



Degree in Physics

Degree's Thesis

*Optimizer to obtain the magnetic  
equivalent of a small satellite*

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## Optimizer to obtain the magnetic equivalent of a small satellite

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### KEYWORDS:

Particle swarm optimization (PSO), Ulysses satellite, European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Mobile Coil Facility (MCF), filter wheel, magnetic dipole.

### ABSTRACT:

This work uses the computational PSO method to optimize a magnetic field created by a device, as well as determining the position and magnetic moment for a dipole. It also simulates the magnetic field created by such device. This method is used for satellites which measure magnetic fields, so that the magnetic field created by the devices included in the satellite can be determined and deducted. The magnetic fields of the devices are measured in the MCF, property of the European Space Agency. We find the optimum values of position and magnetic moment for two dipoles recreating the magnetic field produced by the filter wheel measured in the MCF. We will prove that the PSO method can be used to optimize magnetic fields and recreating them with dipoles.

### PALABRAS CLAVE:

Optimización por enjambre de partículas (PSO), satélite Ulyses, Agencia Espacial Europea (ESA), Centro Europeo de Investigación y Tecnología Espacial (ESTEC), Mobile Coil Facility (MCF), rueda de filtro, dipolo magnético.

### RESUMEN:

Este trabajo utiliza el método computacional PSO para optimizar un campo magnético creado por un dispositivo y encontrar la posición y momento magnético para un dipolo. También simula el campo magnético creado por dicho dispositivo. Este método se utiliza para satélites que miden campos magnéticos, de forma que el campo magnético creado por los dispositivos que componen el satélite puede ser determinado y abstraído. Los campos magnéticos de los dispositivos son medidos en el MCF, perteneciente a la Agencia Espacial Europea. Encontramos los valores óptimos para la posición y momento magnético para dos dipolos recreando el campo magnético producido por una rueda de filtro medida en el MCF. Demostramos que el método PSO puede ser usado para optimizar campos magnéticos y recreándolos con dipolos.

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# Chapter 1

## Introduction

In spacecraft engineering many satellites in outer space are used to measure some interaction with a magnetic field. Ulysses satellite was used to measure solar magnetic fields at the Sun's poles [18]. As this device also creates its own magnetic field, it needs to be considered. The main focus of this paper will be to study the behavior of the magnetic field created by a filter wheel, for this, the Mobile Coil Facility (MCF) at European Space Research and Technology Centre (ESTEC) is used to measure the device's magnetic field [7]. With a computational method, such as the Particle Swarm Optimization, the magnetic field can be recreated using only dipoles [7]. The advantage of this method is that it can be used to consider these dipoles as if they were on the satellite.

In this dissertation, chapter 2 introduces the fundamental framework to understand the magnetic field created by a dipole. For this, Maxwell's equations need to be used and also to consider the multipole expansion. To validate the expressions obtained we will then compare empiric values with theoretical ones. With the help of a simulator like *Ansys Electronics* one can simulate experimental magnetic field of any device [5].

Once the magnetic field equations for a dipole have been validated, we proceed to optimize the magnetic field measured at the MCF facility. Chapter 4 discusses how the MCF measures the magnetic fields of devices used for the Ulysses satellite. The device we will study is a filter wheel which was used for the satellite. To optimize the magnetic field of the filter wheel we will require the PSO method, a computational method used to find optimum values [4]. In this case, the values needed are the position and the magnetic moment of a dipole. Finally, the results obtained with the PSO method are discussed.

The aim of this work is to continue the research on magnetic dipoles made previously by Pedro Manuel Vizcaíno Delgado [21]. For this purpose, we improve the implementation of the PSO method by including experimental data of a filter wheel from the MCF facility. In that way, we expect to find the optimum values of position and magnetic moment for a dipole.

# Chapter 2

## Theoretical elements

### 2.1 Fundamentals of magnetism

During our research with magnetic dipoles, we will encounter problems related to electromagnetism. To start with we will review the fundamental electromagnetic laws and select the expressions need to calculate the magnetic field of any device.

First of all, we will mention Maxwell's equations, this equations are the bricks of electromagnetic theory and therefore the base of this chapter. Maxwell's equations [11], formulated in 1861, consist of four differential equations:

$$\nabla \mathbf{E} = \frac{\rho}{\epsilon_0} \quad (2.1.1)$$

$$\nabla \mathbf{B} = 0 \quad (2.1.2)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.1.3)$$

$$\nabla \times \mathbf{B} = \mu_0 \left( \mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right) \quad (2.1.4)$$

These equations define electromagnetism as we know it.  $\mathbf{E}$  and  $\mathbf{B}$  are the electric and magnetic field respectively, while  $\mu_0$  and  $\epsilon_0$  are the permeability and permittivity constants in vacuum respectively. Finally,  $\mathbf{J}$  is the current density, i.e. the amount of charge per unit of time that passes through an unit area.

First, we have to introduce the concept of magnetic force  $\mathbf{F}_m$  which is the force produced by a magnetic field. For a static point-charged particle it suffers a force  $\mathbf{F}_e=q\mathbf{E}$ . If the particle is moving, it is effected by another force due to the fact that the particle has velocity. This phenomenon can

be described by Lorentz's law [11], which states that the magnetic force is proportional to the charge and velocity of the particle. Equation 2.1.5 shows this force just described.

$$\mathbf{F} = q (\mathbf{E}\mathbf{v} \times \mathbf{B}) \quad (2.1.5)$$

Therefore, a magnetic field can be produced by a moving charged particle. Given a current  $I$ , which is the flux of charged particles, the total magnetic field will be the sum of each magnetic field particle. Due to the difficulty of taking into account every particle of the current we suppose the current as a distribution of moving particles. The expression for the magnetic field created by a static current was formulated by Biot-Savart and it is known as the Biot-Savart law [19] seen in equation 2.1.6.

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_C \frac{I d\mathbf{l} \times \mathbf{r}'}{|\mathbf{r}'|^3} \quad (2.1.6)$$

The integration of equation 2.1.6 is along the path  $C$  in the direction of the current, being  $I$  the current and  $\mu_0$  is the permeability constant in vacuum space. The magnetic field has  $SI$  units are Tesla(T) and  $1T=1N/A \cdot m$ . Following the expression 2.1.6, we will employ Ampère's Law [11], which is used to calculate magnetic fields produced by a closed loop.

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \quad (2.1.7)$$

$$\int (\nabla \times \mathbf{B}) d\mathbf{s} = \oint \mathbf{B} d\mathbf{l} = \mu_0 \int \mathbf{J} d\mathbf{s} = \mu_0 I \quad (2.1.8)$$

Notice that in equation 2.1.8 we have used Stoke's theorem in the first integral [11]. The current  $I$  is the current enclosed by the closed loop. Then, with the expression 2.1.8 we can calculate the magnetic field produced by a wire, which will be  $B = \frac{\mu_0 I}{2\pi\rho}$  where  $\rho$  is the distance from the wire. The demonstration for the wire is the following:

$$\oint \mathbf{B} d\mathbf{l} = \oint \mathbf{B} \rho d\phi = \mathbf{B} \rho \int_0^{2\pi} d\phi = \mu_0 I \Rightarrow \mathbf{B} = \frac{\mu_0 I}{2\pi\rho} \hat{\phi} \quad (2.1.9)$$

Next, we introduce the concept of magnetic vector potential. From Maxwell's equation 2.1.2 it is deduced that the magnetic field is a solenoidal vector field which can be written as the curl of another vector field, called as magnetic vector potential, seen equation 2.1.10.

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (2.1.10)$$

$\mathbf{A}$  being the magnetic vector potential. We can consider Ampère's Law in its differential form:

$$\nabla^2 \mathbf{A} = -\mu_0 \mathbf{J} \quad (2.1.11)$$

As working with  $\mathbf{A}$  can be sometimes really tedious, we define the magnetic scalar potential in equation 2.1.12.

$$\mathbf{B} = -\nabla U \quad (2.1.12)$$

Notice that equation 2.1.12 is similar to the electrostatic potential  $\mathbf{E} = -\nabla V$ . The magnetic vector potential can also be related with the electric field, this is known from Maxwell equation 2.1.4. This is for non-stationary cases, as we will not work in this type of cases, it is out of the scope of this study.

## 2.2 Dipole expansion

In this section we will calculate the dipole expressions. If we have a static current in a small region in space, and we try to calculate the magnetic field produced by the device we can use the dipole approximation. For this approximation to work, it is necessary that the distance of measuring is much larger than the region where the current flows.

