Signal Enhancement for Magnetic Navigation Challenge Problem

Albert R. Gnadt[1], Joseph Belarge[2], Aaron Canciani[3], Lauren Conger[2], Joseph Curro[3], Alan Edelman[1], David Jacobs[4], Peter Morales[2], Michael F. O'Keeffe[2], Jonathan Taylor[2], and Christopher Rackauckas[1]

[1]Massachusetts Institute of Technology, Cambridge, MA, USA
[2]MIT Lincoln Laboratory, Lexington, MA, USA
[3]Air Force Institute of Technology, Dayton, OH, USA
[4]Department of the Air Force AI Accelerator, Cambridge, MA, USA

1 Introduction

Harnessing the magnetic field of the earth for navigation has shown promise as a viable alternative to other navigation systems. Commercial and government organizations have surveyed the earth to varying degrees of precision by collecting and storing magnetic field data as magnetic anomaly maps. A magnetic navigation system collects its own magnetic field data using a magnetometer and uses magnetic anomaly maps to determine the current location. This technique does not rely on satellites or other external communications, and it is available globally at all times and in all weather.

The greatest challenge with magnetic navigation arises when the magnetic field data from the magnetometer on the navigation system encompass the magnetic field from not just the earth, but also from the vehicle on which it is mounted. The total magnetic field is a linear superposition of the magnetic fields of the vehicle and the earth (with additional contributions from sources arising from diurnal variation and space weather, which can be largely removed using ground-based reference measurements), and the magnetometer reports the scalar magnitude of the net magnetic field vector. It is difficult to separate the earth magnetic anomaly field magnitude, which is crucial for navigation, from the total magnetic field magnitude reading from the sensor.

The purpose of this challenge problem is to decouple the earth and aircraft magnetic signals in order to derive a clean signal from which to perform magnetic navigation. Baseline testing on the dataset shows that the earth magnetic field can be extracted from the total magnetic field using machine learning (ML). The challenge is to remove the aircraft magnetic field from the total magnetic field using a trained model. These challenges offer an opportunity to construct an effective model for removing the aircraft magnetic field from the dataset, using a scientific machine learning approach comprised of an ML algorithm integrated with physics of magnetic navigation.

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2 Magnetic Navigation Background

Magnetic navigation is enabled by variations in the crustal magnetic field of the earth, also known as the magnetic anomaly field. The total geomagnetic field is comprised of fields from several sources, the most dominant of which is the core field with values ranging from 25 to 65 microtesla at the surface of the earth, about 100 times weaker than a refrigerator magnet. The magnetic anomaly field typically varies by hundreds of nanotesla, 100 times weaker than the core field. As such, magnetic navigation requires the ability to sense small differences in the crustal magnetic field, which can be mapped and is stable over geologic time spans. The spatial extent of the crustal fields make the fields strong enough for navigation even at tens of kilometers altitude above the earth's surface.

The strength of a static magnetic field arising from a localized source follows the inverse cubic distance scaling law of a magnetic dipole (when the distance to the source is much larger than the spatial extent of the source). This high drop-off rate in magnetic fields means that it is difficult for disturbances to affect magnetic sensors from a distance without exhorting a significant amount of power, making it difficult to interfere with or jam magnetic navigation from ground stations. Thus, the predominant issue with magnetic navigation comes from magnetic interference generated by the aircraft itself. The purpose of this challenge is to effectively remove the magnetic interference of the aircraft from the readings of the on-board magnetometers so that effective magnetic navigation can be performed.

Traditionally the earth and aircraft magnetic fields can be separated using the Tolles-Lawson model [1] as shown in Figure 1. This process uses bandpass filtered measurements from an additional magnetometer, as well as crucial assumptions about the static nature of the aircraft magnetic field, such as:

1. The magnetic sources on the aircraft arise from permanent dipole, induced dipole, and eddy current fields.
2. The permanent dipole sources do not change over time.
3. The induced dipoles depend on the orientation of the aircraft with respect to the magnetic field of the earth.
4. The inductance from electrical current paths is zero, so the eddy currents arise from instantaneous changes of the magnetic flux through a surface.
5. The total-field anomaly due to the aircraft field is the projection of the aircraft field onto the earth field.

