(Univ. Prof. Dr. Friedrich AUMAYR)

Bachelor Thesis

Navigation by measuring the Earth‘s magnetic field with MEMS

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Vienna, January 23, 2018

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Contents

1 Motivation

While GPS navigation is a wide spread system for navigation today, it truly has some negative aspects. With things like the need to always connect to a minimum of 3 satelites and a big amount of energy compared to MEMS (Microelectromechanical Systems). These are the core negative aspects. That is why I thought about alternatives for special needs in navigation. For that reason I looked up for alternatives in older systems of navigation and navigation of animals fusioned with new energy efficient and small MEMS. Those special needs could include navigation for explorers, who are disconnected from anything like civilisation or navigation for small vehicles in an extraordinary environment.

2 Glossary

Coriolis Effect: an effect of the inertial force in a rotating reference frame
Declination: the angle between the true north and magnetic north direction
Equivalent circle: circle on Earths surface on which the given quantity has the same value
Fluxgate-Magnetometer: device to measure the magnetic field in a vector see Chapter 3.4.1
GPS: Global Positioning System; Satelite based navigation system
Inclination: the angle between the magnetic field vector and the horizontal plane
Magnetic Field: the magnetic vector at every point in space
Magnetic Pole: points on Earths surface where the Inclination is 90 degree
MEMS: Microelectromechanical Systems
Navigation: knowing postion and orientation
Radiation Belt: zone around the Earth where high energy charged particles are captured by Earths magnetic field
Satelite: artificial object orbiting Earth
SEM: Scanning Electron Microscope

3 State of the Art

This section will deal with the state of the art of science and technology of the earth's magnetic field, microelectromechanical systems (MEMS) and the navigation of animals by using the earths magnetic field.

3.1 The Earth's Magnetic Field

3.1.1 Form and Strength of the Earth's Magnetic Field

The Earths magnetic field, near the Earth's surface, is approximately a magnetic dipole with the magnetic field South pole near the Earth's geographical North pole and vica versa [1].

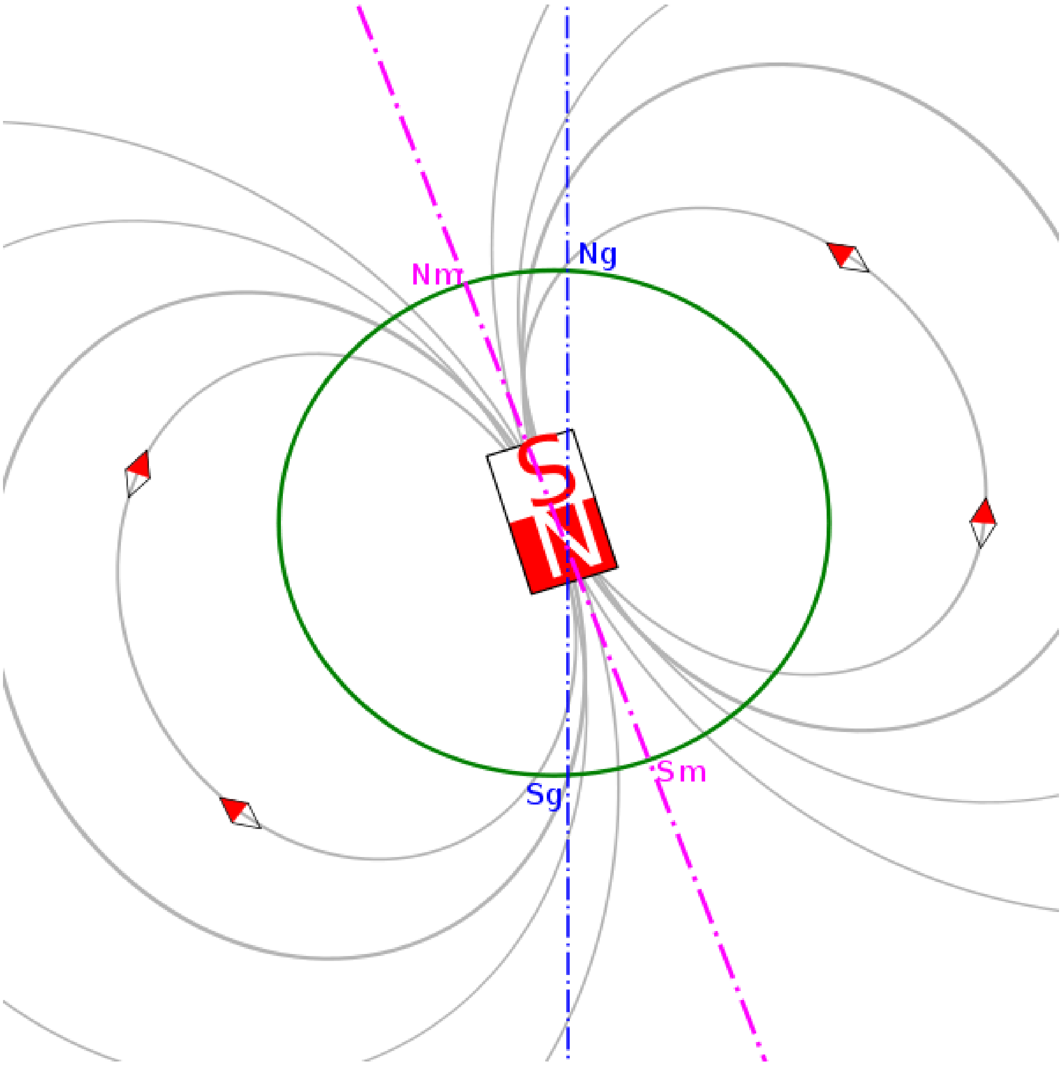


Figure 1: The Earth's magnetic field approximated by a bar magnet

Source: https://upload.wikimedia.org/wikipedia/commons/2/2b/Geomagnetisme.svg

The main part of the Earth's magnetic field has been changing really slowly over more than thousand years. Today its horizontal component is approximately in the north-south direction, in doing so the vertical component is 0 at the equator and rises in direction to the poles, at which the horizontal component vanishes and the vertical component is 100 per cent of the magnetic fields strength. That is called inclination. The inclination angle at the equator is 0 degree whereat it is 90 degree at the poles. In Central Europe the inclination angle amounts to approximately 60 degree [1].