Keep in mind that the dipole expansion is an approximation as we will see. We start by writing the magnetic vector potential:

$$\mathbf{A} = \frac{\mu_0 I}{4\pi} \oint \frac{d\mathbf{r}'}{|\mathbf{r} - \mathbf{r}'|} \quad (2.2.1)$$

If we use Taylor's series for the term in the integral [8], we get:

$$\frac{1}{|\mathbf{r} - \mathbf{r}'|} = \frac{1}{r} + \frac{\mathbf{r} \cdot \mathbf{r}'}{r^3} + \mathcal{O}(\delta^2)$$

As an alternative this expression can be deduced:

$$\begin{aligned} \frac{1}{|\mathbf{r} - \mathbf{r}'|} &= \frac{1}{\sqrt{(\mathbf{r} - \mathbf{r}') \cdot (\mathbf{r} - \mathbf{r}')}} = (r^2 - 2\mathbf{r}\mathbf{r}' + r'^2)^{-1/2} \\ &= \frac{1}{r} \left( 1 - \frac{1}{2} \left( -2\frac{\mathbf{r} \cdot \mathbf{r}'}{r^2} + \frac{r'^2}{r^2} \right) + \mathcal{O}(\delta^2) \right) \end{aligned} \quad (2.2.2)$$

So the magnetic vector potential with the Taylor's expansion [8] can be written as:

$$\mathbf{A} = \frac{\mu_0 I}{4\pi} \left( \oint \frac{d\mathbf{r}'}{r} + \oint \frac{\mathbf{r} \cdot \mathbf{r}'}{r^3} d\mathbf{r}' + \dots \right) = \frac{\mu_0 I}{4\pi} \left( \frac{1}{r} \oint d\mathbf{r}' + \frac{1}{r^3} \oint (\mathbf{r} \cdot \mathbf{r}') d\mathbf{r}' + \dots \right) \quad (2.2.3)$$

Looking at the term of the integral, the first integral  $\oint d\mathbf{r}' = 0$  because the integral of a closed path is zero. This result indicates that there are no magnetic monopoles. The second integral is non-trivial, we have to use Stoke's theorem [8] to solve it:

$$\oint \phi d\mathbf{r}' = \int d\mathbf{s} \times \nabla \phi \quad (2.2.4)$$

So we get:

$$\oint d\mathbf{r}' (\mathbf{r} \cdot \mathbf{r}') = \int d\mathbf{S} \times \nabla (\mathbf{r} \cdot \mathbf{r}') = \mathbf{S} \times \mathbf{r} \quad (2.2.5)$$

where  $\mathbf{S}$  is the vector area,  $\mathbf{S} = \frac{1}{2} \int \mathbf{r} \times d\mathbf{r}'$ . Then, the expression of the magnetic vector potential for the dipole expansion is:

$$\mathbf{A} = \frac{\mu_0 I}{4\pi} \frac{1}{r^3} \oint (\mathbf{r} \cdot \mathbf{r}') d\mathbf{r}' = \frac{\mu_0 I}{4\pi} \frac{1}{r^3} (\mathbf{S} \times \mathbf{r}) \quad (2.2.6)$$

Being the magnetic moment defined as:

$$\mathbf{m} = \frac{1}{2} \int \mathbf{r} \times d\mathbf{r}' = \mathbf{S} I \quad (2.2.7)$$

For expression 2.2.6 the final result is:

$$\mathbf{A} = \frac{\mu_0}{4\pi} \frac{(\mathbf{m} \times \mathbf{r})}{r^3} \quad (2.2.8)$$

We can easily calculate the dipole approximation for the magnetic field applying Maxwell's equation:

$$\mathbf{B} = \nabla \times \mathbf{A} = \nabla \times \left( \frac{\mu_0}{4\pi} \frac{(\mathbf{m} \times \mathbf{r})}{r^3} \right) \quad (2.2.9)$$

With the use of vector operators and identities the result of the curl is as shown:

$$\nabla \times \left( \frac{(\mathbf{m} \times \mathbf{r})}{r^3} \right) = \nabla \times (\mathbf{m} \times \mathbf{r}) \frac{1}{r^3} + \nabla \left( \frac{1}{r^3} \right) \times (\mathbf{m} \times \mathbf{r}) = \frac{r^2 \mathbf{m} - 3(\mathbf{m} \cdot \mathbf{r}) \mathbf{r}}{r^5}$$

The the magnetic field produced by a dipole [8] is the following:

$$\mathbf{B} = \frac{\mu_0}{4\pi} \left( \frac{3(\mathbf{m} \cdot \mathbf{r}) \mathbf{r}}{r^5} - \frac{\mathbf{m}}{r^3} \right) \quad (2.2.10)$$

Equation 2.2.10 can be written for cartesian coordinates. Declaring the position vector as  $\mathbf{r} = (x - x_0)\hat{x} + (y - y_0)\hat{y} + (z - z_0)\hat{z}$  and the magnetic moment  $\mathbf{m} = m_x\hat{x} + m_y\hat{y} + m_z\hat{z}$  both in cartesian coordinates, the result for the magnetic field in cartesian coordinates [21] is shown in equation 2.2.11, 2.2.12 and 2.2.13.

$$\mathbf{B}_x = \frac{\mu_0}{4\pi} \left( \frac{3(m_x(x - x_0) + m_y(y - y_0) + m_z(z - z_0))(x - x_0)}{r^5} - \frac{m_x}{r^3} \right) \quad (2.2.11)$$

$$\mathbf{B}_y = \frac{\mu_0}{4\pi} \left( \frac{3(m_x(x - x_0) + m_y(y - y_0) + m_z(z - z_0))(y - y_0)}{r^5} - \frac{m_y}{r^3} \right) \quad (2.2.12)$$

$$\mathbf{B}_z = \frac{\mu_0}{4\pi} \left( \frac{3(m_x(x - x_0) + m_y(y - y_0) + m_z(z - z_0))(z - z_0)}{r^5} - \frac{m_z}{r^3} \right) \quad (2.2.13)$$

Where  $r = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}$  is the modulus of the vector position. Equations 2.2.11, 2.2.12 and 2.2.13 will be extremely useful later on for the calculation of the magnetic field in our simulation.

# Chapter 3

## Theoretical Validation

In this chapter our main focus will be to check if the dipole approximation presented in Chapter 2 coincide with measured values. Our procedure will be to simulate the equations for the dipole approximation and compare our values with experimental ones.

### 3.1 Simulation of a magnetic field

#### 3.1.1 Description of our device

We will use a simulator to obtain the empiric values to be compared with our simulation. In this case we will use *Ansys Electronics 2021* simulator, this program can mimic magnetic fields produced by many different objects. This program has many utilities such as simulation of circuits, thermal and electro-mechanical among others. It is used worldwide, for example, in product development [5]. This simulator works with different types of materials and also it allows to create the device's geometry. In this case we just want to validate our theoretical expressions with real ones. We choose to simulate a bookend shaped coil, seen in figure 3.2.

A bookend shaped coil consists in a coil with two faces, one in the plane XY and the other in the plane XZ [11]. We make a current flow through the coil in anti-clockwise direction. Using the right-hand rule we can guess the direction of the magnetic field produced, we can see a simplification of this rule can be observed figure 3.1.

We will compare the values simulated with our program, and discuss the values that we have obtained during the simulation with the program *Ansys Electronics* [21].

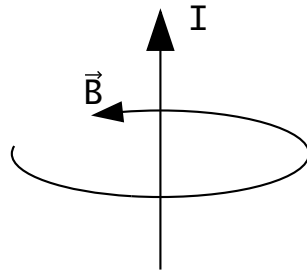


Figure 3.1 – Visualization of the right hand rule

The first step is to calculate the magnetic field using the dipole approximation derived from equations 2.2.11, 2.2.12 and 2.2.13.

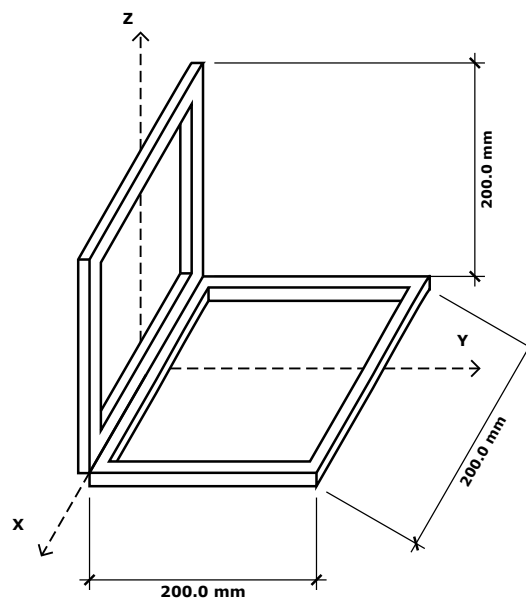
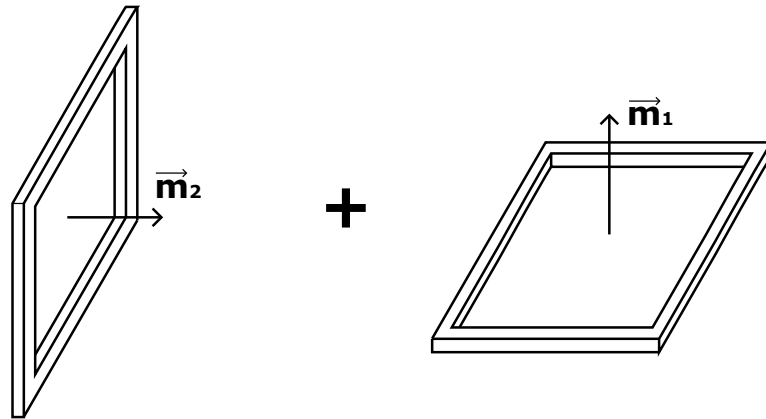


Figure 3.2 – Structure for the square bookend shaped coils with  $L = 200 \text{ mm}$

If we take into account the superposition principle, it results easy to see that the coil in figure 3.3 can be separated into two coils perpendicular to each other. In this way the problem simplifies



and we can calculate the magnetic field separately, and then sum both results to obtain the global magnetic field produced by the two coils. The magnetic moment, as defined in equation 2.2.7, can be written as the sum of each coil separately shown in equation 3.1.1.