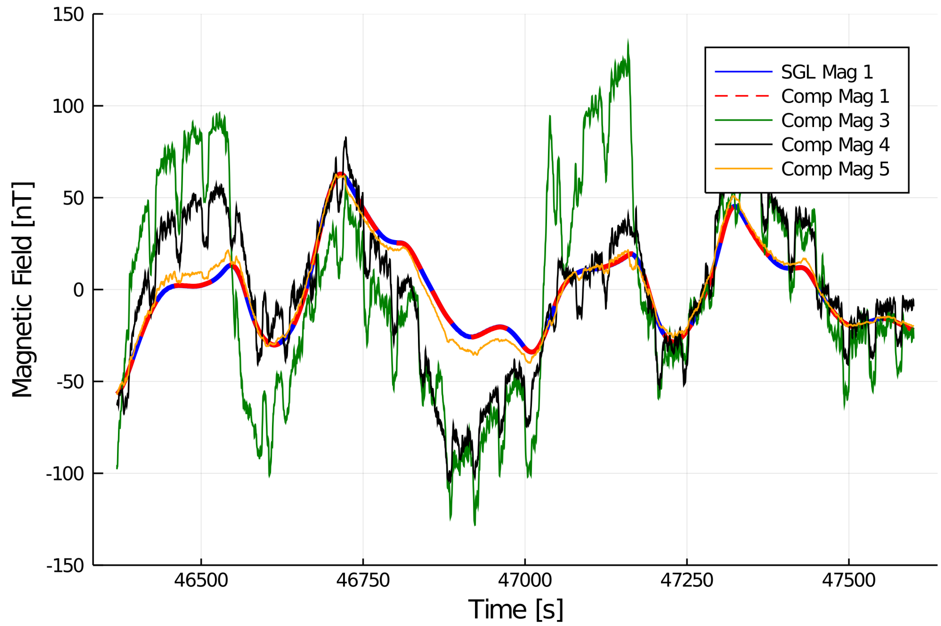

Figure 1: Flight Number 1002 magnetometers compensated using the Tolles-Lawson model.

These assumptions are sufficient when the magnetometer is placed on a 3 meter boom behind the aircraft (tail stinger), because the magnetic field from the aircraft is weak enough relative to the earth at the sensor. However, this is impractical for operational aircraft. The Tolles-Lawson approximation does not produce a compensated signal with sufficiently accurate results when the magnetometer is close to the multiple magnetic interference sources of the aircraft, such as in the cockpit.

3 Challenge Problem

The goal is to take magnetometer readings from within the cockpit and remove the aircraft magnetic field to yield a clean magnetic signal. The key issue is identifying the desired truth signal, of which two options are presented. One such truth signal is the tail stinger which, after professional compensation, is sufficiently accurate for magnetic navigation. It has the fewest differing conditions from the cockpit sensors due to its location far aft of the cockpit, control surfaces, and other sources of aircraft magnetic interference. However, tail stinger data is not available on all operational aircraft, and using this signal alone would likely cause a model to transfer poorly to other aircraft. The other option is to treat the magnetic anomaly map of the collection region as the truth signal. Using the path of the aircraft, the magnetic anomaly signal of the earth's crust over this path can be determined and treated as the truth signal.

The first case wherein the tail stinger is treated as the truth signal has several advantages. The primary advantage is that there is no need to potentially account for for minor position inaccuracies. Additionally, most conditions, such as weather, that were present during the collection would be identical meaning that additional compensation due to known conditions would likely be unnecessary.

The second case wherein the magnetic anomaly map is used as the truth signal yields a case wherein a reference map that would be used for navigation is the target signal. This approach has a major advantage wherein the actual desired signal is the target. However, the map has issues which could make the problem more difficult. First, the signal at the altitude of data collection must be interpolated from the raw map, which adds an additional step of processing. Additionally, the map may be under-sampled in which case the truth data may not be available in the raw map and would need to be interpolated in order to yield the truth signal.

The process of using both truth signals is extremely similar. Both cases can be treated as having 2 outputs; however, each has a natural output that is more useful for evaluation. When training to the tail stinger it is more useful to do a signal comparison rather than comparing to the predicted path along a map as the signal comparison is attempting to determine whether or not the algorithm is learning the aircraft magnetic field. Contrasting this when training to the anomaly map it is more useful to do a comparison to the route as it is possible that the ideal algorithm for navigation purposes is not generating the most optimally enhanced magnetic signal but is instead generating the most optimally enhanced positioning signal.