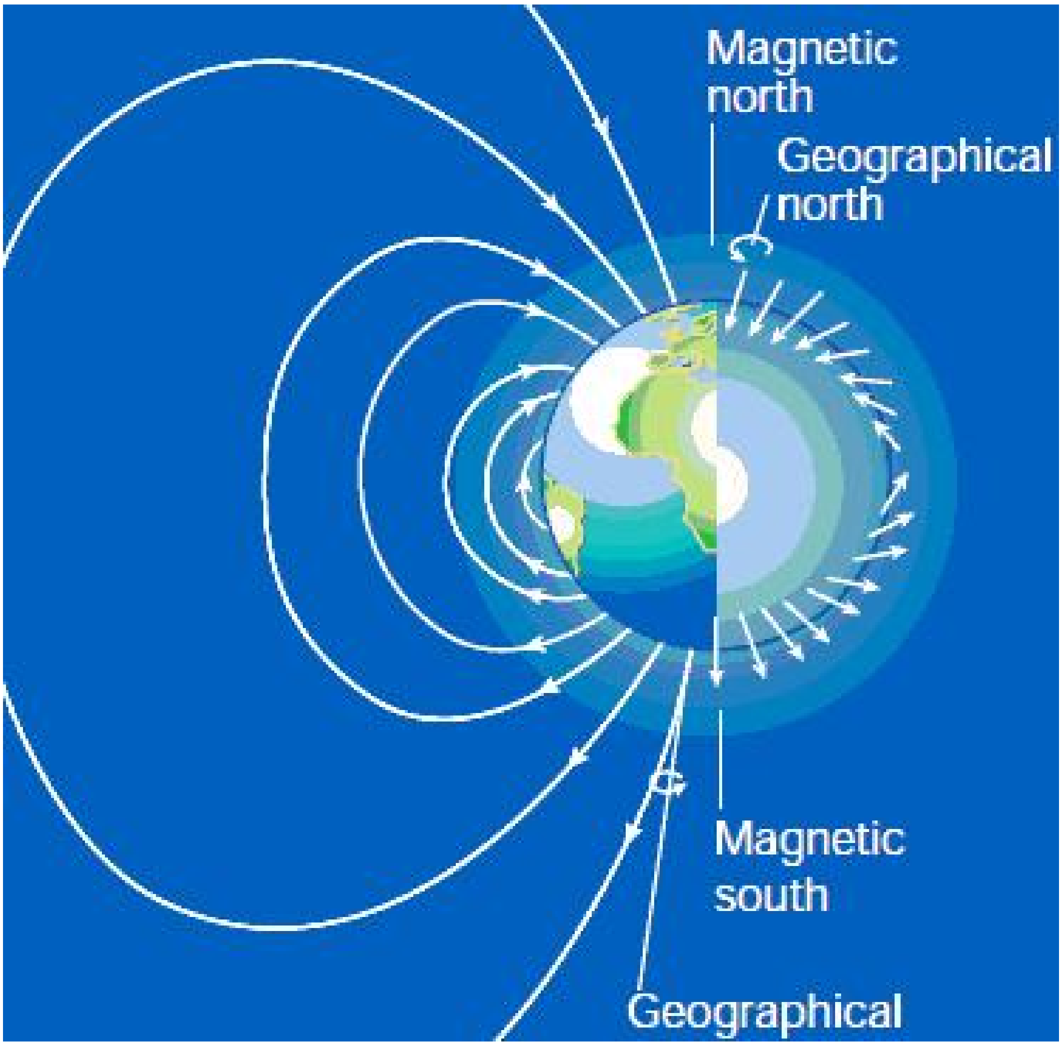


Figure 2: Inclination on the globe [2]

There are also some anomalies and deviations which are called declination like the South Atlantic Anomaly where the inner Radiation Belt comes really close to the Earth's surface and therefore it interferes with the magnetic field and weakens it. Other anomalies are areas where a large amount of iron can be found on the surface [1].

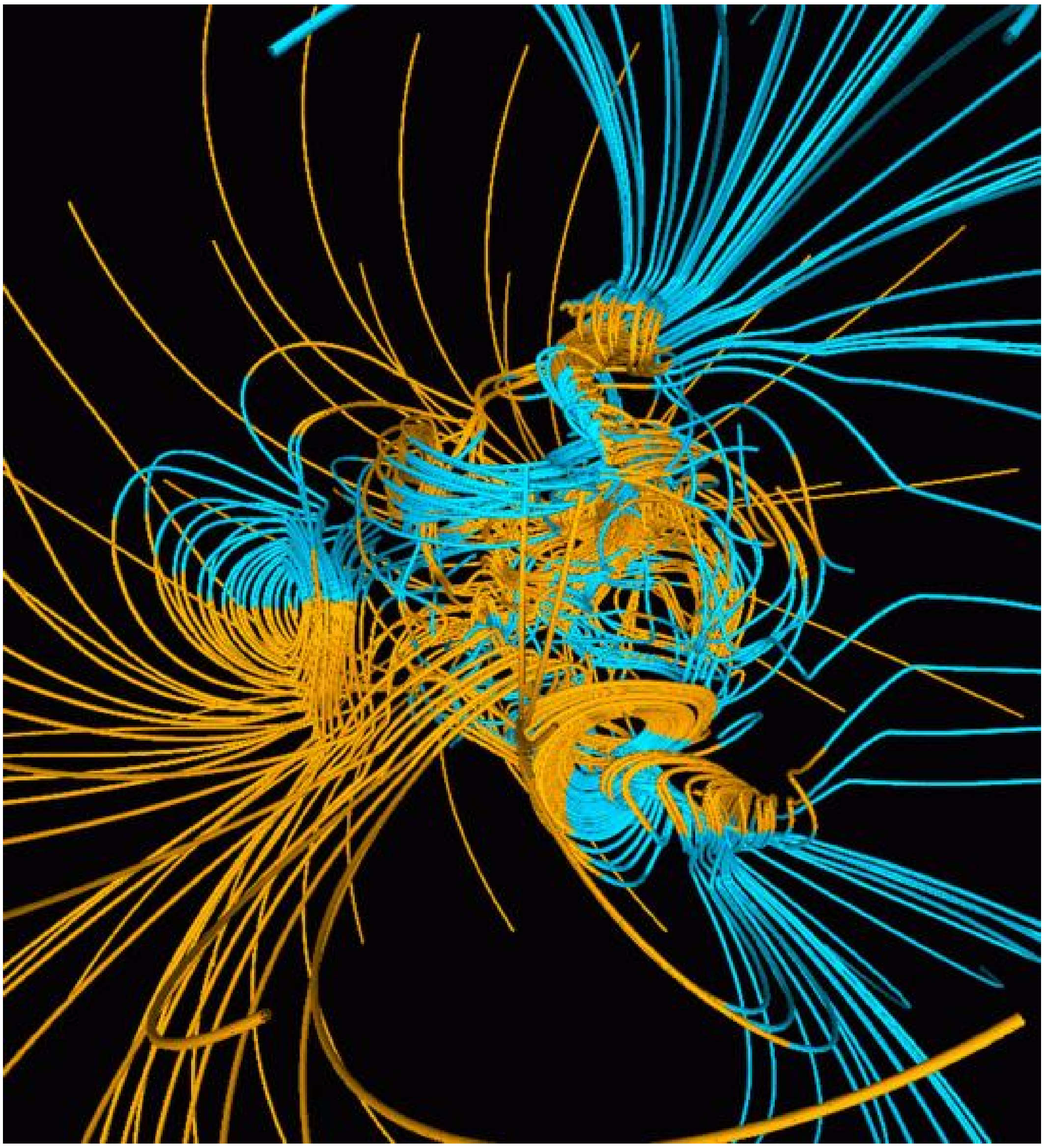


Figure 3: Simulation of chaotic anomalies of the Earth's magnetic field [3]