**Figure 3.3** – Structure for the square bookend shaped coils seen as individual coils

$$\mathbf{m} = \mathbf{m}_1 + \mathbf{m}_2 = (I_1 \cdot S_1)\hat{k} + (I_2 \cdot S_2)\hat{j} = (I_1 \cdot L_1^2)\hat{k} + (I_2 \cdot L_2^2)\hat{j} \quad (3.1.1)$$

$I_1, I_2$  are the current of each coil and  $S_1, S_2$  are the surfaces. For each coil its initial position  $(x_0, y_0, z_0)$  is different, so for the square coils we write the initial position as seen in table 3.1. Changing the initial position of the coils will affect the results obtained, therefore the definition of the initial positions is crucial to run the program.

Coil	$x_0$ [mm]	$y_0$ [mm]	$z_0$ [mm]
Coil 1	0.0	0.0	0.0
Coil 2	0.0	0.0	100.0

**Table 3.1** – Initial position components for square coils in figure 3.3.

The current that flow through both coils is  $I = 100\text{A}$  and the area of the coils is  $S = L^2 = (0.2)^2\text{mm}^2 = 0.04\text{mm}^2$ , now we have every constant necessary to calculate the magnetic

field using the dipole approximation. For the calculations we will use a programming language called Python, because of its general-purpose and easyness to learn. We implement the expressions 2.2.11, 2.2.12 and 2.2.13 in the program to calculate the magnetic field.

### 3.1.2 Implementation in a Python program

To write the program, first libraries such as numpy, math and matplotlib have to be implemented. Numpy is a Python library useful to work with arrays, math is a basic Python library for general math constants and operators, and finally matplotlib is a library for creating figures and graphs in Python [1]. In figure 3.4 we show the libraries used in our program.

```
## Libraries used in this program.
# -) Numpy library: Used to work easily with arrays and math operators.
# -) Math library: Basic math library with the fundamental math operators.
# -) Matplotlib library: Python library used to plot data and make good-looking
    ->graphs.
import numpy as np
from numpy import random
import math
import matplotlib.pyplot as plt
import plotly.graph_objects as go
from mpl_toolkits.mplot3d import Axes3D
from matplotlib import cm
from plotly.subplots import make_subplots
```

Figure 3.4 – Libraries imported into the program

Once the libraries have been defined, we proceed to define the set of position vectors. Because of the geometry of the magnetic field produced, we define the region using spherical polar coordinates to simplify calculations. For  $R$  constant, we measure at a distance  $R = 1500$  mm from the origin, creating a sphere of measurements with constant radius  $R$ . These points defined in figure make a sphere with constant radius.

```
#Definition of cartesian coordinates
X=R*np.sin(theta)*np.cos(phi) #[m]
Y=R*np.sin(theta)*np.sin(phi) #[m]
Z=R*np.cos(theta) #[m]
```

Figure 3.5 – Definition of cartesian coordinates from spherical coordinates

Then we define the magnetic moment and initial positions for each coil. The magnetic moment as defined in equation 2.2.7 takes into account the current flow through the coils. The initial position vector tells where are the coils situated in the region of space.

```

#Definitions of magnetic moment for Coil 1
mx_1=0.0
my_1=0.0
mz_1=I*L**2.0
#Definitions of magnetic moment for Coil 2
mx_2=0.0
my_2=I*L**2.0
mz_2=0.0

```

Figure 3.6 – Definition of the magnetic moment for each coil

```

#Definitions of the coils initial positions (x0,y0,z0)
x0_1=0.0 #[m]
y0_1=0.0 #[m]
z0_1=0.0 #[m]

x0_2=0.0 #[m]
y0_2=-100.0*10**-3.0 #[m]
z0_2=100.0*10**-3.0 #[m]

```

Figure 3.7 – Definition of the initial positions for each coil

Now equations 2.2.11, 2.2.12 and 2.2.13 can be computed, obtaining the magnetic field  $\mathbf{B}_x$ ,  $\mathbf{B}_y$  and  $\mathbf{B}_z$ , and then plot the modulus  $|\mathbf{B}|$  in comparison with the simulated magnetic field. In figure 3.8 we show equations 2.2.11, 2.2.12 and 2.2.13 implemented in the program.

```

#Position modulus R and scalar product m*r for coil 1
R_1=np.sqrt((X-x0_1)**2+(Y-y0_1)**2+(Z-z0_1)**2)
mR_1=mx_1*(X-x0_1)+my_1*(Y-y0_1)+mz_1*(Z-z0_1)

#Position modulus R and scalar product m*r for coil 1
R_2=np.sqrt((X-x0_2)**2+(Y-y0_2)**2+(Z-z0_2)**2)
mR_2=mx_2*(X-x0_2)+my_2*(Y-y0_2)+mz_2*(Z-z0_2)

#Magnetic field Bx, By and Bz for coil 1
Bx_dip_1=k*(((3.0*mR_1*(X-x0_1))/R_1**5)-(mx_1/R_1**3))
By_dip_1=k*(((3.0*mR_1*(Y-y0_1))/R_1**5)-(my_1/R_1**3))
Bz_dip_1=k*(((3.0*mR_1*(Z-z0_1))/R_1**5)-(mz_1/R_1**3))
#Magnetic field Bx, By and Bz for coil 2
Bx_dip_2=k*(((3.0*mR_2*(X-x0_2))/R_2**5)-(mx_2/R_2**3))
By_dip_2=k*(((3.0*mR_2*(Y-y0_2))/R_2**5)-(my_2/R_2**3))
Bz_dip_2=k*(((3.0*mR_2*(Z-z0_2))/R_2**5)-(mz_2/R_2**3))

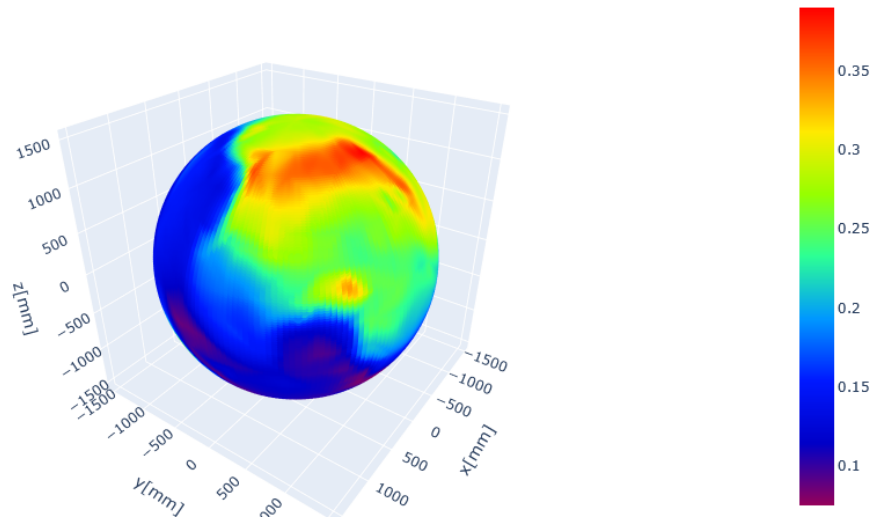
#Sum of each magnetic field for coil 1 and coil 2
Bx_dip=Bx_dip_1+Bx_dip_2
By_dip=By_dip_1+By_dip_2
Bz_dip=Bz_dip_1+Bz_dip_2

```

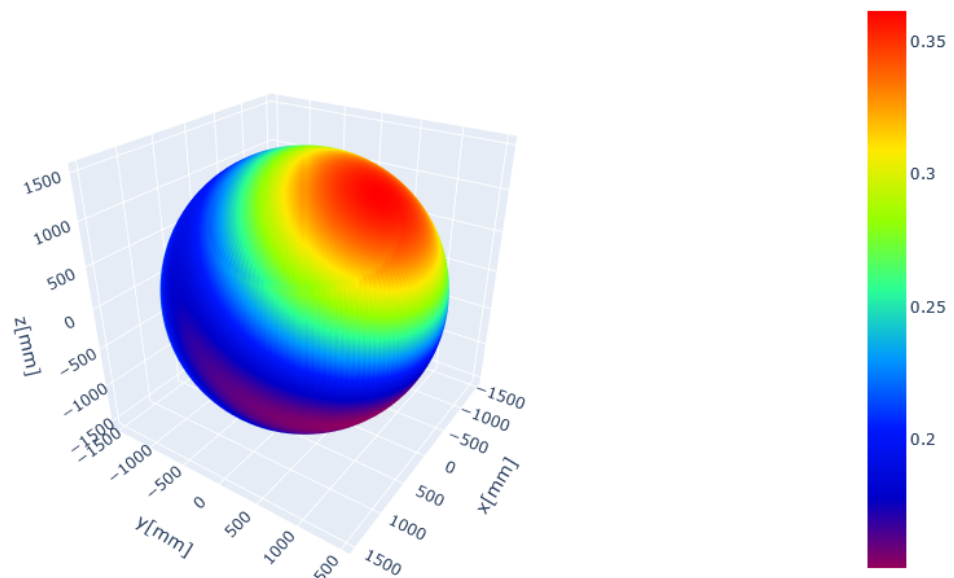
Figure 3.8 – Definition of equations 2.2.11, 2.2.12 and 2.2.13 implemented in the program

### 3.1.3 Results and discussion

The program proposed allows us to simulate the theoretical magnetic field and compare it with the simulation in the *Ansys Electronics* program. In figure 3.9 we show the magnetic field obtained in the simulator and in figure 3.10 we show the magnetic field calculated with equations 2.2.11, 2.2.12 and 2.2.13.

