System Requirements

Measurement and Performance

Range: 30 µT to 60 µT

The Earth's magnetic field is primarily generated by convection in the molten outer core, which creates a planetary dynamo sustaining a global magnetic field that is felt everywhere on earth. This magnetic field ranges from 30 µT to 60 µT which is 30,000 nT to 60,000 nT. The sensor in this magnetometer must be sensitive within this range of 30 µT to 60 µT.

Resolution: 1-10nT

Daily quiet variations in Earth's magnetic field are a slow regular swing in strength from day-to-day, typically in the range of 10-100nT. To capture this subtle shift, a magnetometer must have a resolution of about 10 nt or lower. Substorms, which are short-lived disturbances caused by energy release in the magnetotail and auroral electrojects, usually produce 100-300nT swings at high latitudes. At midlatitudes such as Colorado, they may only appear weakly. Geomagnetic storms are large-scale global disturbances caused by solar wind streams or coronal mass ejections, with strengths ranging from weak storms (-30 to - 50nt DST) to great storms (Dst<-350nt). These events set the sensitivity requirements of the system. A resolution in the range of 1-10nT would ensure that daily variations, substorms, and geomagnetic storms can all be measured effectively. This is a pretty low resolution for many cheap sensors, go to "Reducing Random Noise: signal averaging" to see how a sensor's resolution can be artificially boosted to this resolution.

Sampling Interval: ~1Hz

Daily quiet variations are smooth day-to-day swings and do not require a high sampling rate. In the INTERMAGNET network, 1-minute averages are standard. Substorms, however, are more rapid and last tens of minutes. To capture their sudden onsets, a magnetometer would need a much higher sampling rate. Ground-based magnetometers in North America and Canada during the THEMIS mission used 2 Hz sampling (2 measurements per second) to measure substorms. Geomagnetic storms occur over hours to days, and even 3-hours sampling, like what is used in the Kp index, can capture them. In order to reliably capture the smallest disturbances, a sampling interval of 1 Hz would be ideal.

Calibration and Offset: Self-callibrating sensor

Magnetometers can show a nonzero reading (an offset) even when no magnetic field is present. This offset can be caused by a variety of factors, such as remnant magnetization in the sensor. Taking readings in opposite directions can measure the offset in this situation. Built-in offset compensation within a sensor would be ideal for handling this automatically. There is also offset caused by temperature changes, so testing across temperatures would be useful for determining if the offset is significant. In addition, sensors can drift over time, so selecting a sensor that maintains stability is crucial. For practical use in the field, calibration should be possible remotely and without disassembling the instrument, making built-in calibration a requirement for the sensor selection.

Time keeping: Wifi enabled microcontroller

In order for the data collected to be compared to other data sources, the system must keep accurate timestamps. This timekeeping can be handled by a Wi-Fi-enabled microcontroller (a small programmable computer) that can sync its internal clock with the local time in order to timestamp the data. This also has the advantage of not having to transmit data through a physical wire, making the system not reliant on a wired connection. There must also be a way to instruct the magnetometer to take one reading per second. A microcontroller provides this through a timing loop, ensuring a consistent 1Hz sampling interval.

Electrical

Power Source: Solar powered with chargeable battery

In order to keep the magnetometer from being reliant on a cable for power, the system's power should be supported by solar power via a small solar panel fixed on top of the magnetometer or possibly detachable to be placed nearby in a sunny area. Solar power is unreliable when there is a lack of sun, so during the night and during cloudy weather. This means that there must be a way to store power collected during sunny times in a battery. On the safest side, this stored power should be enough to run the magnetometer for an entire week. On the shortest scale, the battery should be able to run 36 hours which would account for a night cycle, a sun-less day and another night, hoping the next day will be sunny. Another fail-safe would be to make the system compatible with a portable charger. The system is designed to be small, so the size of the battery is a constraint.