Source: https://de.wikipedia.org/wiki/Datei:Geodynamo_In_Reversal.gif

The geomagnetic poles of the Earth's magnetic field aren't at the exact positions of the geographical poles. The axis of the Earth's magnetic field is displaced to the geographical axis by approximately 11.5 degree [4].
As mentioned before the Earth's magnetic field, near the Earth's surface, is approximately a magnetic dipole like a tilted bar magnet (see Figure 1). It has got a

dipole moment of $M = 7.746 \cdot 10^{24}\,\mathrm{nT} \cdot \mathrm{m}^3$ [1].
For calculating the dipole field in dependence on the distance R and the magnetic latitude λ, you can use the dipole formula (see Formula 1) [5].

$$B(R, \lambda) = \frac{M}{R^3}\sqrt{1 + 3 \cdot \sin^2(\lambda)} \tag{1}$$

At the magnetic equator the magnetic field's strength is about $30\,\mu\mathrm{T} = 30,000\,\mathrm{nT}$ and at the magnetic poles it is approximately twice as strong. In Central Europe the magnetic field's strength is about $48\,\mu\mathrm{T}$.
Inside Earth the magnetic field's strength increases rapidly with growing depth whereas the multipolar parts are growing higher than the dipole parts. So a better approximation would be a multipolar field [1].

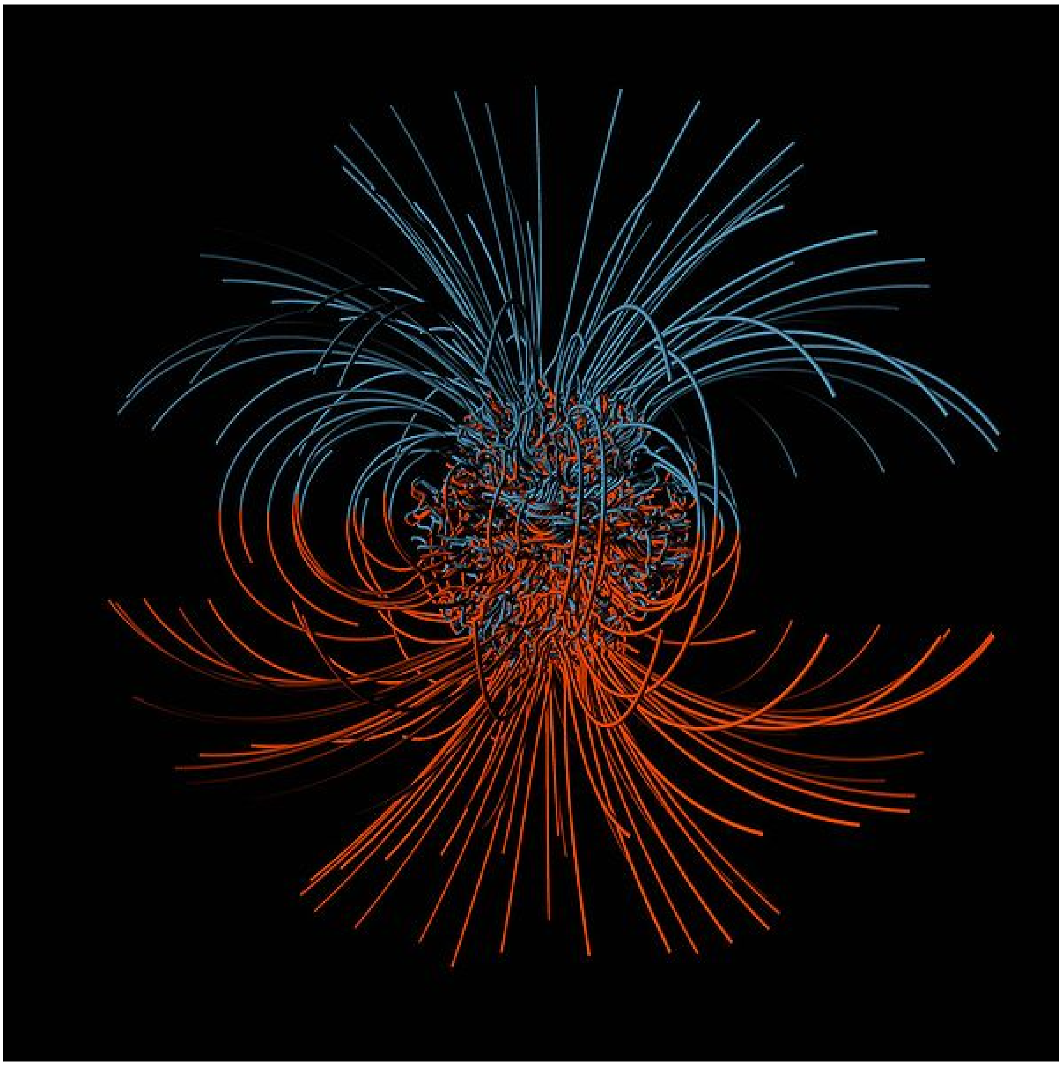


Figure 4: The Earth's magnetic field approximated by a multipolar field

Source: http://www.astropage.eu/wp-content/uploads/2016/09/erdmagnetfeld2.jpg

But for applications on the Earth's surface it is possible to describe 90 per cent as a magnetic dipole [6].

3.1.2 Geodynamo

There are many theories about the origin of the Earth's magnetic field. This section is only about the most popular theory, about the geodynamo.
The Earth's magnetic field is caused by electric currents in the liquid outer core produced by the Coriolis effect and a potential difference between the fluid outer core and the solid inner core whereby more electric currents are induced. Although

many people may expect, it is not created by magnetic materials in the Earth's core, because it is at a much higher temperature state than the curie temperature. Therefore it is not able to produce a magnetic field by magnetic materials like solid magnets do [7].

