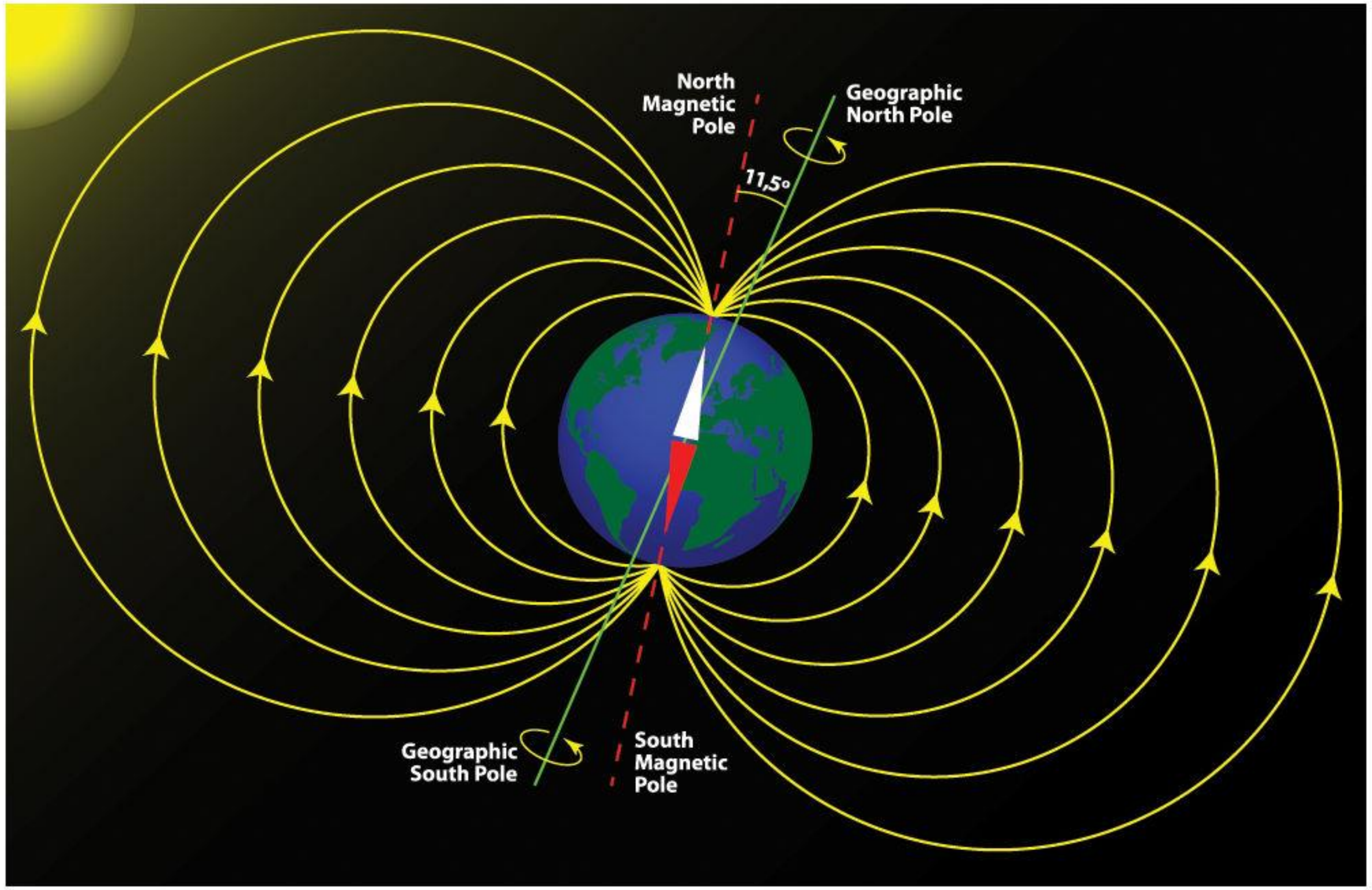
# Magnetometers

Episode 3 is Skye's

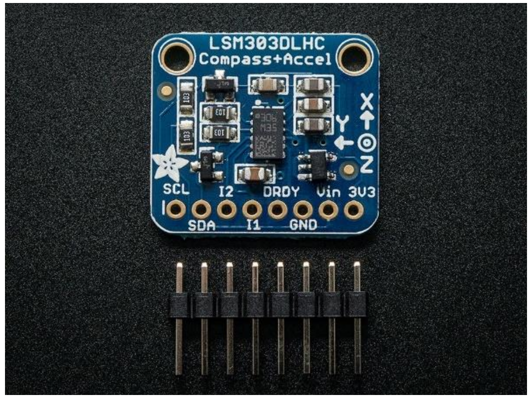
"Know Your Sensor" Series

# Earth’s Magnetic Field

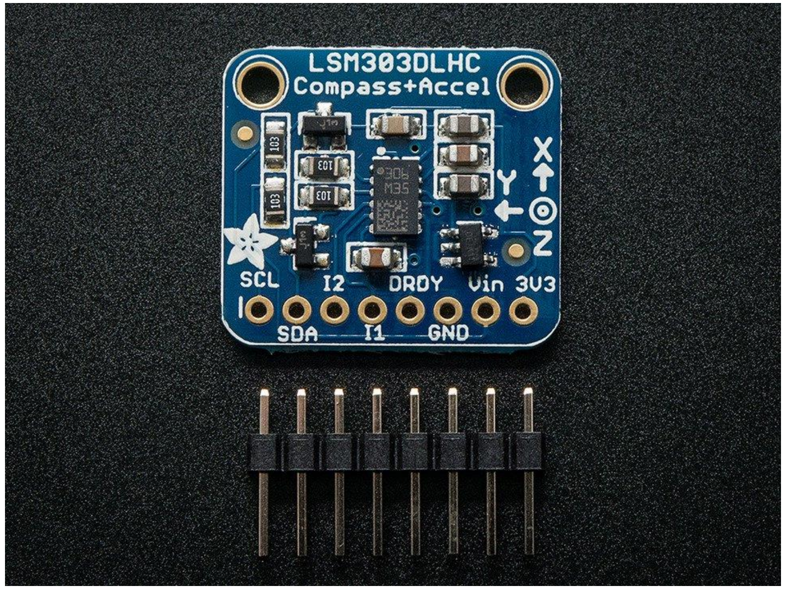


# Magnetometers

- Compass
  - Opposites attract
- Fluxgate
  - Balance the magnetic field with your own
- MEMS
  - Hall Effect causes a difference in voltage across a semiconductor