Power Constraints: Limit continuous wifi-transmission

Making the system solar powered makes the constraint that it must not take a lot of power to run the system. The main power usage will be the microcontroller when it is connected to Wi-Fi. If the solar panel doesn't provide enough power and charge to the battery to keep a continuous Wi-Fi connection, so instead, the only time the magnetometer will be connected to the WiFi is when the user is accessing the data via the webserver to view magnetic field data live or download the data stored in the magnetometer.

Internal Noise: Sensor isolation from electronics and ferromagnetic materials
Noise from the electronics in the magnetometer system can distort the readings of the sensor. Initial testing will be needed to determine the noise level measured from the microcontroller and other electronic components (such as the battery and solar panel) in order to determine the location of the sensor The interference from the MAVEN instruments electronics decreased with distance approximately as 1/r^3, which is why the two magnetometers were placed on boom arms extending away from the main spacecraft body. Currents generate electric fields so any currents within the system need to be noted. Additionally, ferromagnetic material within the magnetometer could affect the readings. Steel contains iron, which is a ferromagnetic material that could reshape the magnetic field, creating offsets. Testing is crucial for identifying and isolating these effects.

Environmental

Operating Temperature: -5°C to 40°C heat sinks or insulation if needed
Magnetometers are affected by temperature because the materials inside the sensor can change properties with heating or cooling. Manufacturers will specify a temperature range over which the sensor can run reliably. In Colorado outside temperatures range of temperatures can be expected to range from -5°C to 40°C. Inside the housing, additional heat from electronics can also raise the temperature (no more than 25°C). This means the sensor should have a temperature range of -5°C to 60°C to be safe. If the system is getting too hot, heat sinks can be added under the microcontroller. If the sensor is getting too cold, thermal insulation could be added. For example, the THEMIS ground magnetometers were filled with paraffin oil which acted as a thermal stabilizer.

Humidity Control: Waterproofing
Because the magnetometer will be running permanently outdoors, the housing for the electronics must be fully waterproof. The housing should be sealed with an O-ring at the seam that it opens and held by screw pressure when it is closed to insure a watertight fit, while also allowing the electronics to be accessible. In addition, the wiring from the power source will need to be connected to the electronics inside the housing. This feedthrough should also be sealed with an O-ring and should not be placed on the top of the housing. A water runoff feature above could also be modeled to keep water off the feedthrough. To limit humidity within the housing, desiccant packets can be placed inside before sealing.

Size: Less that 6”x6”x6”
Magnetometer sensors have become increasingly compact, with designs even small enough to be embedded in phones. The sensor in this system will likewise be small (roughly a square inch) so the main design consideration is the housing that contains this sensor and all the electronics. The smaller the easier it will be to mount outdoors. A large housing is more unsightly and less convenient to place casually in a backyard setting, while a compact design allows more flexibility in placement and makes it easier to keep away from other sources of magnetic interference. In addition, a smaller size makes the housing more accessible to 3D print. The typical mid-sized printers have a volume of 8”x8”x8”, and the printer available for this project (The Kobra S1) has a bed size of 250mmx250mmx250mm. Considering these constraints, the housing should be designed to remain smaller than 6”x6”x6”. The only constraint is fitting the electronics, and allowing enough separation from the sensor and other magnetically noisy components.

Placement: Away from buildings and power lines
It is important to consider the sources of magnetic field in the surrounding environment when choosing where to place the magnetometer. The magnetometer can’t run indoors because of interference from household wiring, appliances, and even reinforced concrete. Even outside there are sources of interference including power lines, buried cables, vehicles, and other larger metal objects. Finding a completely magnetically clean place will be impossible, so the goal is to minimize the local disturbances. The magnetometer should be placed as far as it can be from buildings and power sources but within the microcontroller Wi-Fi range limit. This can be tested once the magnetometer is built.