4 Judging Criteria

For this challenge problem, an evaluation dataset is withheld from participants. The goal is to learn a mechanism for removing the aircraft magnetic field from the build dataset that will generalize to the evaluation dataset. The quality of the submission will be judged according to the root mean squared error (RMSE) compared to the selected truth signal. Detrending may be used to remove any DC offset prior to RMSE calculation. An alternative award for a method that excels in interpretability and verifiability will also be considered. The challenge problem will commence on September 24, 2020 and will run until January 4, 2021. Judging will take place in January 2021. All submissions should be sent to crackauc@mit.edu in the form of a Git repository with code that can perform predictions on the evaluation dataset without any modifications to the source code required. It is recommended to include an up to 5 page arXiv compatible manuscript that explains the methodology.

5 Description of the Magnetic Navigation Data

A campaign was conducted to collect magnetic field data. During the data collection, flight patterns were planned such that data could be collected at varying heights above ellipsoid (HAE), where the aircraft is flying at a constant altitude above the earth's assumed perfectly ellipsoidal shape, and over varying drape surfaces, where the aircraft is flying at a constant altitude over actual crustal features, such as mountains and valleys.

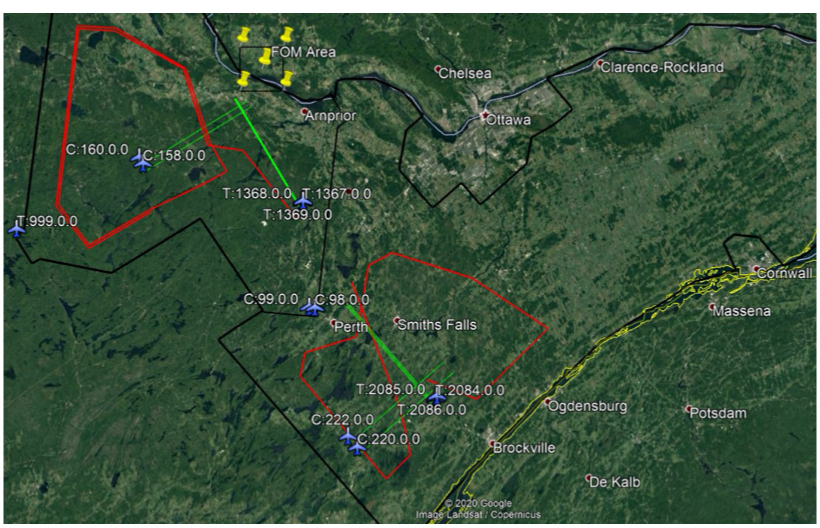

Figure 2: Map showing SGL flight regions. The far west region is the Renfrew flight area. The far east region is the Eastern flight area. The black region labeled FOM is the Figure of Merit area.

The measurements were collected by Sander Geophysics Ltd. (SGL) [2] over Ottawa, Ontario, Canada, using a Cessna Grand Caravan equipped with a number of sensors. The measurements were collected in three flight areas. The flight area north of Arnprior is the Figure of Merit (FOM) region. The western-most flight area is known as the Renfrew flight area, while the furthest east area is known as the Eastern flight area. All three flight areas are shown in Figure 2.

To collect the total magnetic field measurements, five optically-pumped, cesium split-beam scalar magnetometers, and four vector fluxgate magnetometers were positioned in the aircraft. One scalar magnetometer was positioned on a tail stinger to collect magnetic measurements with minimal aircraft magnetic field noise. The remaining four scalar magnetometers, as well as the three vector magnetometers, were placed inside the cabin of the aircraft. The locations of the sensors within the cabin can be found in Table 1.

Table 1: Summary of Scalar and Vector Magnetometer Locations. The reference point is the front seat rail. X is positive in the aircraft forward direction, Y is positive to port (left facing forward), and Z is positive upward.