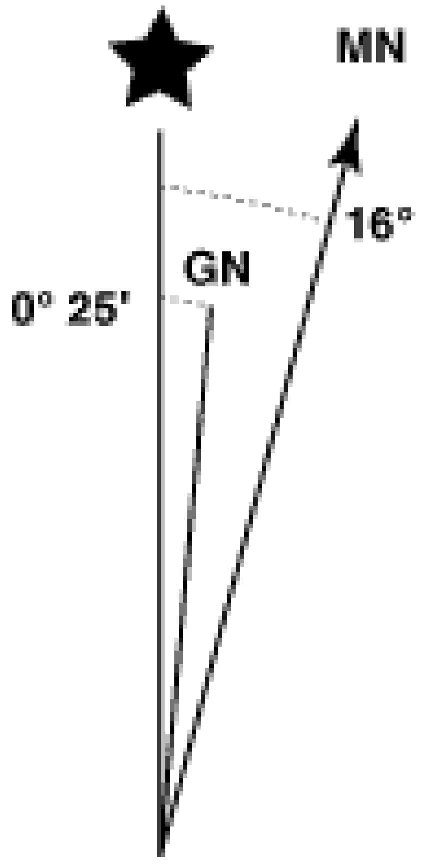
# Ada Fruit LSM303



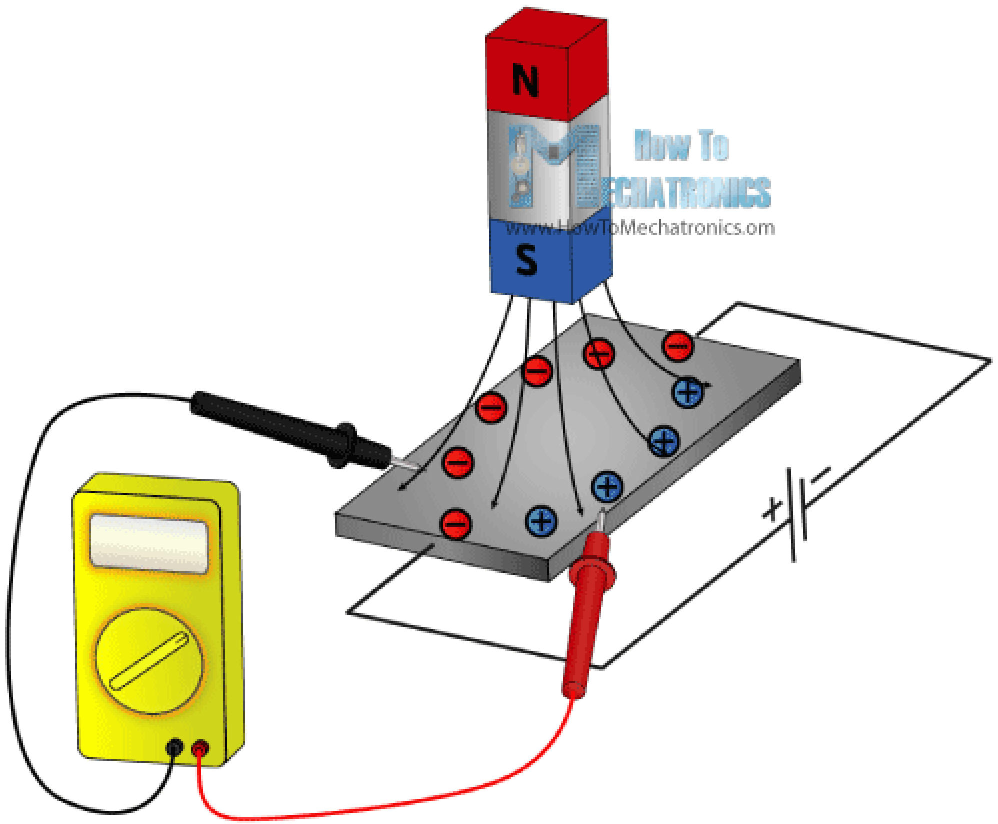

- $15
- I2C interface
- 5V0 or 3V3
- 3 axis magnetometer
- 3 axis accelerometer
- Arduino library available
- Demo based on this part
- Lots of parts like this on the market

# At Least Three North References

- Magnetic
  - Headings relative to the magnetic north pole.
- True
  - Headings relative to the geographic (spin axis) north pole.
- Grid
