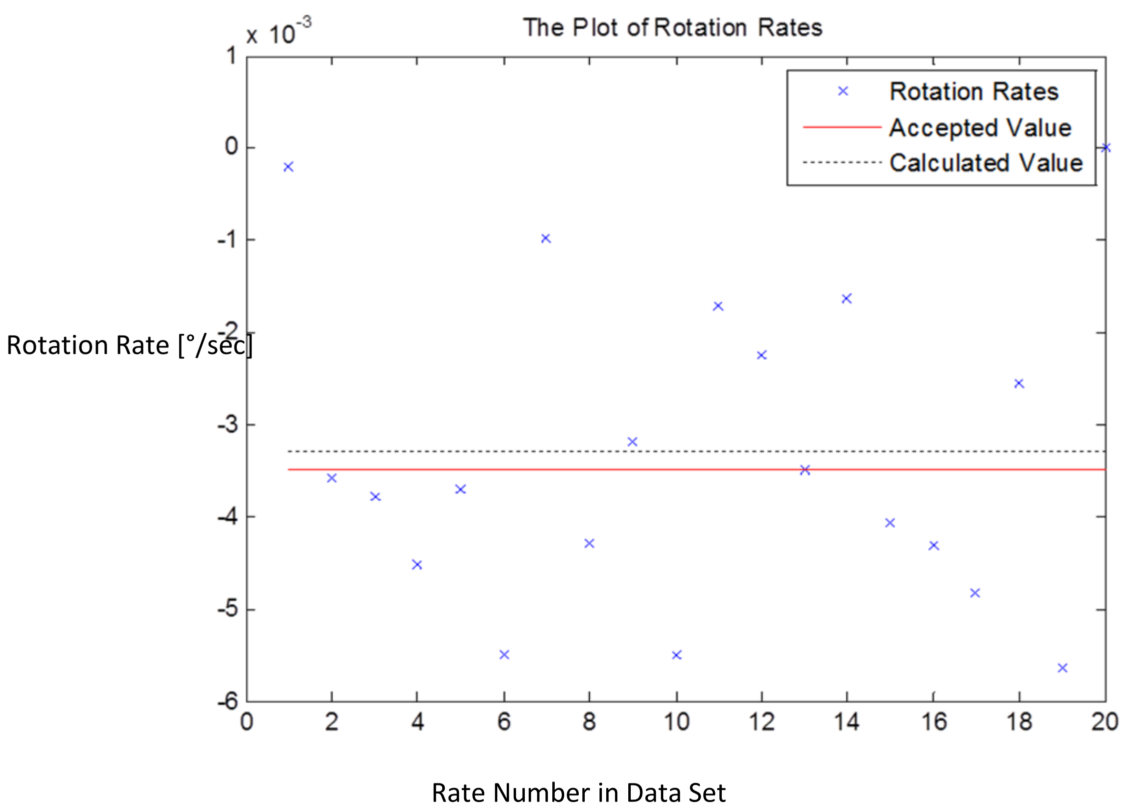


Figure 8: Plot of Rotation Rates for a run with the AD646

Updated Filter

This script was eventually able to be modified once the rate table was able to be controlled by a script in Matlab. Initially, the rate table was run on its own software which is why two computers were needed. After the switch was made, a single computer was able to run a script that performed all of the desired functions of spinning the rate table, taking data, and filtering the data. The new script was also able to collect data only while the gyroscope was stationary and create a new vector of data for each stop. The resulting filter was able to be greatly simplified and allowed for easier collection of data. An example of the unfiltered data for the STIM210 is seen in Figure 9 and can be compared to the data after it has been filtered in Figure 10.