There are some requirements when a planet could create a magnetic field [7]:

- It has to have a large amount of conductive liquid.
  The Earth's outer core consists of, 6 times the volume of the moon, liquids with a high amount of iron in them around the inner core, which is nearly pure solid iron.

- There has to be a large amount of energy.
  The Earth's core is very hot (near 5000 degrees), which comes from the hotter era of Earth. Additionally, there are also radioactive elements in the Earth's core, which produce heat by radioactive decay.

- The planet has to rotate.
  The Earth turns on its axis one time per day and with this rotation the Coriolis effect cause the induction of electric currents, which induce the magnetic field.

3.2 Animal's Navigation by Sensing the Magnetic Field

There are many animals, which use the Earth's magnetic field for navigation such as birds, lobsters, sea turtles, bacterias and deers. In this section you can find information about what they sense and how they use it for navigation.

3.2.1 Birds

Many birds in Europe have to fly to south in autumn and to north in spring to live in a comfortable environment temperature wise. For that they navigate by sensing the magnetic field to know if they are on the correct path. Birds use the inclination of the magnetic field. If the inclination of the magnetic field increases, they know that they are flying north (just north of the equator). The outcome of an experiment, which should show that birds are oriented by magnetic fields, is shown in figure 5 [8].

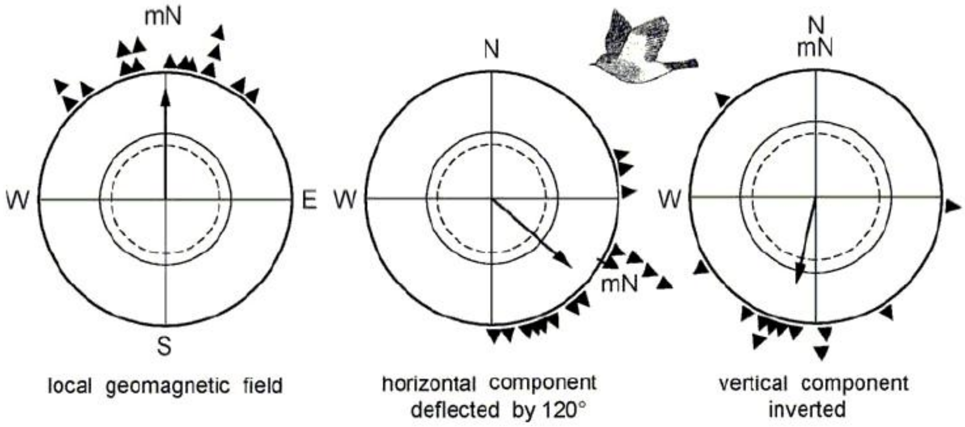


Figure 5: Outcome of a bird experiment with different magnetic field directions [8]

After some experiments, scientists found out that the magnetic sense of birds is located in their right eyes and is only activated if it detects blue light. Birds can sense the inclination of a magnetic field with the help of a chemical receptor, which needs blue light for the chemical reaction, that creates a chemical compound. It is different with other inclinations and so the bird knows in which direction it is flying. In figure 6 is the outcome of an experiment with blue and red light and the same magnetic field as in the experiment of figure 5 [8].

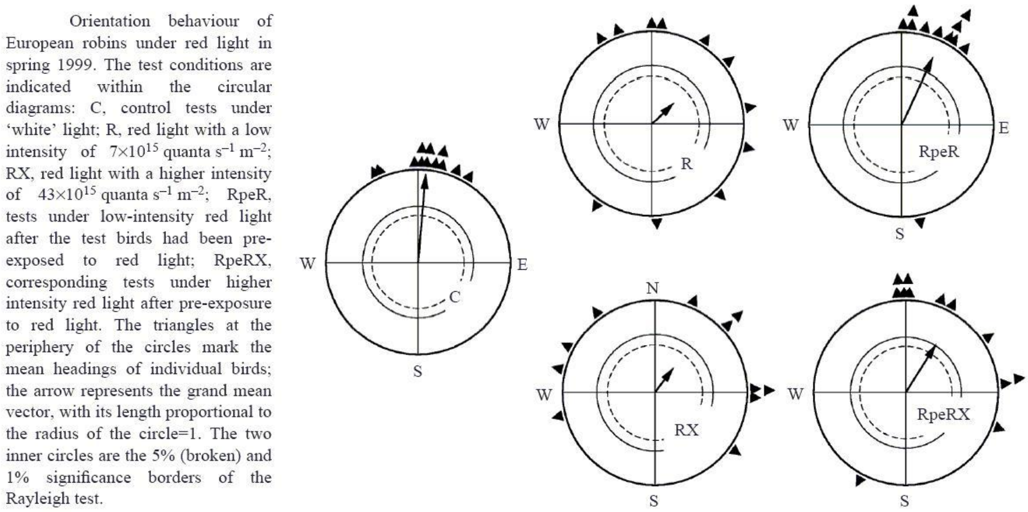


Figure 6: Outcome of a bird experiment with different colored light [8]

3.2.2 Lobsters

Lobsters, like the Panulirus argus, use their magnetic sense to migrate over 200 kilometers on the dark ground of the Gulf of Mexico and the Caribbean. Many experiments were done about their magnetic sense including finding their home from an abnormal point in the Gulf of Mexico. Another experiment was a bit more complex. The Lobsters were influenced by magnetic coils so they can't track the way they were moved at the start. After that the lobsters were on their own to find their home.
In conclusion most of them found the way to their home and the most were also walking the correct and straight way to their destination. Some scientists think that the lobsters use the inclination and the strength of the Earth's magnetic field to spot them. That could work because the inclination and the fields strength have different equivalent circles on the Earth's surface like figure 7 shows for the Gulf of Mexico [9].