Software and Data

Firmwear: MicroPython
A microcontroller is like a tiny computer that one can program to do specific things. The firmware is the set of instructions that is stored on the microcontroller's flash memory. It’s the software that is directly run on the hardware (the microcontroller). In this project, the Raspberry Pi Pico W will be the easiest microcontroller to learn how to program. The language it uses is MicroPython, which is a version of Python that is optimized for microcontrollers. The firmware needs to be able to instruct the magnetometer to take a measurement, handle the sensor calibration routines, collect magnetic field readings and attach timestamps, write the data onto the SD card, and run a webserver.

Data space: 1 GB per year
At a frequency of one data point per second, a lot of data points need to be stored over a year (or more). Here is a very rudimentary estimate of how much data this is. A magnetometer contains a measurement in 3 directions. At most each measurement would record 7 digits (corresponding to the digits of a 100,000nT reading). If you assume four bits (a single bit is either 0 or 1) is needed to describe each number, there are 7*4=28 bits required for each direction. 28 bits * 3 for 3 directions = 84 bits per reading. Lets round this up to 150 bits to account for any additional information that might be recorded, like the timestamp. 1 bit = 0.125 byte, so 150 bits of information is 150*.125 = 18.75 Bytes of data per second. Multiply this by the seconds in a year 18.75 * 3153600 = 59130000 bytes = .591GB.The maximum space needed for a year's worth of 1Hz data is around a GB, which is very achievable in today's data storage systems. This corresponds to the THEMIS mission which used a 2Hz sampling rate and recorded just over a GB per magnetometer per year.

Data Storage: Locally on 8GB SD card
In large networks, continuous data transmission is very useful for reporting magnetic field data such as the Kp-index which reports geomagnetic disturbance levels from multiple observatories every 3 hours. However, this project involves single and one primary user so continuous WiFi transmission is not necessary. Instead, the most reliable and power-efficient way to store this 1GB per year data is locally within the magnetometer itself. A 8 GB SD card will be connected to the microcontroller, which will write all collected data to this card. This provides enough storage for many years of operation without the power demands of conscious data uploads. This will also ensure that any WiFi connection issues will not cause lost data.

Wireless Data Access: Webserver
The user should be able to access and download the full archive of magnetic field data remotely, as well as view live magnetometer readings. This will be done using the microcontroller's wifi capabilities. If using the Raspberry Pi Pico microcontroller, a webserver can be accessed by a computer using the same wifi, by typing the Pico's IP address into a browser. Downloading instantaneous data for live-viewing won't be an issue since Wifi connection speeds are typically 70 Mbps (megabits per second) on the low end which is 70 million bits per second compared to the 150 bits per second occurring during streaming. WiFi upload speeds are 5 Mbps on the lower end which would take about 15 minutes to download an entire year's worth of magnetometer data.

Web Server Interface: intuitive in HTML
The SuperMAG network emphasizes the importance of making data from more than 300 ground-based magnetometers easily accessible to the public. This involves an

intuitive interface that allows the public to find and download data online. Having an intuitive design is very important for presenting the data collected by this magnetometer project. Data hidden within the code of the system, accessible only by commands will not suffice for easy data analysis. Instead, the data access page should be navigable by buttons and organized in an easy-to-understand way for viewing or downloading on the web server. Data visualization should also be a part of this user-interface, with customizable plots easily creatable. HTML will be the best coding language to create this interface.

Reducing Random Noise: Signal Averaging

An affordable sensor might not hit the 1-10nT resolution required to measure some geomagnetic activity because the sensor RMS noise (root mean square noise) can be higher than this. However, signal averaging can reduce this RMS noise. We want data taken at 1Hz (one data point recorded every second), but many sensors can sample far faster than 1Hz. If you take 100 data points in 1 second (sampling rate of 100Hz) with a given RMS noise of 50nT and then average this data, the RMS noise of the averaged value will be the original RMS noise divided by the square root of the number of samples which will be 5 nT. $\sigma(avg) = \sigma(single)/sqrt(number\ of\ samples)$. This technique only works on random noise which is uncorrelated between values. It wouldn't work on offsets, temperature drifts, or interference since those remain steady over time.