  - Headings relative to the top of a paper map. Used a lot by the military.



# MEMS Magnetometer



# What a Magnetometer Senses

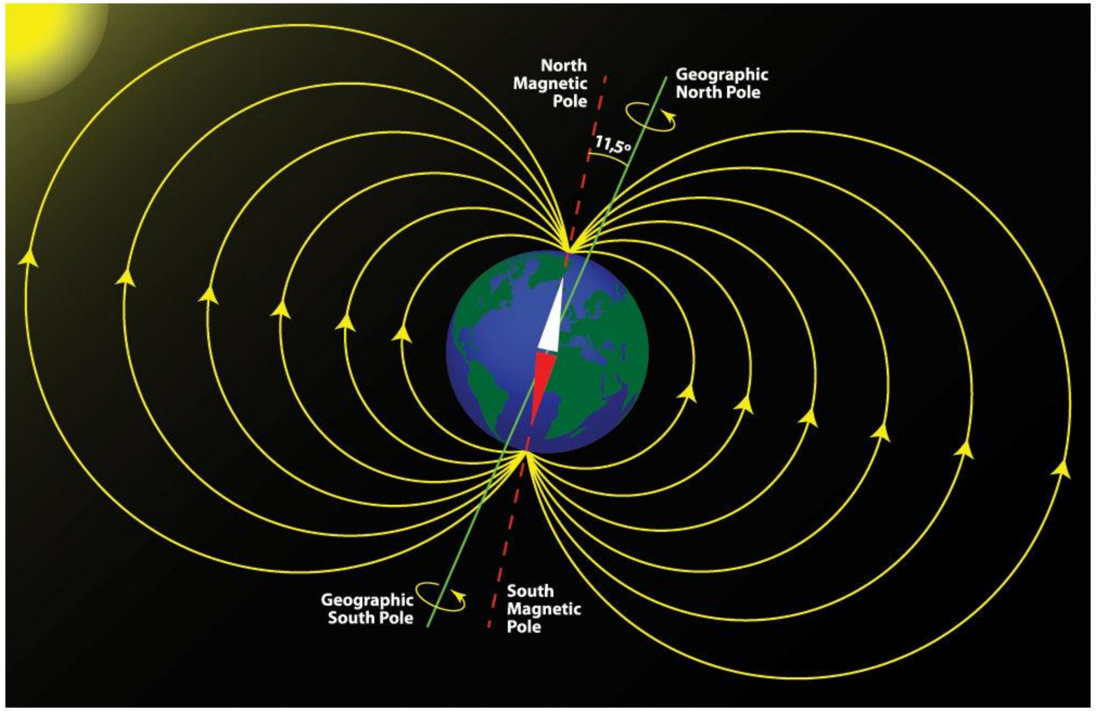
- It senses the LOCAL magnetic field.
- It does not measure just the Earth’s magnetic field.
- It will report a combination of:
  - The Earth’s magnetic field
  - Any local magnetic fields caused by magnets
  - Any local magnetic fields causes by electric currents
  - Any ferrous materials that will distort the combined magnetic fields.