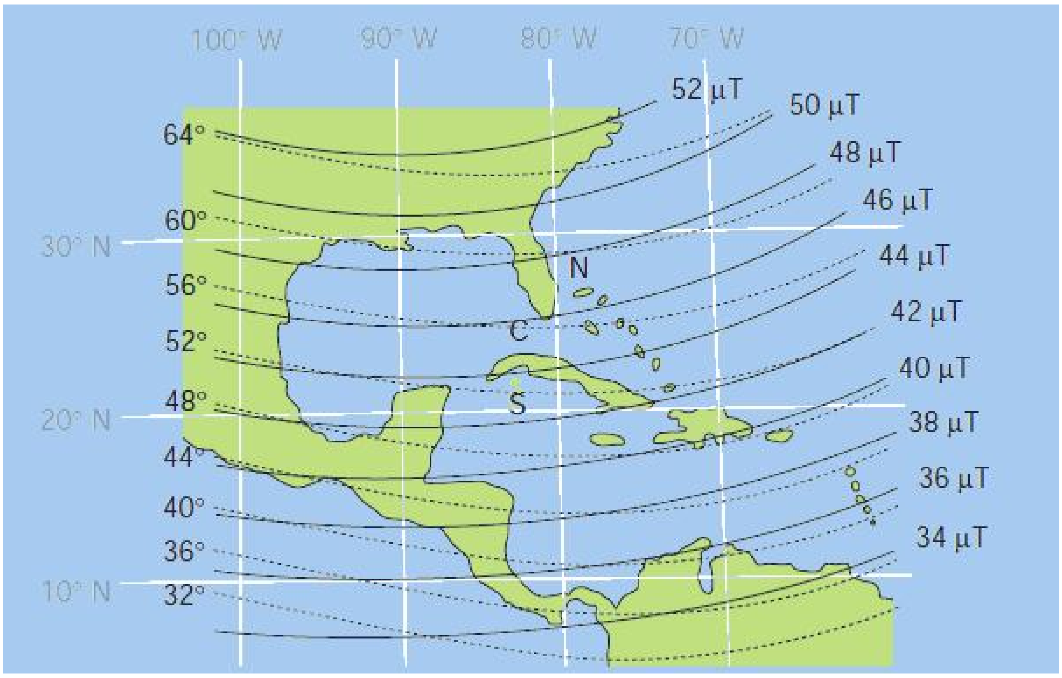
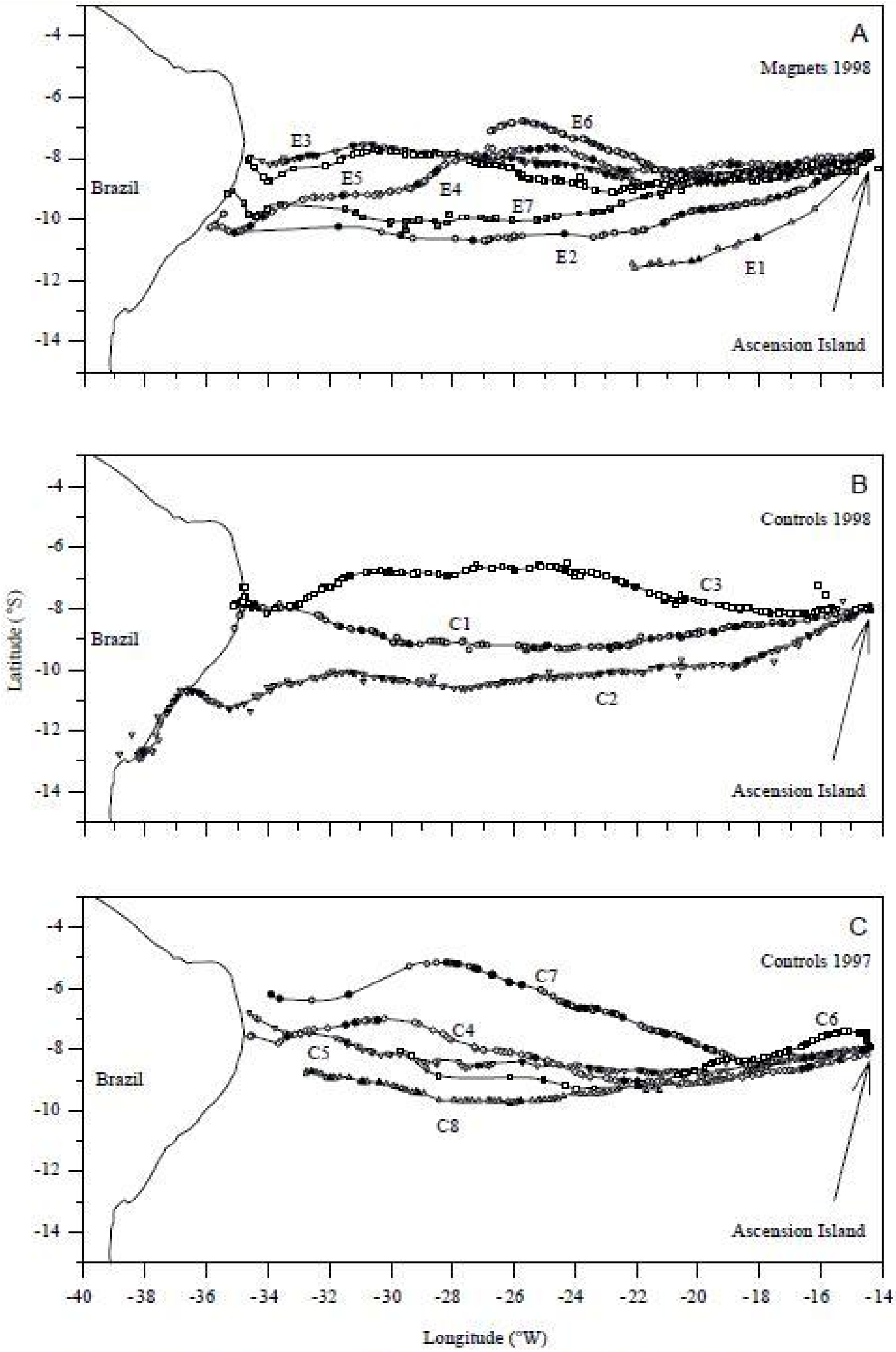


Figure 7: Equivalent circles of the fields strength and the inclination at the Gulf of Mexico [9]

3.2.3 Sea Turtles

Sea turtles migrate through long parts of the Atlantic ocean to live near Brazil. After having gained their adult age, they come back to their ascension island. In

order to reach their goal they use a very sensitive magnetic sense, so they can travel to their real ascension beach. Many scientists think they use the same form of magnetic sense as lobsters do [10].
In figure 8 you can see some experiments by tracking sea turtles from the year 1997 and 1998.



Migratory routes of tracked turtles. (A) Magnetically treated turtles released in 1998 (E1–E7), (B) control turtles released in 1998 (C1–C3) and (C) control turtles released in 1997 (C4–C8). Fixes disregarded in the reconstruction of the routes (see text) are shown, but not joined by lines. Filled symbols, fixes in the three most accurate classes; open symbols, less accurate fixes (see text).

