Brief foray into practical high sensitivity magnetometry, a method for weak magnetic field survey, magnetic storms monitoring and possible extensions to airspace defense

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Abstract: *In the following pages I make a brief overview into practical use of a resistive magnetometer to create a powerful low intensity magnetic field survey device capable of sensing minute variations of the intensity of the terrestrial magnetic field. Generally used as a tool for orientation in the guise of the ubiquitous "digital compass" that is generally available even on most mobile devices today, a magnetometer has enormous potential to be used for surveying magnetic storms, various perturbations of the ionosphere linked to solar or EMP distal activity as well as perturbations caused by moving objects -either ferro- or paramagnetic in nature. They can extend and supplement other instruments and together with other types of sensors, for example acoustic infrasonic ones- can be used to confirm presence of large and fast perturbations such as thunderstorms or the occasional rocket launch.*

Key Words: *magnetometer, low intensity magnetic field perturbation, magnetic storm survey, EMP extra long-range detection, complementary sensor*

1. MAGNETOMETERS AND THEIR WORKING PRINCIPLES

Magnetometers are devices that measure the intensity of magnetic fields, either stationary or varying, and are based on a multitude of principles, spanning from simple magnetic forces on suspended magnets to differential induction effects in a set of specially arranged coils, to optical methods using magnetic properties of some optic fiber materials especially in high intensity magnetic fields, or even quantum effects for the optically pumped variants to thin metallic films with varying electric resistance or Hall effect in semiconductor wafers and even quantum interference in superconductors.

Magnetic fields are necessarily vectorial 3D fields characterized by both intensity and (local) direction. Magnetic field lines are always closed, and even in the case of a (locally) homogenous magnetic field, the presence of either ferromagnetic or para- or diamagnetic materials changes the local field intensity. This fact foreshadows a key characteristic of magnetometers- even those used to measure weak and stationary magnetic fields, such as the terrestrial one, for the purpose of navigation- they are perturbed by the presence of these materials in their proximity, as well as by variable magnetic fields generated by motors, switching power supplies or generally current bearing wiring. These are the causes of the so-called soft and hard iron perturbation of a magnetometer and they manifest as variable/unstable indication or increased or diminished values for the measured field values. That is the main reason a calibration of a magnetometer is a very location-dependent and therefore common operation.

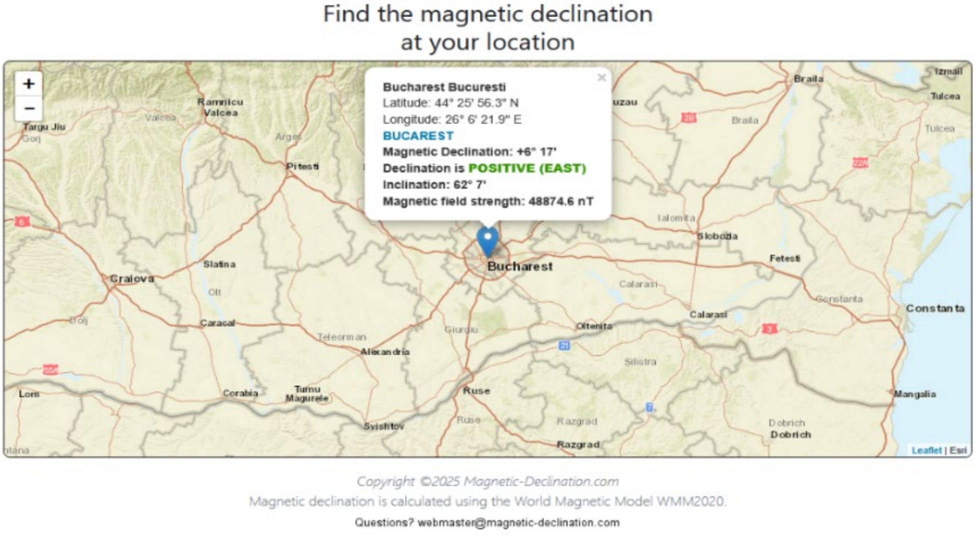

Figure 1. Magnetic field strength values and magnetic declination values are available for all locations using data from periodically updated surveys [1], [2] and are usable as a basis for calibration of magnetic sensors. Detailed maps are also available from large scale surveys for magnetometer certification for navigation purposes.