# Environment

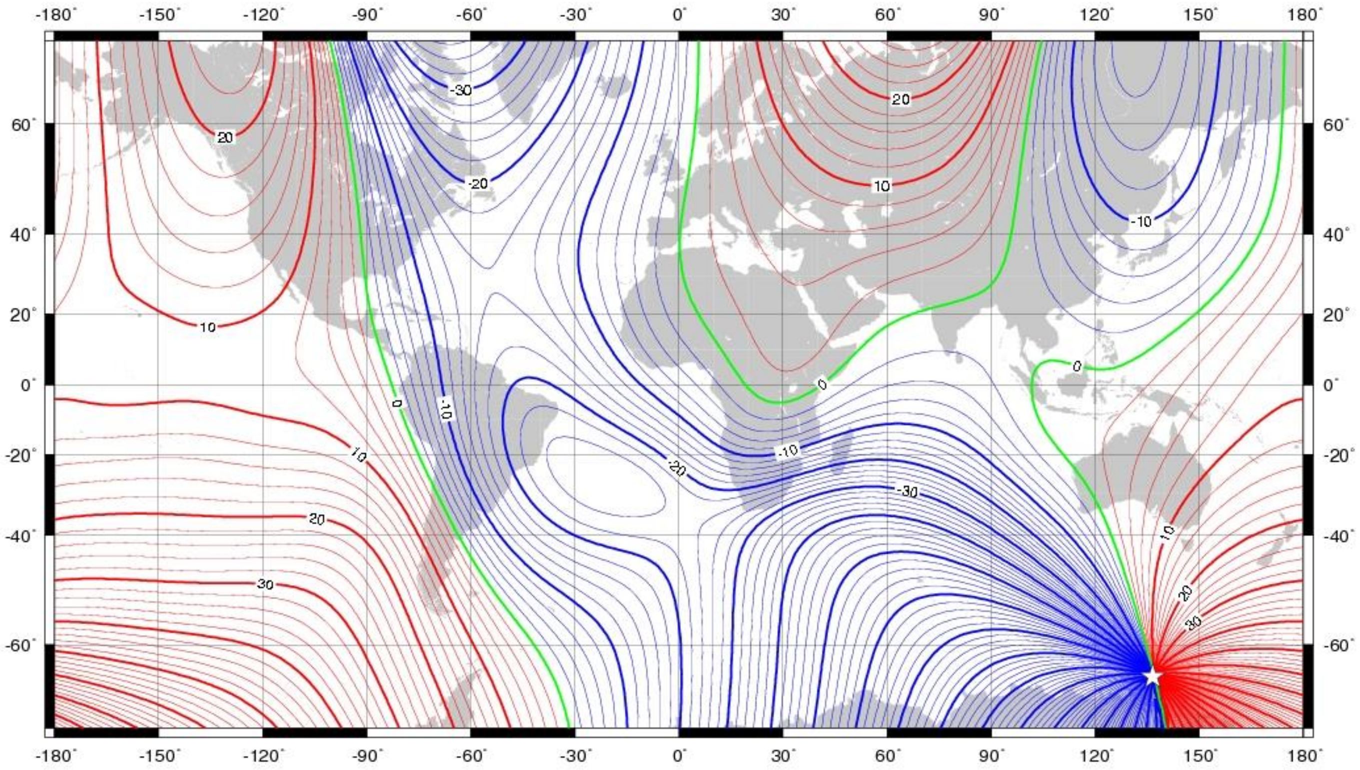
- Sources of magnetism
  - Magnets
    - Magnetic encoders, latches, arthritis gloves, screw drivers, …
  - Motors
    - Many motors use permanent magnets and generated a field when powered.
  - Current in wires
    - Residential, overhead, and buried wires
  - Ferrous metals
    - All stainless steel is magnetic to come degree; Austenitic stainless is your best choice.
  - Natural iron deposits
    - Michigan
  - Internal Earth magnetic field
    - Duh

# World Magnetic Field

- Earth’s field is not as clean as this image



# It is Truly an Ugly Mess




Declination (magnetic variation) at 2015.0 from the World Magnetic Model (WMM2015). Red - positive (east), blue - negative (west), green - zero (agonic line). Contour interval is 2°, white star is location of a magnetic pole and projection is Mercator. This is an example of an isogonic chart. Credit: British Geological Survey (Natural Environment Research Council).