Figure 8: Tracked turtles which came back to Ascension Island [10]

3.2.4 Bacteria

Bacteria in the sea need to get to the bottom of the ocean to find their living environment. So they have small magnets in their bodies, which drift the bacterias in the direction of the magnetic field. Inasmuch the Earth's magnetic field on the northern part of Earth has its direction to the ground, the bacterias always find the ground of the ocean[8].

3.2.5 Deer

After having monitored deer, some scientists found out that deers always sleep in north-south direction. Very little is know about what they sense and why they do this but they have to have a compass related sense[8].

3.2.6 Summary

In table 1 you can find a short summery of what and with which method the animals mentioned above use their magnetic sense.

Animal	What they sense	For what they need it
Bird	inclination	migration
Lobster	inclination and fields strength	migration
Sea Turtle	inclination and fields strength	migration
Bacteria	magnetic vector	finding food
Deer	magnetic vector?	sleeping direction?

Table 1: Summery of the magnetic senses of the animals mentioned above

For sure the magnetic sense is not the only sense this animals have. It is assisted by visual landmarks with most of the animals. Only the lobster and the bacteria can find their right places without seeing anything [8] [9] [10].

3.3 Old Navigation Systems of Humans

First of all, a chinese man discovered in 655 that some materials were influenced by a unseen force and when putting them in a force free state, the materials always point in one direction (nearly north). So they built the first compass. With that new navigation tool they could navigate much better to different spots when using a map to help [11].

Figure 9: An ancient compass lying on an old map

Source: https://d2gg9evh47fn9z.cloudfront.net/800px_COLOURBOX4214940.jpg

The problems with using a mechanical compass are:

- It needs to be spherically seated because of the inclination of the magnetic field.
- If there are some other magnetically active things around the compass it could guide the compass in a false direction.
- Because of some magnetic anomalies near the Earth's surface the compass could also lead into a false direction.

The first item is obvious solved by spherically seats but the second problem is a bit more difficult. The magnetic distortions of e.g. the ship you are on needs to be measured and has to be balanced with additional magnets around the compass or you use a "mother compass" on the position where all magnetic distortions of the ship are balanced. People had not been able to solve the third item for a long time therefore some ships were lost because of magnetic anomalies [1].

So people knew in which direction they were going. But for navigation they also needed to know where they were. This problem was solved by looking at the sun at daytime or at the stars at nighttime. But for that they needed solid clocks to know what time it was and which date it was. That is why they built good solar clocks and after that good and solid mechanical clocks [12].

For instance if you know what time it is and you know that the star constellation Perseus normally is at a different angle at your hometown you can find out the longitude of your position by measuring this angle. To get the latitude of your position, you could find out the solar altitude at midday on a specific date [12].

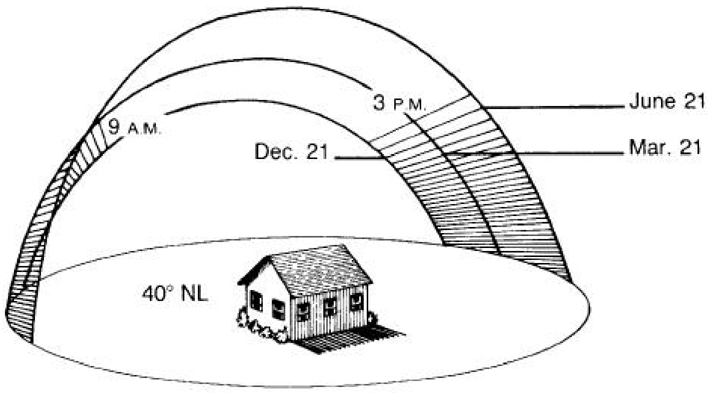


Figure 10: Solar altitude at different dates at the latitude of 40 degrees north

Source: http://articles.extension.org/sites/default/files/styles/large/public/Solar_Air_Solar_Exposure.gif

3.4 Measuring a Magnetic Field with a Fluxgate Magnetometer

3.4.1 Basics of a Fluxgate Magnetometer

First of all, there are two different types of magnetic sensors:

- total magnetic field sensors (scalar magnetometers)
- vector component magnetic field sensors (vector magnetometers)

The Fluxgate magnetometer is capable of measuring in 3 dimensions thus producing a magnetic vector.
A normal Fluxgate magnetometer is like a compass but the magnetic field is not measured by a needle but with the help of an electro magnet. It has got a ferro magnetic metal bar with a wire surrounding it (electro magnet). By running an electric current through the wire the bar begins to enhance a magnetic field [14].

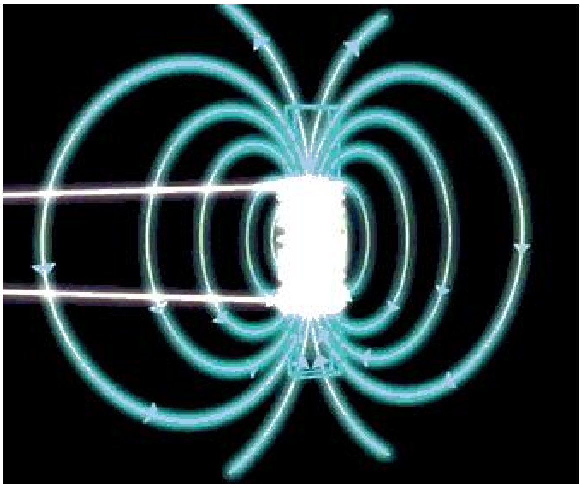


Figure 11: Electro magnet enhancing a magnetic field [13]

If you change the direction of the electric current the direction of the magnetic field will also change. If you do that again and again the integration over the graph would be zero.

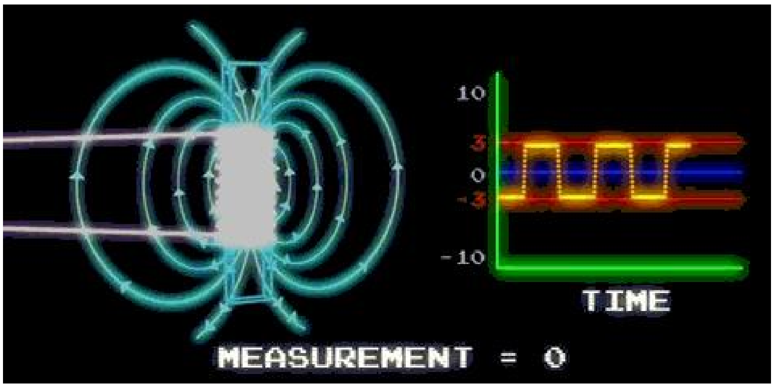


Figure 12: Measurement by changing the direction of the electric current without an external magnetic field

If there is another magnetic field influencing the electric magnet, the difference of the electric current can be measured.