For navigation purposes, a sensor fusion with accelerometers and GPS and implementation of various flavors of Kalman filters is a workable solution, the other sensors being used to reduce apparent spiking and erroneous reported GPS movement from data affected by interference. Each instance of sudden motion (unexpected and large displacement or sudden direction change at impractical angles) should be accompanied by corresponding accelerometer readings. Large drifts in direction or apparent heading changes are to be detected by accompanying magnetometer reading changes. The problem is that GPS signals are irregular, perturbed by trees, large buildings, etc. while the magnetometer also is prone to interference from metallic structures as well as power lines or electrically noisy equipment. So modern orientation techniques combine fixed-point readings with inertial platform data and GPS/magnetometer filtered data to better approximate proper motion trajectory. In electrically noisy environments or under jamming GPS and magnetometers can be unreliable, so other methods such as optical and inertial, celestial navigation or dead reckoning are predominantly used while monitoring the jammed sensors for a moment of clear reading.

But for our purposes, a stationary magnetometer has a fixed calibration and perturbations will only be caused by magnetic fields or magnetic permittivity changes in the environment-consistent with either electromagnetic phenomena or moving bodies in the proximity of the magnetometer.

A magnetometer’s sensitivity can be increased using the so-called magnetic lenses – an arrangement of magnetic materials and/or energized coils that can shape and concentrate magnetic fields. Contrary to the active magnetic lenses used for instance in electron microscopy, magnetic lenses used to enhance a magnetometer’s sensitivity and directionality can be passive- in fact these can be in their most trivial form- metal rods with tapered ends and metal plates, curved or straight.

Calibrating a magnetometer

Regardless of the operation principle, the generic calibration for a magnetometer must take into account the in-built bias (either geometric, if it is a multi-axis device with three orthogonal single plane sensors or electronic- as a deviation due to each sensor's construction and internal structure) and the local influences of the perturbations in the environment, so calibrations must be performed at each measurement campaign.

To calibrate a magnetometer practically one must know the expected terrestrial magnetic field strength at the given location- for example using a world magnetic model, such as the one published by the National Centers for Environmental Information (USA) – an agency working under NOAA [1], as shown in Figure 1. There we can find for every location, the X, Y, Z components of the geomagnetic field as well as the horizontal or total intensity of the same, but also geomagnetic inclination (the angle of the local field lines to the ground) as well as the geomagnetic declination (magnetic variation, or difference between geographical and magnetic North) [2], [3].

For this particular sensor (QMC58883L Three axis magnetometer and compass) there is an established calibration routine that starts with reading the sensor raw values indicated for a single point where the sensor is kept in a plane and rotated with respect to the axis perpendicular to it. The raw values for the natural magnetic field read on the other two components (X and Y respectively) should align on a circle centered in the mean value of the local magnetic field intensity- but that is in absence of any perturbations or sensor gain errors. In reality the result is an elongated ovoid shape like in figure 2 below (locally measured data in the lab). A magnetometer output is a voltage proportional to the local component of the magnetic field B, but is affected by hard and soft iron distortions.

Hard iron distortions are understood to be caused by the permanent magnetization of metallic components and casing around the magnetometer, either by the Earth's magnetic field or other external magnetic fields, while soft iron distortions are simply the interference by the terrestrial magnetic field induced in the normally not magnetized components close to the detector (non-permanent magnetization or the interference itself, superposed on the actual magnetic readings).

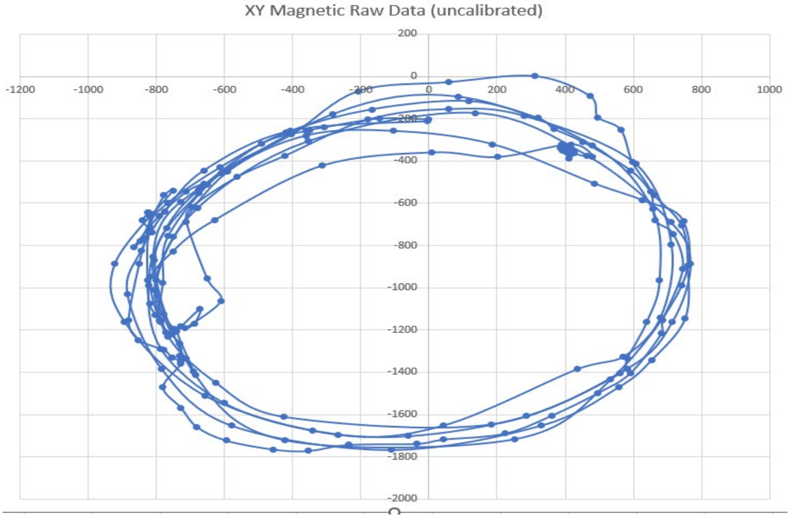

Figure 2. Raw magnetometer data collected as the sensor was spun around the z axis, keeping the X and Y axes as level as possible. Small deviations are caused by mechanical effects of the wires to the platform and by the numerous magnetic interferences in the lab. Data source: Author's measurements in the local lab.