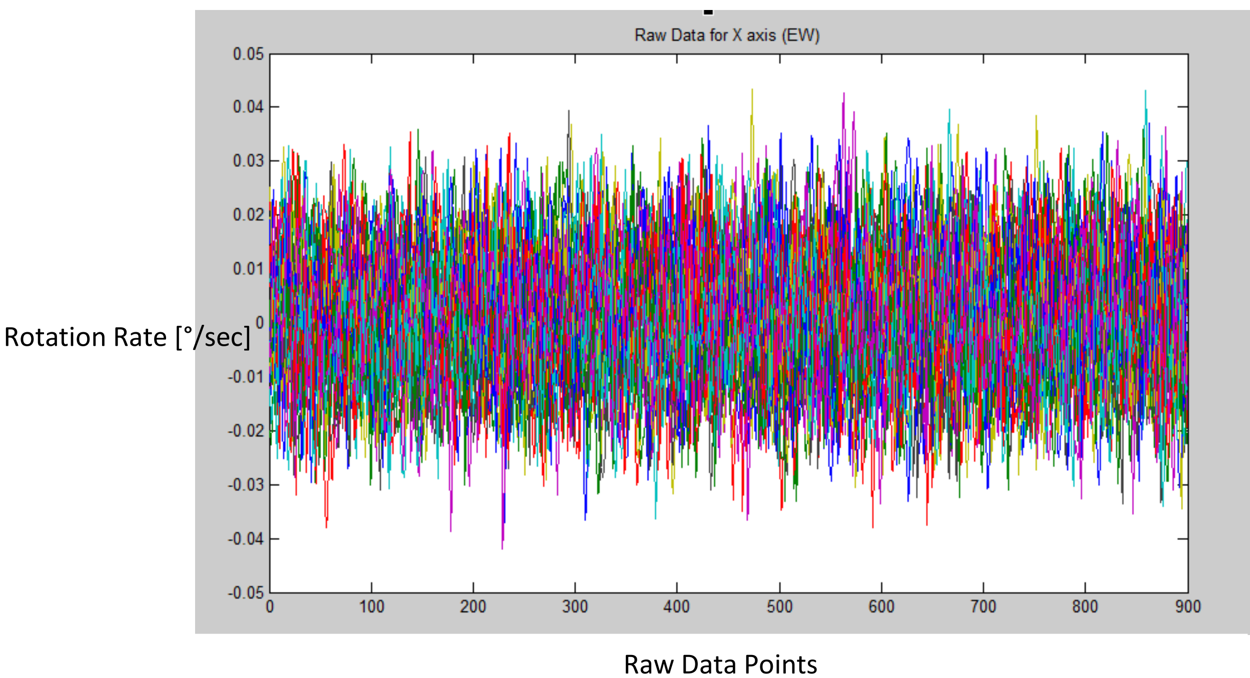
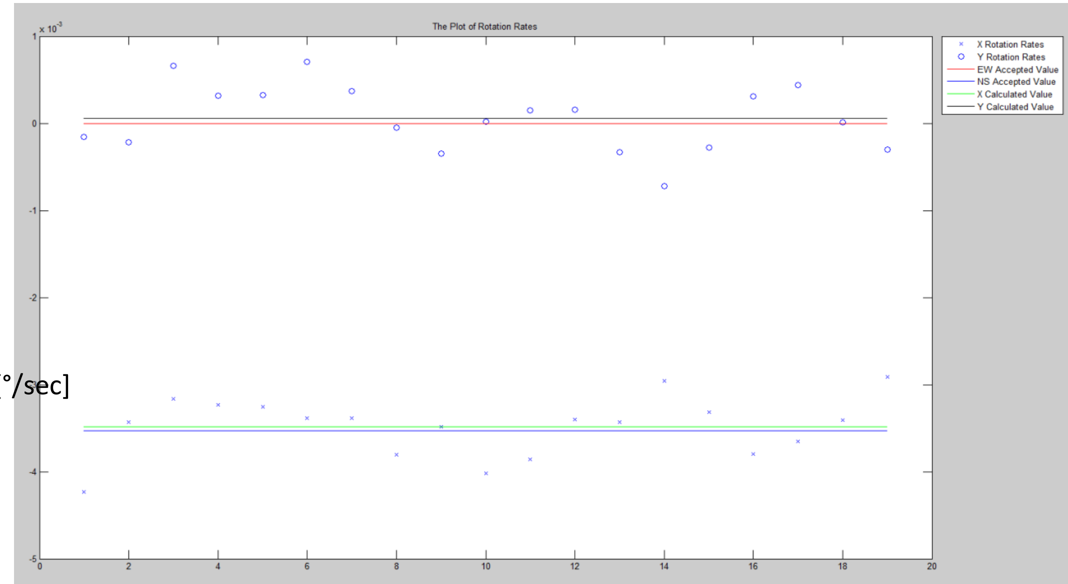


Figure 9: A plot of the X axis data (EW) for the STIM210. The multiple vectors create the different color plots.