# Deviations from the simple model

Declination (error between True and Magnetic north)

14.6 degrees in Nashua

Inclination (how steep the flux lines are from vertical)

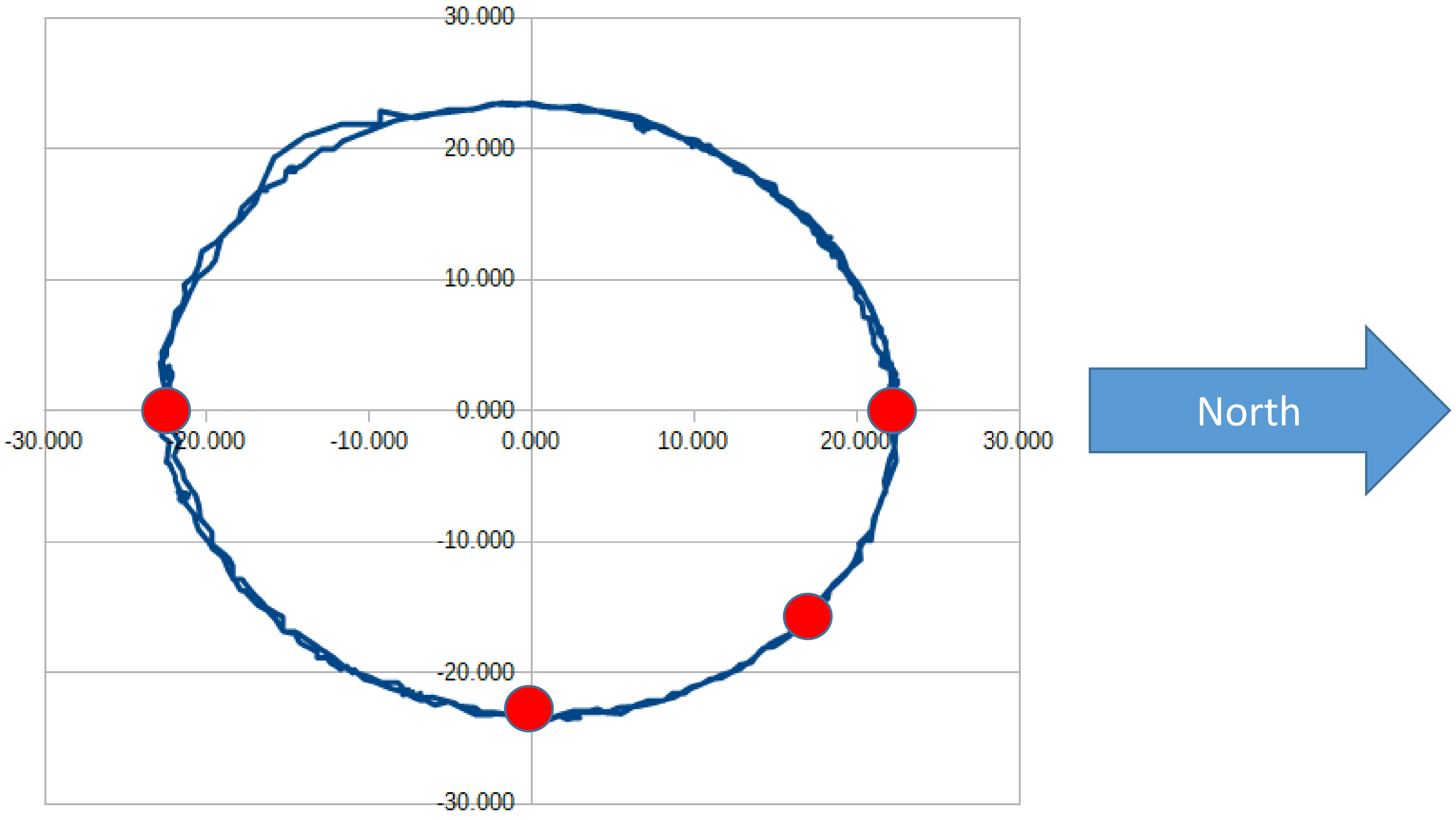
67.5 degrees in Nashua

This demands a full 3D calibration

# World Magnetic Model

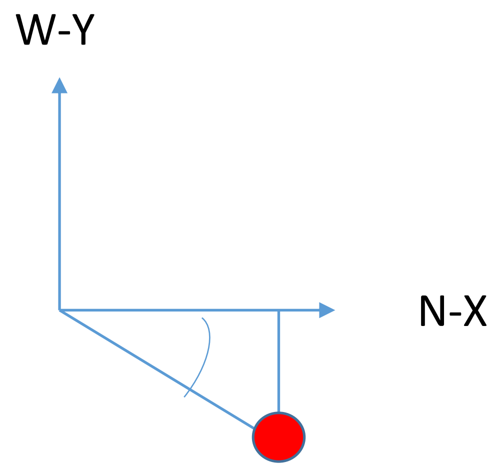
- The previous image was generated using the WMM
- Equations that provides the field characteristics at each point on Earth.
- You give it Lat/Lon/Time and it will tell you:
  - Strength in X, Y, and Z direction
  - Difference between Geo and Magnetic north (magnetic variance/declination)
  - Inclination of the flux lines
- This only models the large scale field distortions