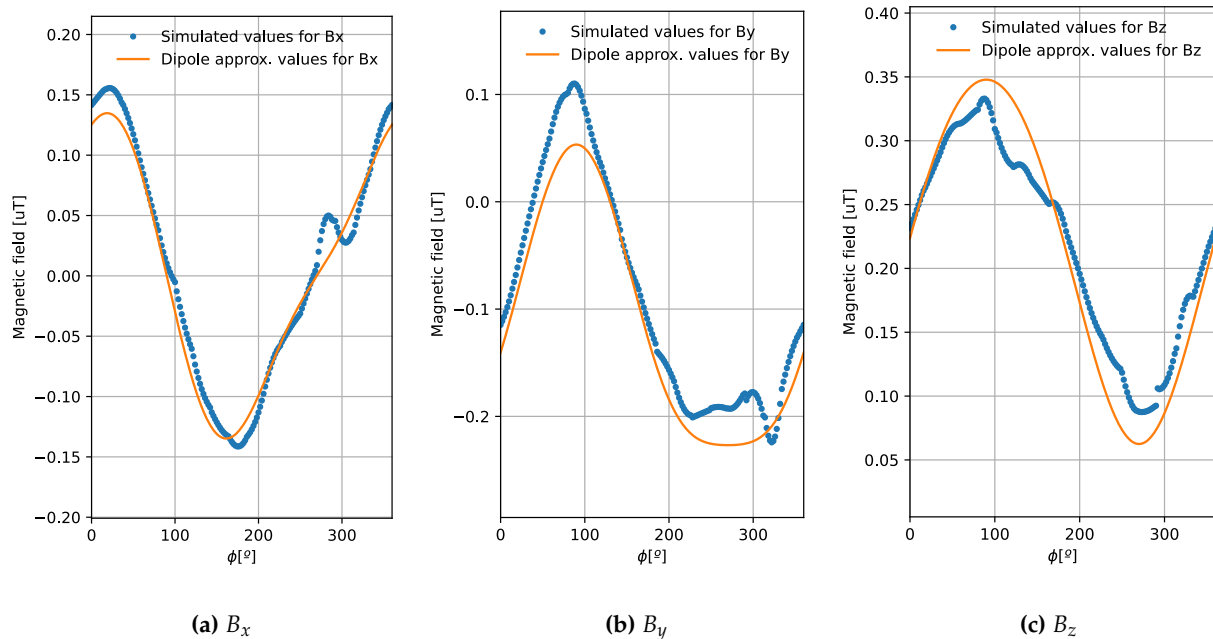


**Figure 3.9** – Magnetic field in microteslas [ $\mu T$ ] obtained with the simulator *Ansys Electronics* for a radius  $R=1500mm$ .



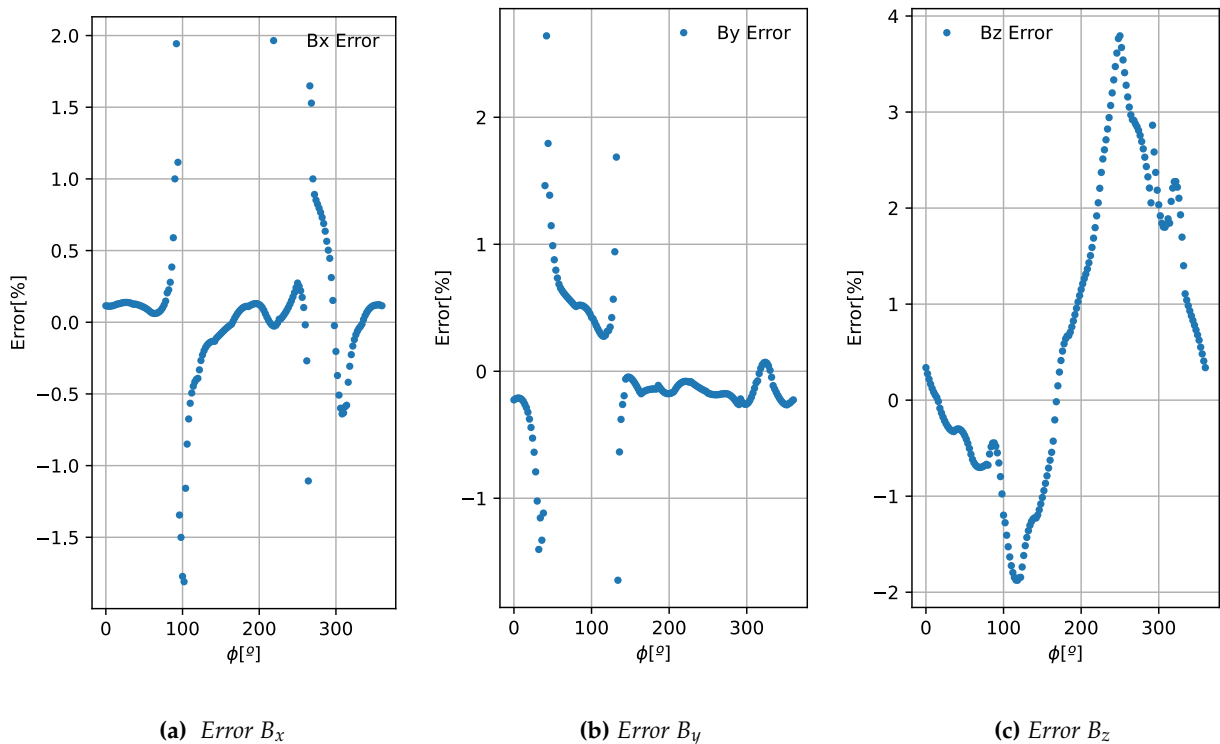
**Figure 3.10** – Magnetic field in microteslas [ $\mu T$ ] obtained with equations 2.2.11, 2.2.12 and 2.2.13 in our program.

Now, we can compare now the two results by plotting the relative error. First, in figures 3.11a, 3.11b and 3.11c we plot the magnetic field for a constant  $\theta = 20^\circ$ . Then from figures 3.12a, 3.12b and 3.12c we can see that the error between the two simulations.



**Figure 3.11** – Calculations of the magnetic field for each component  $B_x$  (a),  $B_y$  (b) and  $B_z$  (c) for  $\theta = 20^\circ$ , comparing simulated and approximated magnetic field

As we can see from figures 3.11a, 3.11b and 3.11c the magnetic field of the simulated and dipole approximation coincides and the error seen in figures 3.12a, 3.12b and 3.12c ranges from 0.1% to 4%.



**Figure 3.12** – Calculations of the error for each component  $B_x$  (a),  $B_y$  (b) and  $B_z$  (b) for  $\theta = 20^\circ$

Based on the results, we can suggest that equations 2.2.11, 2.2.12 and 2.2.13 can be used to calculate the magnetic field produced by any device. The maximum error obtained was 4%, which can be accepted taking into account the approximations made. For the rest of this paper we will use equations 2.2.11, 2.2.12 and 2.2.13 to calculate the magnetic field for each component.