Rotation Rate [°/sec]

Raw Data Points

Figure 10: A plot of the X and Y axis data for the STIM210. The multiple vectors create the different color plots. The circle points are for the X axis rotation rates and the star points are for the Y axis. The red and blue lines are the accepted values for the X and Y axis respectively. The green and black lines are the calculated values for the X and Y axis.

Swanson and Schlamminger

In addition to the nearest neighbor filter which was used, we also tried a few others such as Swanson and Schlamminger, next nearest neighbor, next next nearest neighbor, and a sliding average filter. The Swanson and Schlamminger is similar to the nearest neighbor, except it places an equal weight on all vectors while ours places less weight on the first and last vector. After a comparison between results of both filters was made, it was determined that there was no noticeable difference in the results between the two filters. Therefore, we decided to keep using our filter for the time being.

S & S filter = UV; with U = (data vector) and V = $\left(\frac{1}{N+1}, \frac{-1}{N-1}, \frac{1}{N+1}, \frac{-1}{N-1}, \dots, \frac{1}{N+1}\right)$

$$Our\ Filter = \frac{\frac{N_1 - S_1}{2} + \frac{N_1 - S_2}{2} + \frac{N_2 - S_2}{2} + \frac{N_2 - S_3}{2} + \cdots + \frac{N_n - S_n}{2}}{n}$$

Next Nearest and Next Next Nearest Neighbor

We also looked at recycling each set of data multiple times in Next Nearest Neighbor and Next Next Nearest Neighbor. Nearest Neighbor relates three vectors of data to each other, one North for every two South. Next Nearest Neighbor relates five vectors to each other and Next Next Nearest neighbor relates seven. The same principle is used for both of these; the thinking is that one can recycle data taken in the same set in order to get more results. By reusing vectors of data, we are able to get more rotation rates within one data set. However, these added rotation rates did not translate to better results. Thus, the current Nearest Neighbor filter was kept once again.

Sliding Average

The sliding average filter was mainly used to look at the effect that temperature had on the rotation rates. This script was the only one that was applied to the STIM210. The sliding average works in such a way that it smoothes the data by making it more linear. This data was graphically compared with temperature in another script called moving average as seen in Figure 11. As seen, there appears to be no significant correlation between the rotation rate data and temperature data for the STIM210.

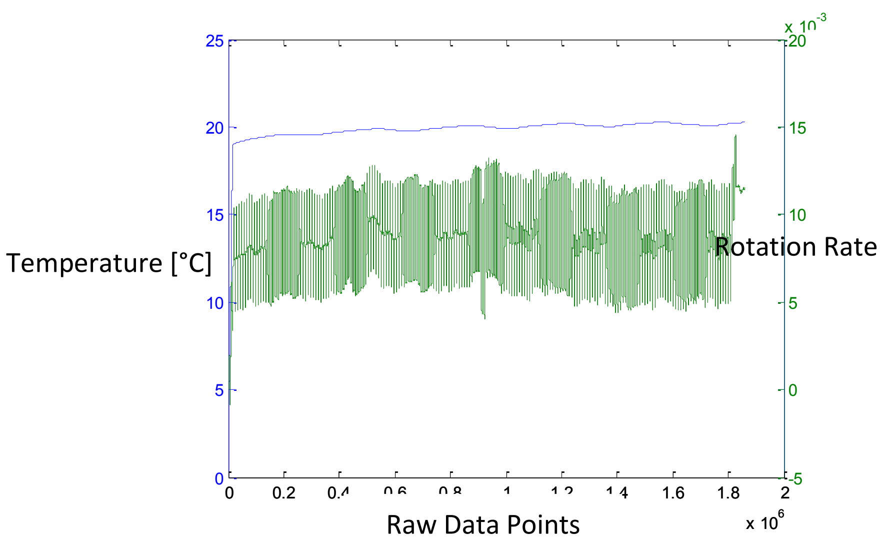


Figure 11: Plot of Filtered temperature and rotation rate data for STIM210. Temperature is blue and rotation rate is green.