  - It does not account for the car at the end of your street!

# Typical Results in a Benign Environment



# Computing Heading (2D solution)

- Assuming XY axis is in the horizontal plane
- Measure strength in X and Y (horizontal) axis
- Take $\tan^{-1}$ on X and -Y value
  - Hdg = atan2(-Y, X)
- Adjust angle for orientation of X and Y relative to device



# Getting True North from Magnetic

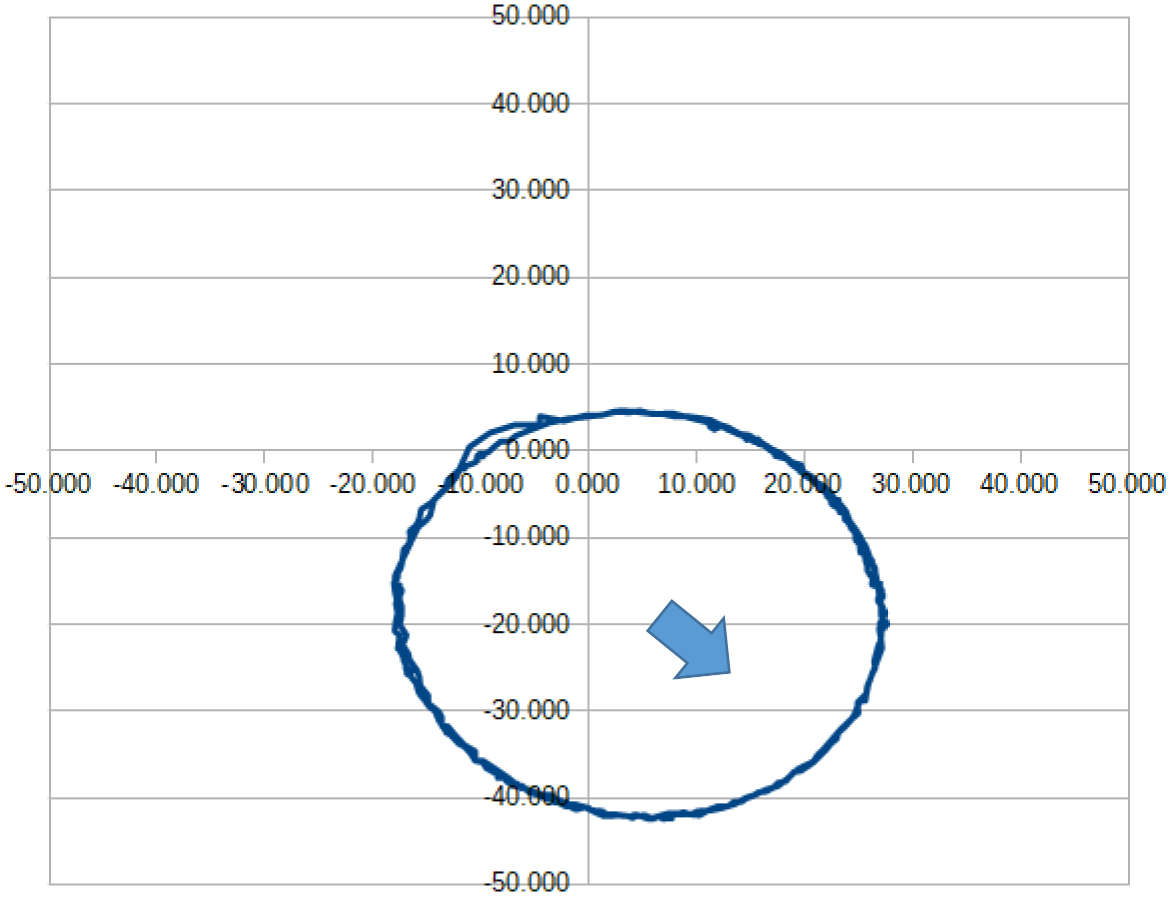
- True = Mag + magnetic variation
- Here in Nashua the magvar is 14.58 West or (-14.58)
- You can compute from WMM, lookup online, or get from some GPS.
- Remember that magvar changes place to place and year to year.
- Example:
  - Compute 35 degrees from magnetometer
  - Add a negative 14.58
  - Get a true heading of 20.42 degrees