## Chapter 4

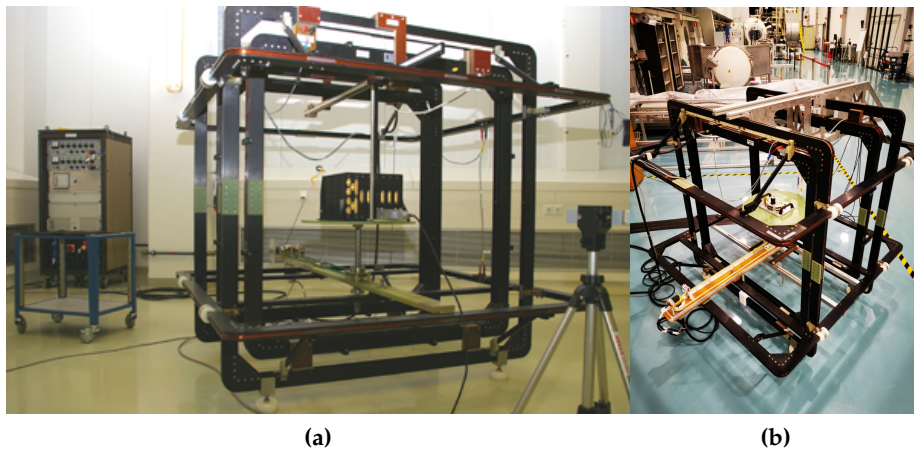
# Methodology and analysis

In this chapter we will discuss the methods used to implement the equations to calculate the magnetic moment and position for a unknown device. If we measure a magnetic field that a device produces it is possible to such magnetic field using only dipoles. This will be employed for later to take into account the magnetic field when the device is mounted in a satellite in outer space. To measure the magnetic field of a device, the Magnetic Coil Facility (MCF) is used, which is a set of coils and magnetometers that the European Space Agency (ESA) has in order to measure magnetic fields. The next section shows how the MCF works. We will show the Particle Swarm Optimization method, also referred as PSO.

### 4.1 Magnetic Coil Facility and Ulysses satellite

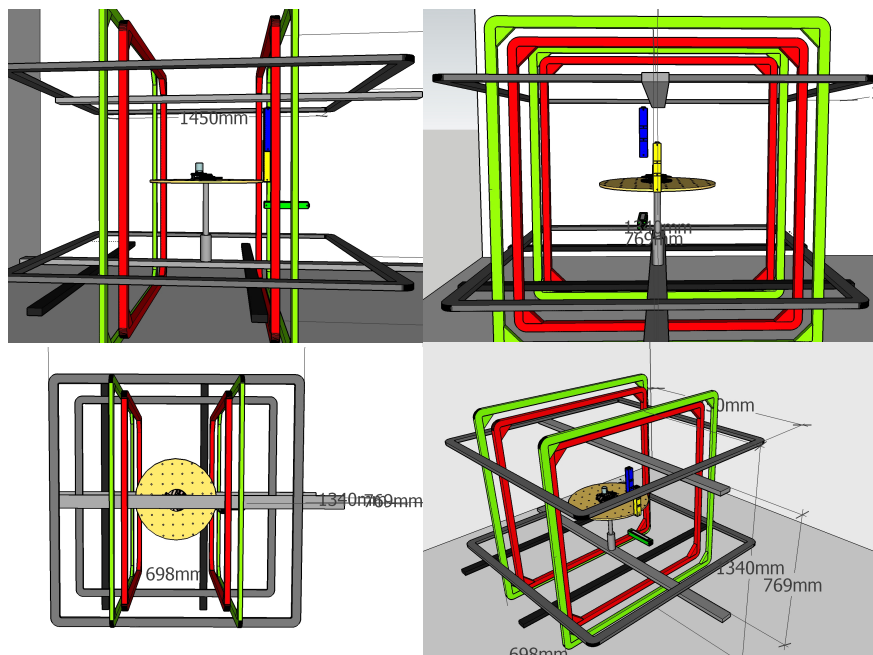
The MCF is a set of Helmholtz coils which cancels Earth's magnetic field inside the MCF. The Helmholtz coils form a cube in such a way that two coils are parallel to the ground, and perpendicular to this coils and to the ground two other coils are placed [2]. This disposition is such that inside the MCF the magnetic field is null. In figure 4.1 we can see the MCF and the disposition of the coils.

The way the MCF works is the following, each pair of coils vertical and horizontal cancel the magnetic field in its direction [2]. The later one cancels the vertical component of the magnetic field. The vertical, perpendicular to the ground, cancels the horizontal component. The other vertical set of coils are called deperm coil, and they serve to demagnetize the device once Earth's magnetic field has been cancelled [2].



**Figure 4.1** – Pictures of the MCF in the ESA facility. On the left (a) picture of the MCF at ESTEC [3] and on the right (b) picture from the project.

To cancel the magnetic field, we make a current flow through the coils in the opposite direction that want to cancel out, working similar to Helmholtz coils. First the horizontal magnetic component is cancelled and then the vertical component. Once the magnetic field is null inside the cube, we proceed to demagnetize the device with the deperm coils. In figure 4.2 we can appreciate the disposition of the coils of the MCF.



**Figure 4.2** – 3D model of the MCF made using Sketchup



#### 4.1.1 MCF orientation

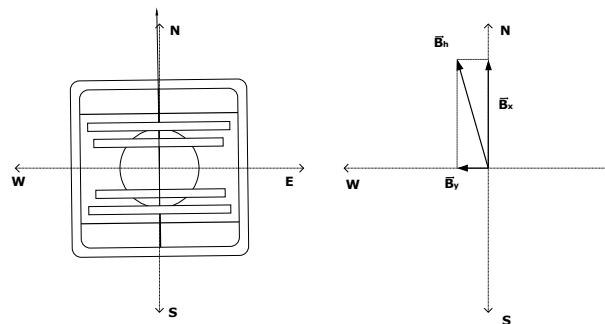
We can discuss that in the MCF lacks one set of coils. As we know, Earth's magnetic field has three components  $B_N$ ,  $B_W$  and  $B_V$ , so for each pair of coils one magnetic component is cancelled. We can ignore this discussion if we orientate the MCF in such a way that the North and East magnetic fields are cancelled at the same time. To do this we have to know the location of the MCF as Earth's magnetic field depends on the location. Considering that if the experiment was carried out in the GranaSAT's laboratories, Granada ( $37^{\circ}7'58.8''N, 3^{\circ}38'9.6''W$ ) with altitude of 700m we have to orientate  $\phi = 1.39^{\circ}$  to the East with respect to the North. To calculate the orientation of the MCF in Granada we have used the following data [12] seen in table 4.1.

Magnetic field component	Magnetic field value [nT]
$B_x$	19893.84
$B_y$	-483.16
$B_z$	24268.77

**Table 4.1** – Magnetic field values for GranaSAT's laboratories ( $37^{\circ}7'58.8''N, 3^{\circ}38'9.6''W$ ) and 700m above sea level. This calculation has been made for the year 2021 [12].

Where in table 4.1  $B_x$  is positive when facing North and negative facing South, for the same reason  $B_y$  is positive for East and negative for West and  $B_z$  positive pointing downwards and negative upwards. To calculate the horizontal component we simply find the tangent between North component and East component. So the angle of orientation is the one shown in equation 4.1.1. In figure 4.3 a drawing of how the MCF should be oriented is presented.

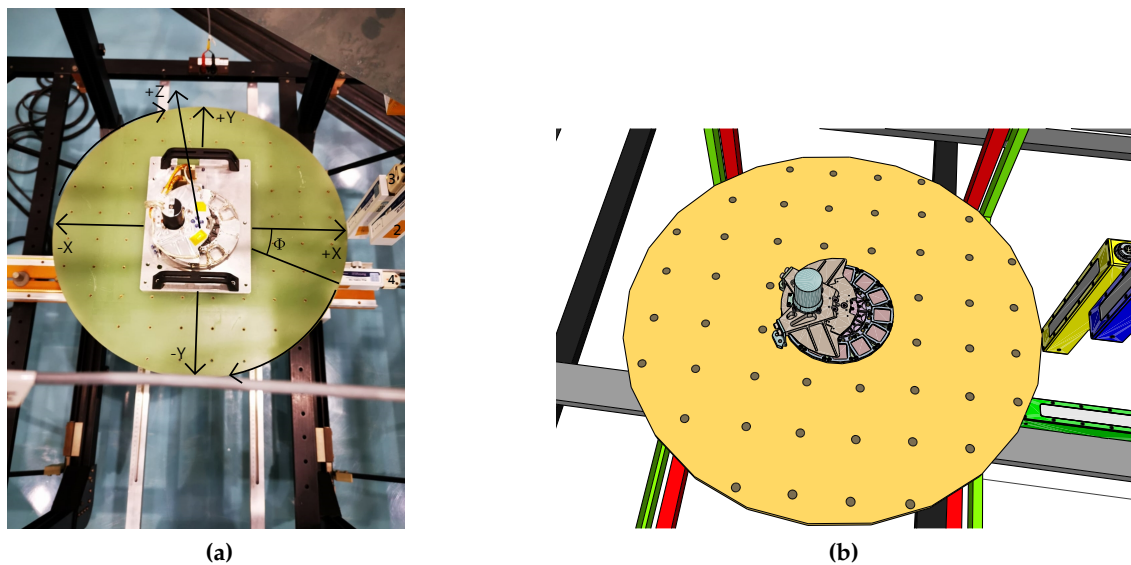
$$\alpha = \text{atan} \left( \frac{B_y}{B_x} \right) \quad (4.1.1)$$



**Figure 4.3** – Representation of the orientation of the MCF if the measurement was made in Granada and the horizontal magnetic field component.