From the data for the location, we extract the expected values of the three components as well as the local angle of the field with respect to the ground.

Placing the magnetometer at the specified angle, the readings of the three axial components should be in accordance- but they are not. Moreover, I experimentally observed the readings have strong offsets due to the presence of external perturbations from a very electrically noisy environment (power lines at close proximity and switching supplies that power the very controller that manages the sensor).

All these precautions and the high inherent sensitivity to magnetic perturbances suggest a stationary magnetometer (situated in a well known locally determined and unchanged or compensated for magnetic environment) is a good detector for electromagnetic and topologic distortions of the magnetic field (such as those caused by motion of ferro, para or diamagnetic materials through any magnetic field, such as the terrestrial one).

A simplified calibration procedure involves a series of simplifying assumptions- if the three magnetometers (each sensor for its corresponding X, Y and Z axis) are identical or close to identical, the scaling is close to unity.

Rotating the three-axis magnetometer around each axis and averaging the values for the other two axes, we can extract an average X, Y and Z value.

The mean of the three average values should help to get the scaling factor for each magnetometer – independent of any external value or measurement apparatus. This corrects for inner sensor geometry/positioning and external offset but assumes three identical sensors and correct geometric rotations of the module can be carried out by the operator.

The scaling factor can then be deduced as a ratio of the mean value for each component to the global mean.

A practical while not rigorous method as used in the working code for the GY271 three axis magnetometer module (used for drone navigation and digital compasses in civilian applications), [4], [5], [6] uses these estimations (1):

```
offset_x = (max(x) + min(x)) / 2
offset_y = (max(y) + min(y)) / 2
offset_z = (max(z) + min(z)) / 2
avg_delta_x = (max(x) - min(x)) / 2
avg_delta_y = (max(y) - min(y)) / 2
avg_delta_z = (max(z) - min(z)) / 2
avg_delta = (avg_delta_x + avg_delta_y + avg_delta_z) / 3        (1)
scale_x = avg_delta / avg_delta_x
scale_y = avg_delta / avg_delta_y
scale_z = avg_delta / avg_delta_z
corrected_x = (sensor_x - offset_x) * scale_x
corrected_y = (sensor_y - offset_y) * scale_y
corrected_z = (sensor_z - offset_z) * scale_z
```

Figure 3. Pseudocode snippet using information from [4].[5].[6] describing how magnetometer offset and scaling of the three axis components are computed in a civilian drone navigation application/flight controller

This procedure, although widely practiced, is mathematically incorrect and does not take into account the local values of the magnetic field, and should not be used as a scientific measuring device for the terrestrial magnetic field, because it does use a completely empiric, comparison-based arithmetic and the assumption that the three sensors are exactly identical. In practice however it has been proved accurate enough for navigation of small civilian drones.

The orientation section of the code uses the magnetic declination and the differential values of the magnetic fields, not its actual value, therefore the procedure is adequate.

Figure 4 below shows the hard and soft iron corrections introduced by the calibration, as well as the effect of moving a metallic object next to the detector.

The magnetic sensor was rotated around the Z axis and the field values in the XY plane around a fixed point are plotted with the necessary corrections. These are very large, the lab is a very magnetically noisy environment- but the good functioning of the magnetic sensor is verified by using it in a compass mode- and the azimuth aligns with those detected by a military issue compass (Levenhuoek AS-20).