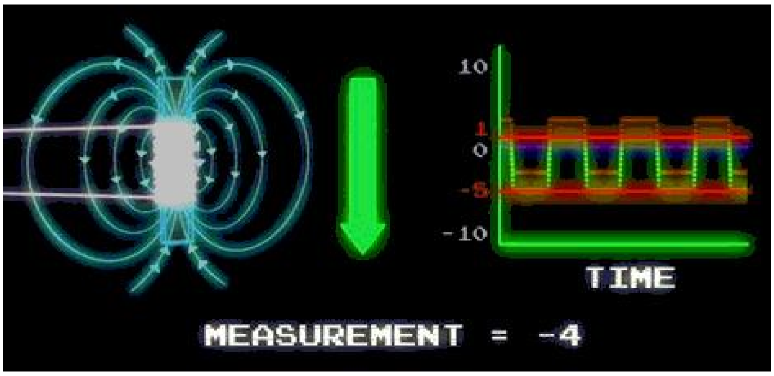


Figure 13: Measurement by changing the direction of the electric current with an external magnetic field

You can place three of the Fluxgate magnetometers in 90 degree angle to each other to get a three dimensional vector.

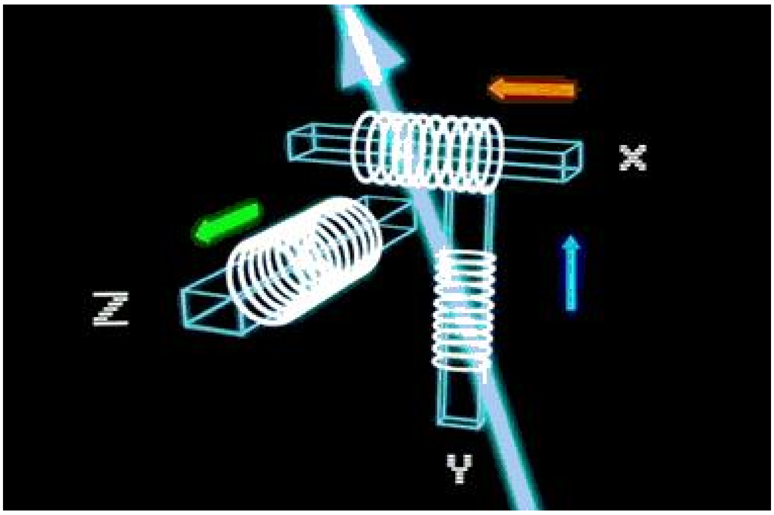


Figure 14: 3D-Measuring with three Fluxgate magentometers [13]

With Fluxgate magnetometers it is possible to measure magnetic fields in the range of 0.1 nT to 1 mT [14].

3.4.2 Fluxgate Magnetometer as Microelectromechanical System (MEMS)

The assembling of a MEMS-Fluxgate magnetometer is the same as a classic Fluxgate magnetometer but they differ in size. A MEMS-Fluxgate magnetometer is about $2x2x0.02$ mm big. In figure 15 is shown what the MEMS-Fluxgate magnetometer looks like seen through a SEM [15].

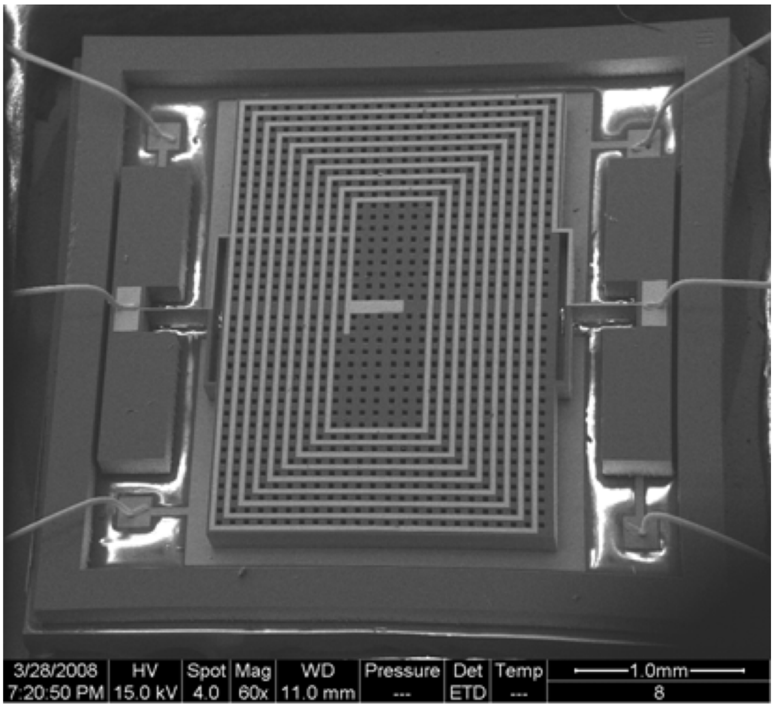


Figure 15: Image of planar interwining magnetic coils wrapped around the magnetic core material

With MEMS-Fluxgate magnetometers it is possible to measure magnetic fields in the range of 60 nT to 500 μT [15].

4 Navigation by Measuring the Earth's Magnetic field with a MEMS-Fluxgate Magnetometer

This section is about creating a navigation system independent of satellites but measuring the Earth's magnetic field with MEMS-Fluxgate magnetometers.

4.1 Theory

As this project is only about MEMS-Fluxgate magnetometers you get the magnetic vector

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}. \tag{2}$$

The magnetic fields strength is then

$$B = \sqrt{x^2 + y^2 + z^2}. \tag{3}$$

In order to get the magnetic latitude λ from measuring the strength of the magnetic field B you take formula 1 and convert it to λ.

$$B = \frac{M}{R^3}\sqrt{1 + 3 \cdot \sin^2(\lambda)} \tag{4}$$

$$\Rightarrow \frac{R^3 \cdot B}{M} = \sqrt{1 + 3 \cdot \sin^2(\lambda)} \tag{5}$$

$$\Rightarrow \left(\frac{R^3 \cdot B}{M}\right)^2 - 1 = 3 \cdot \sin^2(\lambda) \tag{6}$$

$$\Rightarrow \sqrt{\left(\frac{R^3 \cdot B}{M \cdot \sqrt{3}}\right)^2 - \frac{1}{3}} = \sin(\lambda) \tag{7}$$

$$\Rightarrow \arcsin\left(\frac{R^3 \cdot B}{M \cdot \sqrt{3}} - \sqrt{\frac{1}{3}}\right) = \lambda \tag{8}$$

with $R = 6,371\,\text{km}$ and $M = 7.746 \cdot 10^{24}\,\text{nT} \cdot \text{m}^3$