### 4.1.2 Measuring with the MCF

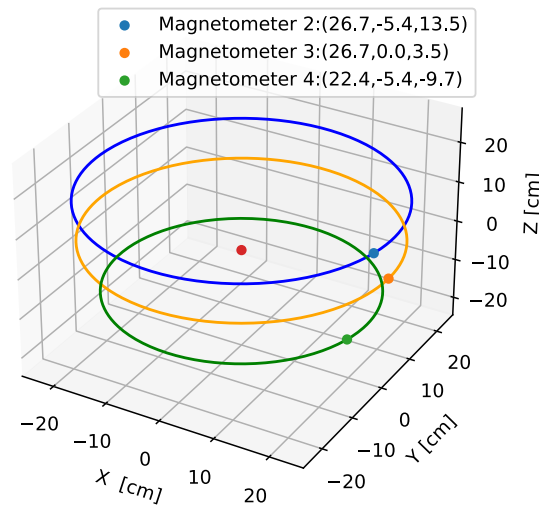
This section is dedicate to show how the MCF measures the magnetic field. To measure the magnetic field we use magnetometers which are devices responsive to magnetic fields. In this case Bartington Fluxgate Magnetometer Mag-13MS60 is used. With this magnetometers we can measure magnetic field in the three axes. The magnetometers are place inside the MCF, and on a circular tray we put the device to measure its magnetic field [2]. The magnetometers can measure in three axes but only at a local point, so to measure a circumference of points around the device we have to spin the tray. Spinning the tray once gives all the points of a circumference with constant radius. In figure 4.4a we can see a picture taken when the device was measured in the facility. In figure 4.4b we have made a 3D model of the tray and magnetometers, for the magnetometers we have used a pre-made model [6].



**Figure 4.4** – Position of the magnetometers in the MCF. On the left (a) a picture taken in the facility when the measurement was made. On the right (b) a 3D model made with Sketchup representig the filter wheel and magnetometers.

For this project, we have the measurements of a device, called filter wheel, which was used in the MCF. The aim is to optimize the magnetic field of this particular device to find the dipoles which create the same magnetic field.

For every magnetometer, we get a circumference of points with constant radius. This measurements will later be used to make the optimization and find the dipoles to simulate such magnetic field. Figure 4.5 shows the position of the magnetometers used in the MCF.



**Figure 4.5** – Position of the magnetometers used to measure the magnetic field of the filter wheel in the MCF

The magnetometers seen in figure 4.5 and 4.5 can also be moved to measure the magnetic field at different points.

## 4.2 Particle Swarm Optimization

This section is dedicated to explain the details of the Particle Swarm Optimization method or PSO. This optimization method is inspired by the movement of birds [4]. Many nature's species behave as a swarm like birds, fishes and bees to name but a few. Each individual behaves based on its location and the location of the others forming the swarm, keeping memory of the best location individually and socially. The swarm explores finding its best location depending on its objective. PSO uses this method to find the best values using a swarm of particle and each individual particle.

### 4.2.1 Velocity and position definition

We create a swarm on  $N$  particles, with initial random position and velocity. The position indicates its location in space at a time  $t$ , and the velocity indicates how fast the particle moves to the next location [4]. Once the initial swarm is created we evaluate each individual particle. Then we move each particle using equation 4.2.1.

$$v_n(t+1) = wv_n(t) + c_1r_1[x_n^{best}(t) - x_n(t)] + c_2r_2[s^{best}(t) - x_n(t)] \quad (4.2.1)$$

Where  $v_n(t+1)$  is the new velocity given to the particle  $n$  and  $v_n(t)$  is the current velocity.  $w$  is the inertia coefficient which varies the velocity of the particle making it to slow down or to accelerate.  $r_1$  and  $r_2$  are two random variables between 0 and 1. We also have  $c_1$  and  $c_2$  which

are the cognitive and social coefficients respectively. Finally,  $x_n(t)$  is the actual position of the particle,  $x_n^{best}(t)$  is the best location found individually by particle  $i$  and  $s^{best}$  is the best location found globally by the swarm. Once we have calculated the velocity of the particle we can move it to the next position  $x_i(t+1)$  with equation 4.2.2.

$$x_n(t+1) = x_n(t) + v_n(t+1) \quad (4.2.2)$$

Every time we evaluate the swarm it can happen that the velocity of a particle increases too much difficulting the convergence of the optimization [4]. To change this we make the inertia coefficient decrease linearly with each iteration. Thus the inertia coefficient depending on the iteration is the following:

$$w_n = (w_{max} - w_{min}) \frac{n_{max} - n}{n_{max}} + w_{min} \quad (4.2.3)$$

We also define a maximum value for the velocity in equation 4.2.4 to stop it from reaching high values [4].

$$v_{max} = k \frac{x_{max} - x_{min}}{2}; \quad k \in [0.1, 1] \quad (4.2.4)$$

#### 4.2.2 Fitness function definition

Now that we now how to move the particles it si possible to describe the fitness function. This function is the one that we will use to describe what we want to optimize. Depending on the problem the fitness function can be different. For our specific problem the optimization of a dipole we will use the fitness functions shown in equation 4.2.5, 4.2.6 and 4.2.7. For  $F_1$  we look for the optimum values between measured and computed field [7]. This works with values with the same or similar order of magnitude.

$$F_1 = \frac{\sqrt{\sum_{i=0}^{M-1} \left[ \left( B_x^{(meas)} [i] - B_x^{(PSO)} [i] \right)^2 + \left( B_y^{(meas)} [i] - B_y^{(PSO)} [i] \right)^2 + \left( B_z^{(meas)} [i] - B_z^{(PSO)} [i] \right)^2 \right]}}{\sqrt{\sum_{i=0}^{M-1} \left[ \left( B_x^{(meas)} [i] \right)^2 + \left( B_y^{(meas)} [i] \right)^2 + \left( B_z^{(meas)} [i] \right)^2 \right]}} \quad (4.2.5)$$

For  $F_2$  we define the least mean square for each component [7]. Finally we define  $F$  as the combination of the two fitness function [7]. This definition of the fitness function is used in the PSO method to specify the the program what optimum values we want to find.

$$F_2 = \frac{\sum_{i=0}^{M-1} \left( B_x^{(meas)} [i] - B_x^{(PSO)} [i] \right)^2}{\sum_{i=0}^{M-1} \left( B_x^{(meas)} [i] \right)^2} + \frac{\sum_{i=0}^{M-1} \left( B_y^{(meas)} [i] - B_y^{(PSO)} [i] \right)^2}{\sum_{i=0}^{M-1} \left( B_y^{(meas)} [i] \right)^2} + \frac{\sum_{i=0}^{M-1} \left( B_z^{(meas)} [i] - B_z^{(PSO)} [i] \right)^2}{\sum_{i=0}^{M-1} \left( B_z^{(meas)} [i] \right)^2} \quad (4.2.6)$$

$$F^{(n)} = F_2^{(n)} \left( \frac{F_2^{(n-1)}}{F_1^{(n-1)}} \right) + F_1^{(n)} \left( \frac{F_1^{(n-1)}}{F_2^{(n-1)}} \right) \quad (4.2.7)$$

With each iteration we evaluate the fitness function for each particle. When we find an optimum value, we store it as the best value found for the particle  $x_n^{best}(t)$ . In the same way, when we find the best value for the swarm, we keep it as  $s^{best}$ . After a number of  $N$  iterations the program will reveal the optimum value found.

For our case, we have to find six values, three for position  $(x, y, z)$  and three for the magnetic moment  $(m_x, m_y, m_z)$ . The number of particle used in our program will be 32 particles and our objective will be to find the minimum [7]. To define the velocity of the particle we define the following values:

- Number of iteration  $N$ : 700
- Maximum inertia coefficient: 1
- Minimum inertia coefficient: 0.6
- Cognitive coefficient: 1.5
- Social coefficient: 1.5

It is important to mention that the PSO code used to optimize is made by Joaquín Amat Rodrigo which his code can be found on Github [4]. We have used his Python code to implement the classes into our program and make the optimization with the PSO method.

## Chapter 5

# PSO results and discussions

We will discuss the results obtained during our work. Knowing how the MCF works and how it measures magnetic fields, we can implement the PSO method to find the optimum values for the dipole position and magnetic moment. Such dipoles imitate the magnetic field created by the device measured in the MCF.

### 5.1 Test results

To confirm that the PSO method works we can make a simple test as shown in [7]. For this, we will create a magnetic field using *Ansys Electronics 2021* simulator. This magnetic field is created by three coils acting as perfect dipoles as discussed in chapter 3. We will now describe the characteristic of this coils in table 5.1.