# Hard and Soft Iron

- Hard Iron
  - Distortions that are fixed relative to sensor
- Soft Iron
  - Distortions that vary relative to sensor

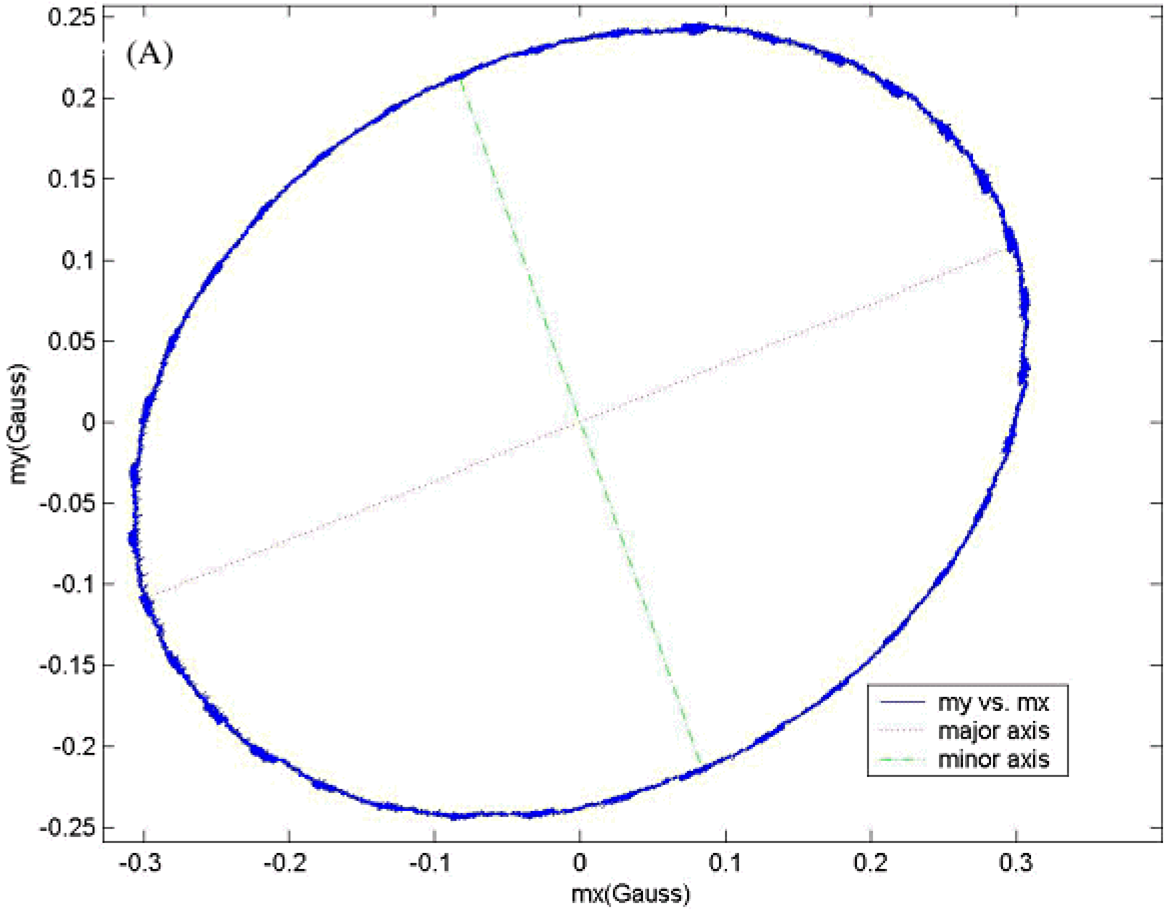
# Hard Iron (2D)

- Drags the circle off center
- Needs bias removed before ATAN will work



# Soft Iron (2D)

- Distorts the circularity
  - Range of XYZ different
  - Easy to correct
- Rotates the ellipse
  - More difficult to correct



# Simple Correction

*X = Xgain * (Xraw – Xoffset)*
*Y = Ygain * (Yraw – Yoffset)*
*Z = Zgain * (Zraw – Zoffset)*

**Or**

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = \begin{vmatrix} Xgain & 0 & 0 \\ 0 & Ygain & 0 \\ 0 & 0 & Zgain \end{vmatrix} * \begin{vmatrix} Xraw - Xoffset \\ Yraw - Yoffset \\ Zraw - Zoffset \end{vmatrix}$$

Subtracting the offset will center the shape at the origin.
Multiplying by the gains will make the ellipsoid more spherical.