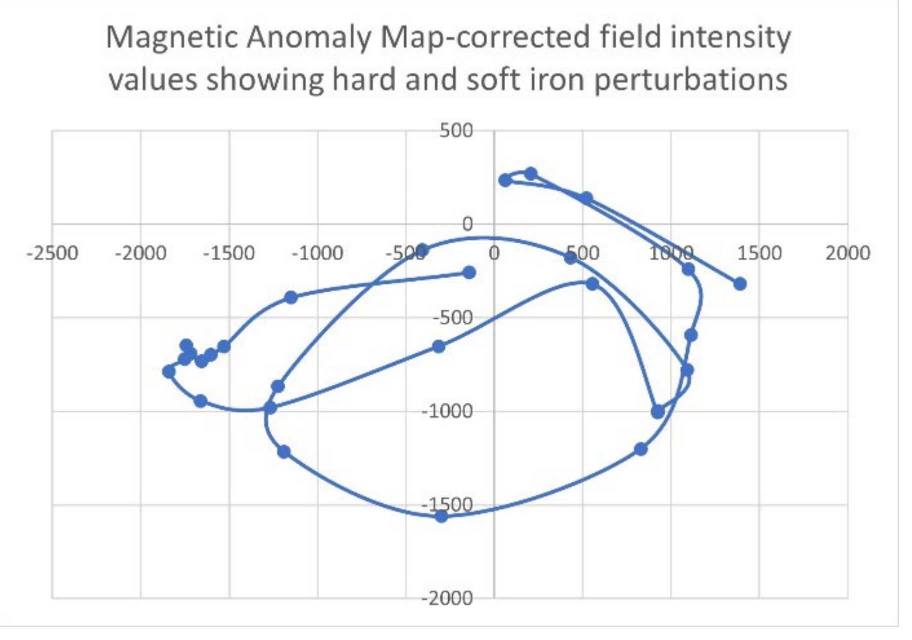

Figure 4. The magnetic anomalies caused by hard and soft iron distortions, superimposed with motion of ferromagnetic bodies in the vicinity of the detector. The magnetic detector was rotated around its vertical Z axis. Values in nanotesla show increased magnetic fields around the workbench (power lines, switching power supplies etc. in the immediate vicinity raise the values of the normal components from around 45-50 nT to 1500-2000 nT. This does not change the proper functioning of the magnetometer -even as an orientation device.

2. USING THE MAGNETOMETER AS A DETECTOR OF MOVING DIA-, PARA- OR FERROMAGNETIC BODIES

Now that we have seen how the hard and soft iron perturbations are eliminated as a necessary part of cleaning up magnetometer data to be useful for navigation, let’s take a look at the other side of the coin: measuring the interference values.

Once established (as per the calibration procedure described in ref. [4], [5] and [6]) and computed as offsets, the values of these interferences are basically subtracted from the raw data – and that already assumes they remain constant- i.e. no external magnetic variable fields or no moving bodies in the vicinity of the sensor.

But any variable reluctance circuit- including the largest of all, the planetary magnetic field with all its interferences and our detector in it-is subject to modifications of the local magnetic permittivity as moving bodies interfere with magnetic field lines, being either ferromagnetic -i.e. concentrating the magnetic field locally, or dia- or paramagnetic- i.e. locally scattering the field lines and weakening the magnetic field. To the stationary magnetic detector, such modifications in the field. compared to the base offset of hard and soft iron distortions appear as modifications in the measured field intensity. In reality they are linked to the motion of various bodies in the vicinity of the detector.

To maximize the use of the magnetometer as detector, a magnetic lens consisting in a highly permeable ferrite or alloy bar can be used in front of a single axis magnetic sensor, to make sure it saturates at low intensities of the magnetic field. Variations in the field are also amplified and the sensitivity extended.

Let us test the fixed sensor in the presence of a moving ferromagnetic and then a paramagnetic body -no rotation this time (figure 5). This observed effect when repeatedly approaching and retreating the perturbing bodies next to the sensor is the basis of remote magnetic moving body detection proposed in this work.

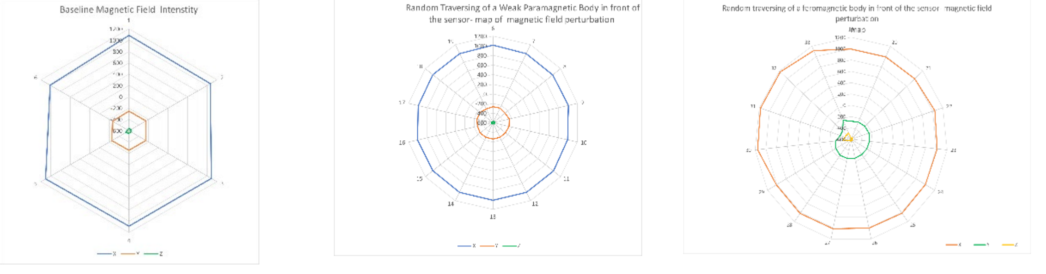

Figure 5. Random movement of paramagnetic and ferromagnetic bodies influence the three components of the field intensity. These radial diagrams show the three components as concentric circles, each radius being one random direction trial and their associated perceived magnetic intensity variation.

3. CONCLUSIONS

A modern and sensitive three axis magnetometer can be used for a variety of purposes, from magnetic storm detection, orientation and general weak magnetic fields measurements to moving body detection as a secondary sensor in an early warning system.
Its ability to detect perturbations of very weak fields mark it as a very sensitive solution for detecting any kind of magnetic interference- either distal electromagnetic fields similar to those used in jamming or strong ionization trails that mark the high velocity vehicle movement through the atmosphere, to auroral electric storms in the high layers of the atmosphere.
Further testing using passive magnetic field concentrators (high permeability alloys with small remanent magnetization) is needed to fully assess the sensitivity range and limits of this type of sensor.

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