CONCLUSIONS

Repeatability

After numerous testing and observations have been completed, a number of conclusions began to form for each of the gyroscopes. The most important conclusion is that the repeatability of the gyroscopes needs to be improved. This is especially true for the AD646. Although we were greatly improving the bias drift from the 12°/hr through filtering to usually less than 5° for a data set, the results were not consistent. It was determined that the signal to noise ratio for the AD646 is near 1:1. In order to get more repeatable results, the ratio needs to greatly increase. This can be attempted by either increasing the signal or reducing the noise. The fact that we were getting fairly accurate results shows that we were improving upon this ratio, but it needs to be better in order to gain consistency.

Ergodicity

The other major conclusion for the AD646 is determining that it exhibits a quality known as ergodicity. Ergodicity means that the time average of a sensor is equal to the ensemble average of several sensors averaged over proportionally shorter times. This means that the gyro exhibits behavior that shows that each calculated rotation rate is independent of the others. We were able to quantify this by collecting long data sets with 900 cycles and 1799 estimates of the rotation rate. When taking the Allan Deviation of this set which is depicted in Figure 12, the resultant plot showed that the deviation was inversely proportional to the square root of the number of estimates. Thus, the longer the data set, or more calculated rotation rates a set has, the more accurate the results. However, due to the nature of the task the gyro will be performing downhole, the time required for a sufficiently accurate earth rotation rate measurement is still greater than required. Although the Sensonor did achieve more accurate results, the sampling period was greater than that which was desired for its application. Since the gyroscope exhibited ergodicity, we were able to determine that through the use of multiple gyroscopes at once, a more accurate reading could be made. Multiple gyroscopes would increase the number of rotation rates calculated per set, resulting in a more accurate overall reading.

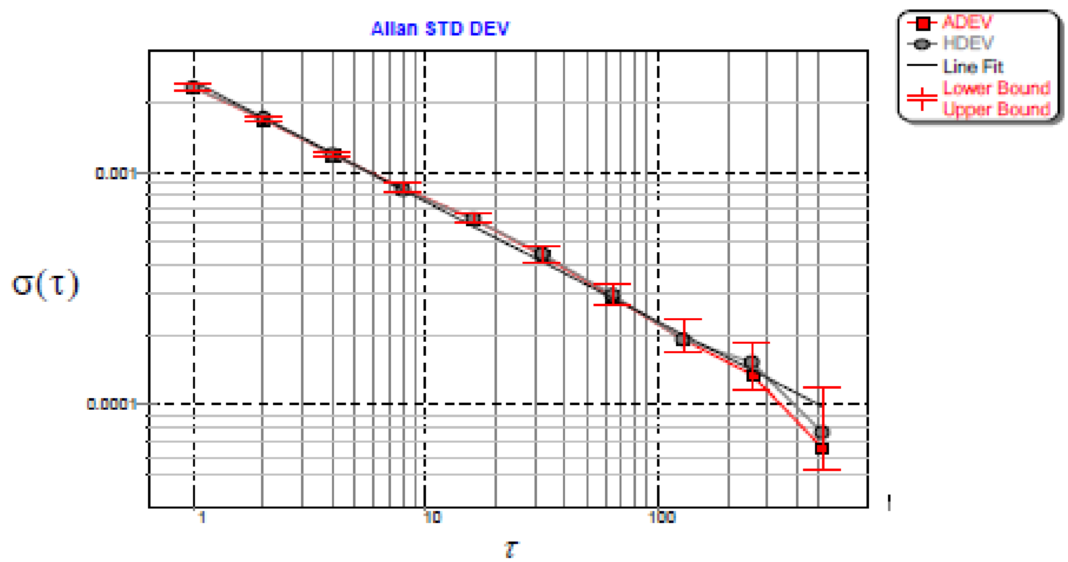


Figure 12: Plot of Allan Variance for 1800 rotation rates with a line fitted with negative slope of 1 over the square root of the number of samples.

FUTURE WORK

Research on MEMS gyroscopes will continue in the future with the focus still remaining on reducing the amount of drift seen by the gyroscope. Temperature will be looked at in detail in order to try to compensate the gyroscope for the effects that temperature has. Work with maytagging and east-seeking will continue to be developed. Multiple gyroscopes will be examined as another option to enhance the signal.

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