Now you know on which Equipotential circle of the strength of the magnetic field you are. For a more precise information of your location on Earth you have to know another thing about the magnetic field, the inclination.
To get the inclination we need the vector of formula 2, need to set the coordinate system right by measuring the gravitation and putting the $-z$-axis in the gravitation direction, and with a trivial trigonometric function you get

$$\sin(\xi) = \frac{z}{B} \Rightarrow \xi = \arcsin\left(\frac{z}{B}\right) \tag{9}$$

with ξ as the inclination, z as the z-component of the magnetic vector and B as the magnetic fields strength

With the inclination you find another equipotential circle on which you should be. By crossing this two equivalent circles you get two points on Earth where you could be. In as much you normally know on which continent you are, you can exclude one point and so you get your location.
In order to establish a full navigation system, you also need to know in which direction you should go. With the Fluxgate-Magnetometers already installed, you have an inbuilt compass which leads the way to a specific place.

4.2 Application

In order to build a navigation system by measuring the Earth's magnetic field one needs:

- a 3D-MEMS Fluxgate magnetometer apparatus
- a small measuring unit for electric currents
- a small computer chip for mathematical issues with a small digital storage for storing the geological information in order to get the equivalent circles for the positioning and maps of the Earth
- a suitable software for the computer chip
- a gravitation sensor
- a suitable user interface with input possibilities (glasses with an eye tracking cursor)

The navigation system could be inbuilt glasses with all components, which know where you are, where you want to go and in which direction you have to move to reach your goal.

4.3 Problems

The biggest problem is the accuracy of todays MEMS-Fluxgate magnetometers. If you would like to measure your position with todays MEMS-Fluxgate magnetometers you could be about 160 km away from the located place. Another thing to worry about are anomalies on the surface, which could differ between 0.01 nT and 1 μT and that would falsify the result of your location drastically.

4.4 Additional solutions

For getting better results there are some good additional solutions for navigation without needing satellites. First of all, you could also install a map of anomalies on your computer chip to spot them or even find your goal because of them and turn the problem into a benefit. Additionally you could also add some other sensors to get better results like solar altitude sensors with precise clocks and acceleration sensors.

5 Navigation by Measuring the Earth's Magnetic Field with Conventional Magnetometers in Smartphones

In addition to the theoretical concept of building a navigation system with MEMS, measurements were made with an IPhone 4 to test the possibility of navigating with the help of the Earth's magnetic field.

5.1 Experimental Setup

An IPhone 4, with the app Teslameter [16], was used to measure the Earth's magnetic field on several different locations and during a flight from Gran Canaria to Vienna. It was always Setup in North-South Directions so that the Y-Axis of the magnetometer is measuring the whole horizontal magnitude. The vertical magnitude is shown on the Z-Axis, as the IPhone 4 was setup properly.

5.2 Locations

The four different locations of measurements were:

- Gran Canaria
- Casablanca
- Barcelona and
- Edelstal.

The locations were chosen, because of the different degrees in latitude and longitude. Another factor was that they were on the path of the flight from Gran Canaria to Vienna, and Edelstal was chosen because it is the hometown of my parents.

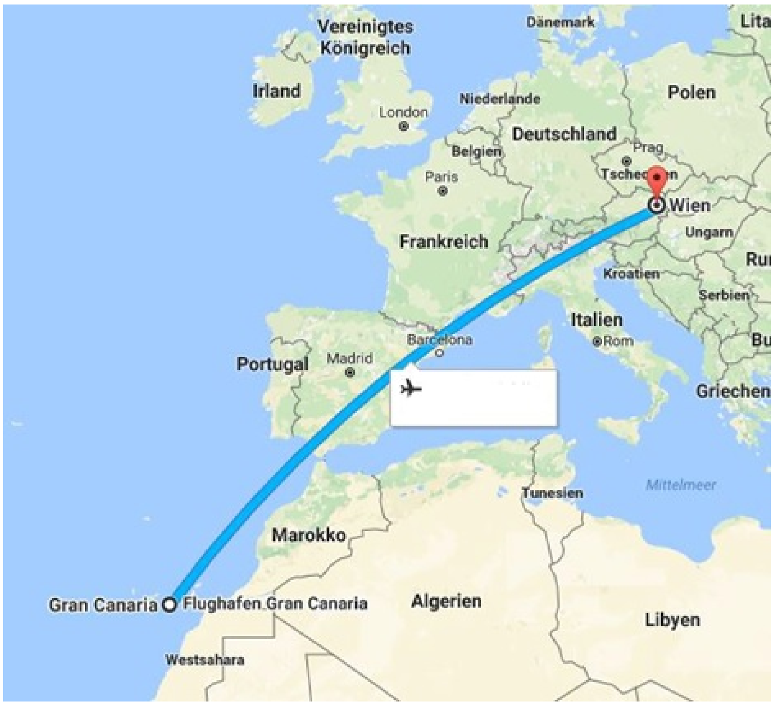


Figure 16: Map of the flight from Gran Canaria to Vienna

Source: maps.google.com

5.3 Measurements

In the following table the outcomes of the measurements of the various places are displayed. The detailed measurements can be found in the attachment.

Location	Y-Axis (in μT)	Z-Axis (in μT)	Total (in μT)	Inclination (in °)
Gran Canaria	32,2	-21,2	38,4	33,4
Casablanca	29,1	-30,3	42,0	46,2
Barcelona	26,2	-36,2	44,8	54,1
Edelstal	19,5	-42,6	47,0	65,4

Table 2: Measurements of the magnetic field in different locations

5.4 Conclusion

If you want to compare the measurements with some calculated results for the Earth's magnetic field you get a pretty good result. These calculations were done with the help of the calculating software on the website `https://www.ngdc.noaa.gov/geomag-web/#igrfwmm` and are displayed in the attachments.

Location	Y-Axis (in μT)	Z-Axis (in μT)	Total (in μT)	Inclination (in °)
Gran Canaria	31,0	-22,9	38,5	36,4
Casablanca	28,9	-29,5	42,0	45,5
Barcelona	24,9	-37,8	45,2	56,6
Edelstal	20,9	-43,9	48,7	64,5

Table 3: Calculations of the magnetic field in different locations

As one can see it is possible to measure the Earth's magnetic field comfortably with a smartphone. The downside is, like with MEMS, that the accuracy is not good enough to produce a serious navigation system. However it would be possible to create an app for smartphones with which you could navigate with an immense error of approximately 1%, which leads to a difference in location of 420 km in each direction.

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