# Simple Calibration

- Tumble sensor in all directions.
- Keep track of max and min in each of the three axis.
- When done collecting data compute
  - Offsets = (MAX + MIN)/2.0
  - Gains = 2.0/(MAX-MIN)
- Save these values for the real time correction
  - Previous equations

# Complex Corrections (avoid if at all possible!)

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = \begin{vmatrix} R11 & R12 & R13 \\ R21 & R22 & R23 \\ R31 & R32 & R33 \end{vmatrix} * \begin{vmatrix} Xraw - Xoffset \\ Yraw - Yoffset \\ Zraw - Zoffset \end{vmatrix}$$

If R (rotation/scale) matrix is all zeroes except R11, R22, and R33 and these are the gains then you have the ‘Simple Correction’.

The off diagonal terms allow you to rotate the ellipsoid back so that it is in line with the coordinate system.

# Complex Calibration (avoid if all possible)

- Collect raw magnetometer data as you tumble the sensor.
- Collect enough data to have a good representation of the ellipsoid.
- Run this data through an algorithm that will find the best fit of the data to an ellipsoid.
- Use the parameters of the computed ellipsoid to compute the rotation matrix to align it with your coordinate system and make it a sphere.
- Use the parameters of the computed ellipsoid to compute the offsets to center the sphere on the origin.

# Tilt Compensation

- Simple ATAN solution fails when the unit is tilted in pitch or roll.
- To determine mag north you need to know where ‘down’ is.
- For this we need an accelerometer.
  - Many MEMS magnetometers come with accelerometers. Imagine that!
- Accelerometer will give you pitch and roll (Gravity Vector)
  - Assuming you are not accelerating. Cue the Kalman Filter.
- Now we need to do some math to rotate our raw data back into a horizontal plane where we can do the simple ATAN.
- This is not obvious math
  - Will be left as an “exercise for the reader”.

# Tilt Compensation Math

Accel = $\begin{vmatrix} Ax \\ Ay \\ Az \end{vmatrix}$ Mag = $\begin{vmatrix} Mx \\ My \\ Mz \end{vmatrix}$ From = $\begin{vmatrix} 1 \\ 0 \\ 0 \end{vmatrix}$

East = Mag ⊗ Accel (cross product)

North = Accel ⊗ East (cross product)

X = East . From (dot product)

Y = North . From (dot product)

Heading = ATAN2(y, x)

# Issues with Tilt Compensation

- Due to significant inclination, an accurate gravity vector is critical.
- Any noise gets into pitch/roll will cause the heading to swing.
- I was forced to filter the accelerometer data to reduce noise generated by motors.
- Acceleration also causes a false gravity vector.
  - Discard data whose gravity vector is not 9.8 m/s/s

# Ignoring Disruptors

- If a know disruptor is active, ignore mag heading
- Check the magnitude of the magnetic vector
  - Sqrt(x^2 + y^2 + z^2)
  - If this is greater than the average you have been seeing, ignore it!
- If your heading changed faster than your robot can turn, ignore it!

# Boresight Adjustment

If sensor is not aligned with platform, you may need to rotate results.

This might be as simple as adding offsets or as complicated as some rotation matrices or quaternion math.

# What can you expect for $30?

- In a benign environment: +-2.0 degrees
  - +- 1.0 degrees with ‘complex’ calibration.
- In a noisy environment: +-180.0 degrees
  - A random number generator would be as accurate.
- If you pay attention to design: +- 5.0 degrees

# Design Rules

- Minimize ferrous metals
  - Stick with stainless 201, 301, 302, 303, 304, 316 fasteners.
  - Plastic, wood, aluminum, brass, and stainless are your friends.
- Minimize magnets
  - Good luck with motors
- Minimize electric currents
  - Inductors in boost/buck circuits are killers as well as motors.
- Locate the magnetometer as far away from the above as possible.
  - An adjacent county is always nice! ☺
- Sometimes possible to shield disruptors with MuMetal ($$)
- Calibrate at each new test location.
- Calibrate after changing batteries or modifying system

# Demo

- Show calibration
- Home to new headings

- Chime in with questions!