Sensor Name	Location	X (m)	Y(m)	Z (m)
	Scalar Magnetometers			
Mag 1	Tail stinger	-12.01	0	1.37
Mag 2	Front cabin aft of cockpit	-0.60	-0.36	0
Mag 3	Mid cabin next to INS	-1.28	-0.36	0
Mag 4	Rear cabin floor	-3.53	0	0
Mag 5	Rear cabin ceiling	-3.79	0	1.20
	Vector Magnetometers			
Flux B	Tail at base of stinger	-8.92	0	0.96
Flux C	Rear cabin port side	-4.06	0.42	0
Flux D	Rear cabin aft side	-4.06	-0.42	0

In addition to the magnetometers, supplemental sensors collected relevant flight data. A subset of this data, such as GPS location, contains information redundant to the truth data. Using this data could lead to falsely accurate models, and therefore should not be used. The data fields shown below were determined to provide information for training, while not providing direct truth data. For information on all data fields collected during flight, see the full challenge problem description [3].

The truth data for training is an uncorrupted measurement of the magnetic anomaly field. This is provided in two ways: first, in the form of the data collected from the scalar magnetometer located on the tail stinger after professional compensation. This data was collected concurrently among the build dataset, and will provide a direct measurement of the uncorrupted signal. Second, a magnetic anomaly map is provided to determine an alternative truth signal. Magnetic anomaly map data provides a unique measure of the magnetic anomaly field for a location in space, and as such is similar to the magnetic anomaly field data collected from the tail stinger.

Four flights were flown to collect data. Each flight contained a different set of objectives, and as such the dataset from each flight has individual nuances. The objectives for Flight Number 1003 were to measure the crustal magnetic field at two altitudes (400m HAE and 800m HAE) in both the Eastern and Renfrew flight regions. The flight was conducted on June 29, 2020 and lasted approximately five hours and forty-five minutes. A summary of the Line Numbers, which describe when a specific flight segment began and subsequently ended, is shown in Table 2. Line Number 1003.10 has been withheld for the evaluation dataset, while the remaining Line Numbers are provided in the build dataset. Other numbers that do not begin with the Flight Number refer to flight over a survey line.

Table 2: Line Number summary for Flight Number 1003. Line Number 1003.10 has been withheld for the evaluation dataset, while the remaining Line Numbers are provided in the build dataset.

Line Number	Description
1003.01	Takeoff and Transit
1003.02	Eastern Free Fly at 400m HAE
1003.03	Climb to 800m HAE
1003.04	Eastern Free Fly at 800m HAE
1003.05	Transit to Renfrew
1003.06	Descend to 400m HAE
1003.07	Continue transit to Renfrew
1003.08	Renfrew Free Fly at 400m HAE
1003.09	Climb to 800m HAE
1003.10	Renfrew Free Fly at 800m HAE
1003.11	Transit to home

6 Description of the Starter Code

A basic set of starter Julia code files have been provided in the MagNav.jl package available at `https://github.com/MIT-AI-Accelerator/MagNav.jl`. This code is largely based on previous work of [4]. The files in the `src` directory perform the following key tasks:

- Get flight data
- Get map data
- Create the Tolles-Lawson matrix based on physics model
- Determine the Tolles-Lawson coefficients using linear regression
- Calculate position errors
- Upward continue a magnetic anomaly map from a lower altitude
- Interpolate an anomaly map
- Detrend to remove a trend line (mean, slope) from a vector
- Determine the magnetic anomaly map gradient at a given position

A sample run file has also been provided in the `runs` folder. Here the usage of functions in the package is shown, and Figure 1 should be plotted as a baseline result. The scalar magnetometers have been compensated using the Tolles-Lawson model, then detrended to remove DC offsets.

Summary

This challenge problem leverages a unique dataset to provide the opportunity to explore scientific machine learning. Ideally a solution would leverage both novel machine learning techniques as well as more traditional physical modelling techniques such as those found in the Tolles-Lawson equations. The problem of enhancing the magnetic signal presented here should provide many opportunities to advance the state of the art from multiple angles.

Acknowledgements

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References

[1] Walter E. Tolles. Magnetic field compensation system, April 1955. US Patent 2,706,801.

[2] Sander Geophysics Ltd. High resolution magnetic gradiometer surveys, 2020.

[3] Albert R. Gnadt, Joseph Belarge, Aaron Canciani, Lauren Conger, Joseph Curro, Alan Edelman, Peter Morales, Michael F. O'Keeffe, Jonathan Taylor, and Christopher Rackauckas. Signal enhancement for magnetic navigation challenge problem, 2020.

[4] Aaron J. Canciani. *Absolute Positioning Using the Earth's Magnetic Anomaly Field*. PhD thesis, Air Force Institute of Technology, 2016.