Coil	Radius[cm]	Magnetic Moment [mAm <sup>2</sup> ]	Position( $x_0, y_0, z_0$ ) [cm] / Plane
Coil 1	2.7	150	(0, 0, 0) / YZ
Coil 2	3.1	-200	(0, 0, 0) / XZ
Coil 3	3.0	180	(0, 0, 0) / XY

**Table 5.1** – Characteristics of three coils used to test the PSO method [7].

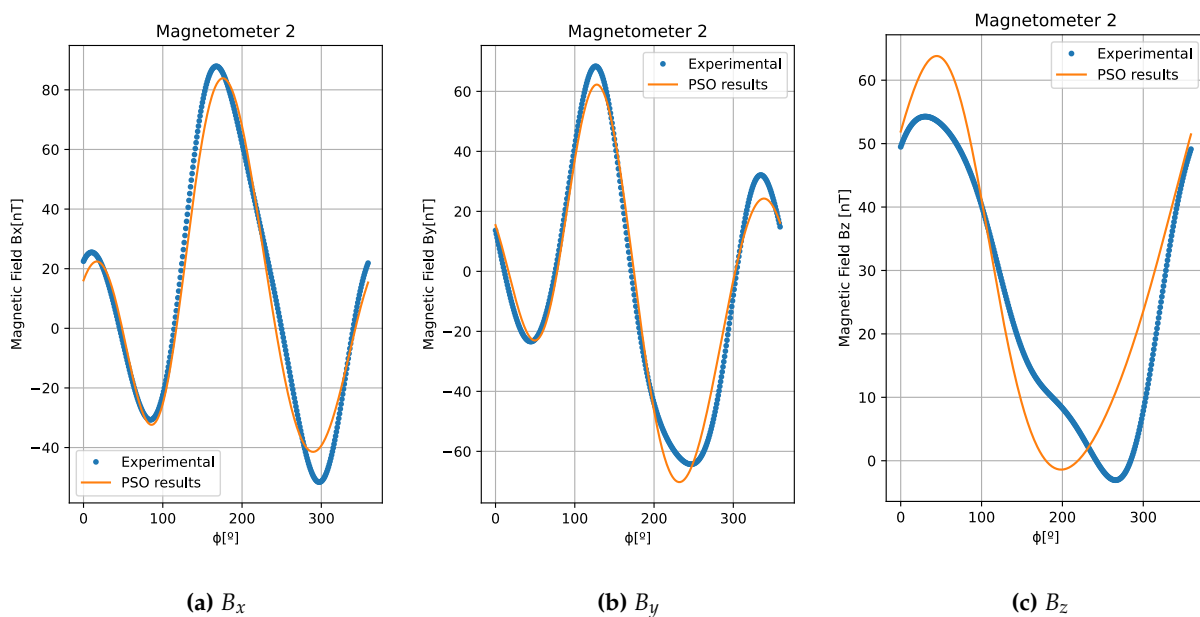
Once the magnetic field has been simulated, we can implement the magnetic field measurements into the PSO program. For this case, limits for position and magnetic moment are set. For the position vectors the limits defined are  $(x, y, z) \in [-15, 15]$ cm. In the same way, for the magnetic moment we define the limits as  $(m_x, m_y, m_z) \in [-800, 800]$ mAm<sup>2</sup>.

If we run the PSO program with the characteristics shown in chapter 4, we get that the optimum values for position and magnetic moment are  $(0.08, 2.4 \cdot 10^{-5}, 0.47)$ cm and  $(158.4, -211.2, 166.4)$ mAm<sup>2</sup>, which are the same values obtained in [7].

## 5.2 Optimization for a filter wheel

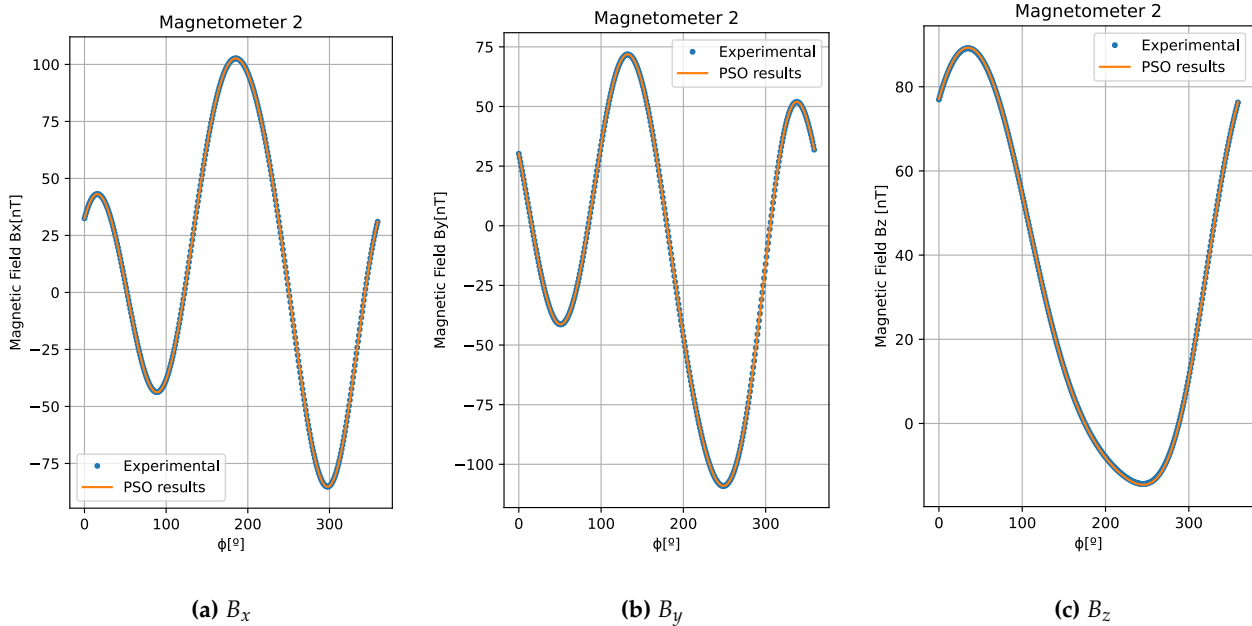
With the measurements of a filter wheel obtained experimentally in the MCF we will find the optimum values. As seen in figure 4.5 we have three magnetometers measuring  $B_x$ ,  $B_y$  and  $B_z$  field. We define as we did before the limits of exploration of our program as  $(x, y, z) \in [-25, 25]$ cm and  $(m_x, m_y, m_z) \in [-20, 20]$ mAm<sup>2</sup>.

When we run the program for a first time we get the optimum values for a single dipole  $(-0.27, 2.20, 4.33)$ cm and  $(5.64, -5.22, -8.52)$ mAm<sup>2</sup>. The values obtained are represented in figures 5.1a, 5.1b and 5.1c comparing the PSO-computed values and the experimental ones.



**Figure 5.1** – Representation of the PSO-computed values and experimental for a filter wheel measuring with Magnetometer 2

As we can see from figures 5.1a, 5.1b and 5.1c the magnetic field created by the computed dipole approximates to the experimental magnetic field. But the error is considerable due to the fact that we are simulating just one dipole. Sometimes only one dipole is not enough a complex magnetic field such as the one created by the filter wheel. To solve this problem we compute another dipole to make the correction needed. In this way we run the program for another dipole considering the magnetic field the experimental one minus the PSO-computed one. Using the same characteristic we get the following results, for position  $(3.81, 2.70, 2.03)$ cm and  $(1.73, -4.74, -2.43)$ mAm<sup>2</sup> for magnetic moment. In figures 5.2a, 5.2b and 5.2c we represent the values obtained for adding a second dipole.



**Figure 5.2** – Representation of the PSO-computed values and experimental for a filter wheel measuring with Magnetometer 2 for both dipoles

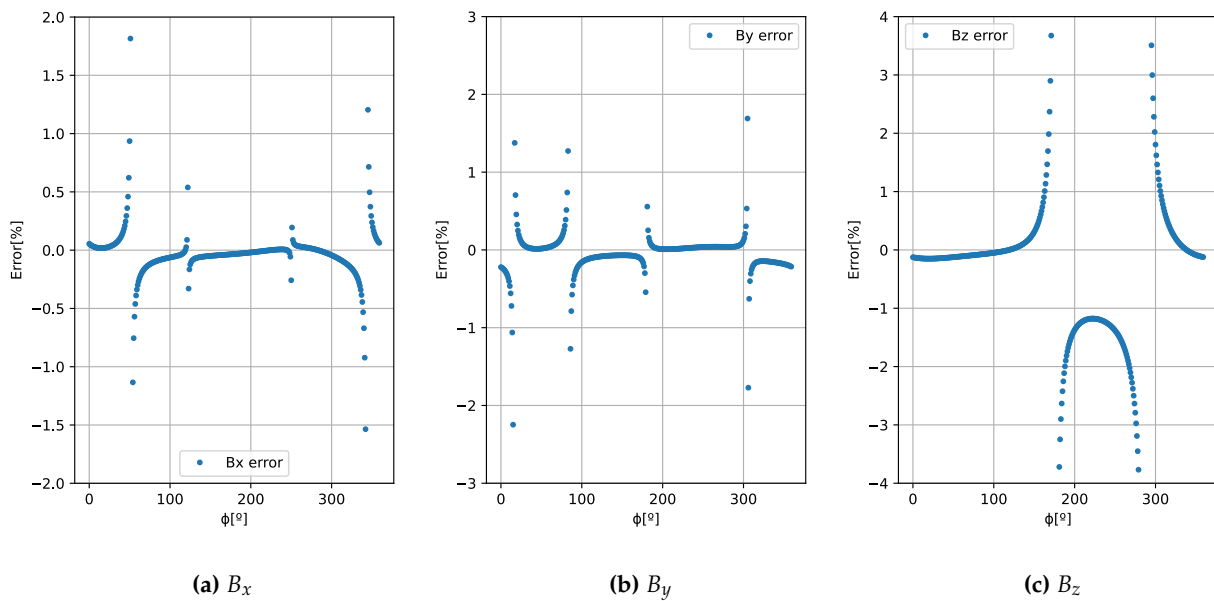
Clearly figures 5.2a, 5.2b and 5.2c show that the results coincide with the experimental ones. The error obtained is less than 4%, which is acceptable, and we can validate the PSO method for the simulations of a magnetic field produced by a filter wheel with two dipoles. Results for both dipoles are shown in table 5.2.

Dipole	Position $(x_0, y_0, z_0)$ cm	Magnetic Moment $(m_x, m_y, m_z)$ mAm <sup>2</sup>
Dipole 1	$(-0.27, 2.20, 4.33)$	$(5.64, -5.22, -8.52)$
Dipole 2	$(3.81, 2.70, 2.03)$	$(1.73, -4.74, -2.43)$

**Table 5.2** – Results obtained for position and magnetic moment for both dipoles simulated.

These results from table 5.2 serve the purpose so that it can be possible to create the same magnetic field only using dipoles. It is important to consider the magnetic field created by the device when it is placed in Ulysses satellite. In most cases devices sensitive to magnetic fields are used to measure magnetic fields [7], so the magnetic contributions created by the device in the satellite have to be taken into account when measuring solar magnetic fields [18].





**Figure 5.3** – Representation of the magnetic field error of the PSO-computed values for two dipoles.

To check the code for the two programs made for this paper one can visit them in Github. The code for the program made to test the PSO is shown in [14]. For the main program which optimizes the filter's wheel magnetic field see [13].

## Chapter 6

# Conclusions

To conclude this paper, we have state the following:

- The dipole approximation can be used to simulate a magnetic field produced by dipoles, because the error obtained when comparing empirical data with the approximation model is less than  $\epsilon = 4\%$ .
- It is important to consider the facility location, as the measurements can be affected by the orientation of the MCF.
- The PSO method has been proven to work for the calculation of position and magnetic moment of a dipole. As the values obtained are similar as those obtained previous works. However, as the PSO method is stochastic, sometimes the program has to be run a more than once to get reliable results.
- The optimization made for only one dipole is insufficient to recreate accurately the magnetic field produced by the filter wheel. Therefore two dipoles have to be employed to make corrections of the magnetic field.
- The optimization for a filter wheel using the PSO method retrieves an error smaller than 4%. Thus the method can be used to optimize magnetic fields.

Finally, to improve our program and thus the results obtained, we suggest some improvements. First, for this dissertation we have used the dipole approximation, an improvement for this would be to also consider the quadrupole approximation to obtain better results. Secondly, to optimize the running time of the program we recommend to use a python module called multithreading which can be used to run different simulations of the PSO code at the same time. This can be done by using multiple cores of the CPU. For example, we could optimize the magnetic field measured by magnetometers 2, 3 and 4 at the same time to obtain more reliable values. Finally, another suggestion to improve the results is using more dipoles.

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## Propuesta de Trabajo Fin de Grado en Física

**Tutor:** Prof. Andrés Roldán Aranda

**Departamento y Área de Conocimiento:** Dpto. Electrónica y Tecnología de los computadores

**Título del Trabajo:** **Optimizador para obtención del equivalente magnético de un pequeño satélite.**

**Tipología del Trabajo:**  
(Segun punto 3 de las Directrices del TFG aprobadas por Comisión Docente el 10/12/14)

(Marcar con X)

1. Revisión bibliográfica		4. Elaboración de nuevas prácticas de laboratorio	
2. Estudio de casos teórico-prácticos		5. Elaboración de un proyecto	
3. Trabajos experimentales	X	6. Trabajo relacionado con prácticas externas	

### Breve descripción del trabajo:

La medida de las características magnéticas de los productos electrónicos que forman un pequeño satélite es muy necesaria para conocer el comportamiento del satélite cuando esté en el espacio profundo. Para ello en la Agencia Espacial Europea y la NASA se usan modelos magnéticos simplificados que se componen para conocer el comportamiento magnético completo del satélite.

Esta técnica es más importante cuando se trata de una parte de un satélite [1] que debe soportar el **boom** donde se realiza la medida del campo magnético exterior cercano a un planeta. Los subsistemas del satélite deben estar caracterizados para que a partir de la medida 3D del campo exterior y descontando lo aportado por el satélite, se pueda medir con precisión el campo magnético existente en un punto del espacio.

El alumno usando Python, ver figura 1, implementará el método de modelado descrito en [2] .

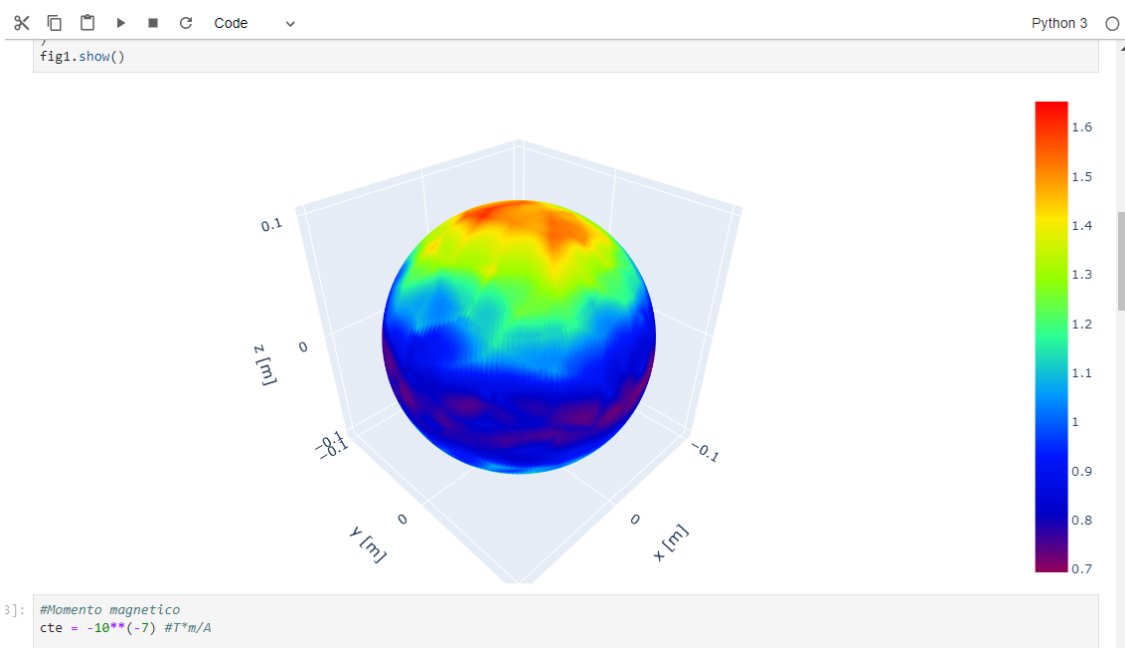


Figura 1. Modelado de un dipolo magnético usando Python.



**Objetivos planteados:**

- Se implementará el método de optimización de momentos magnéticos del artículo.
- Se realizarán simulaciones magnéticas para comprobar que la implementación funciona.

Es estudiante se integrará en el equipo del Grupo de Electrónica Aeroespacial de la UGR.  
Se busca estudiante interesado en aplicaciones experimentales con vocación de trabajo en equipo.

**Metodología:**

El alumno comenzará el trabajo leyendo la documentación que el tutor tiene preparada donde se describen las técnicas de modelado, simulación y medida. Para el análisis vectorial [2] previo se usarán los notebook de [Jupyter-Lab](#) en Python.

Se recomienda contactar con el tutor ([amroldan@ugr.es](mailto:amroldan@ugr.es)) al recibir la confirmación de asignación del TFG.

**Bibliografía:**

- [1] [ECSS-E-ST-20-07C-Rev1](#) - 7 February 2012.  
[2] Particle Swarm Optimization for Multiple Dipole Modeling of Space Equipment, Elisa Carrubba, Axel Junge, Filippo Marliani, and Agostino Monorchio IEEE TRANSACTIONS ON MAGNETICS, VOL. 50, NO. 12, DECEMBER 2014  
[2] [Magnetic Moment easy measurement](#).

Pinchar [aquí](#) para ver otros TFG anteriores realizados por alumnos del Grado en Física bajo mi tutoría.

***A rellenar sólo en el caso que el alumno sea quien realice la propuesta de TFG***  
*Alumno/a propuesto/a:*

Granada, 6 de mayo 2020

Sello del Departamento