Hochschule Wismar
University of Applied Sciences
Technology, Business and Design
Fakultät für Ingenieurwissenschaften,
Bereich Electrotechnik und Informatik

Master - Thesis

Development of a Technique and software to derive differential absorption and Faraday rotation from raw data of the wave propagation sounding rocket experiment.

Master of Engineering (M.Eng.)

Course of Graduation : Information and Electrical Engineering.

1. Supervisor : Prof. Dr.-ing. habil Andreas Ahrens
(Hochschule Wismar)

2. Supervisor : Dr.Boris Strelnikov
(Leibniz Institute of Atmospheric Physics)

Author : Mr.Aditya Kapadi
Matr.No: 271598

Date of Birth : August 11,1995

Born in : Vadodara, India

Date of Submission : November 28, 2019

Declaration of Author

I, Aditya Kapadi, declare that this thesis titled, **"Development of a Technique and software to derive differential absorption and Faraday rotation from raw data of the wave propagation sounding rocket experiment"** and the work presented in it are my own. I confirm that :

- This work was done wholly, while in candidature for a Master degree at this university.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. this thesis is entirely my own work.
- I assured you that neither this, nor a similar work has been presented to another examination committee.

Signature:

Date:

Master of Engineering (M. Eng)

Development of a technique and software to derive Differential Absorption and Faraday Rotation from raw data of the wave propagation sounding rocket experiment.

Proceeding

In this thesis the main motive is to compare these "wave propagation" (WP) signals with the known rotation of the rocket, i.e.defined sin. From the comparison one has to derive phase shifts for every evolution of the payload. Additionally, one has to derive amplitudes of the signal (i.e max and min value per revolution).

The measurement principle of the absorption is that, when we transmit the electromagnetic wave from the ground transmitter the receiving antenna receive the signal and after lift-off the rocket at 60 s receiving antenna start to acquire the signal.

As per shown the raw data in the fig.(3.3) there are 4 different frequencies are given. As the fig.(3.3) demonstrates the frequency 1.300 MHz it shows when the receiver open at 60 s after lift-off signal acquires and after that absorption started and gives the total reflection for the signal.

After describing the raw data and applying the Faraday rotation and differential absorption we need to use signal processing techniques to obtain the final output.

On the other hand the given calibration data which is already measured from the Faraday box 13(b) and we expected the linear output for the calibration data but to make it linearised we need to use calibration curve.

Additionally, the raw data has contain gaps between the data so to fulfill the data gaps we need to use interpolation. Afterwards ,to fit the calibration data point in a linear form we used curve fitting and as we earlier used cubic spline interpolation it has given us the lower degree polynomial order which helps us to fit the calibration data into linear form it is also called as Polyfit function.

Though, the given spin frequency of rocket is 3.27 Hz and when we compared the both data, we could measure the minimum and maximum amplitude and eventually we can derive the phase shifts for every revolution of the payload and amplitude difference of the signal (i.e max and min value per revolution).

Complications

While developing a technique and software for signal processing of the raw data acquired by the wave propagation rocket experiment there are vital complications which are described below :

- Meanwhile in the python programming there are lot of noisy WP- signals has taken place in the given raw data.
- During the raw data processing it seems that there are data gaps in (WP - signals) it because of the broken time-series. To deal with this crunch we have applied a signal processing technique called "Interpolation" (Cubic-spline).
- On the other hand, the measured calibration data is not in linear so the calibration data points has been taken and generate the calibration curve.
- Subsequently, due to the data gaps in WP- signals there are singularities in WP-signals and it generates standing - wave influence, which can make signal to change it's periodicity.
- Once again a signal processing technique is used to fit this calibration curve, it is called "curve fitting". But here we used polynomial function because it gives the lowest polynomial degree for the data and it exactly fit to the data series which has generated.
- When, we have compared the spin frequency with interpolated data it has detected the minimum and maximum values (points) but there are not always present.

- We should smooth and filter the data to improve the data quality and remove the unwanted noise so we can obtain minimum and maximum values(points).

- After successful realization of above mentioned signal processing techniques it has estimated the errors and derived the final output of this thesis and these are Phase shift and Amplitude difference. But, to gain the phase shift and amplitude difference we have taken the time difference and amplitude difference which were generated from minimum and maximum values.

Contents

Chapter 1

Preface

The state of atmosphere near the ground has been monitored and recorded for almost two centuries.([[11]])

Satellite observations only cover perhaps 20-30 years, but electron densities and their effect on radio wave propagation have been studied for over 80 years.

The electron densities of the mesosphere and lower thermosphere (the D- and E-region) are best studied using sounding rockets which are only available to the scientific community since the late 1940's ([[13]])([[8]]).

The thesis is about the data processing to derive the Faraday rotation and differential absorption using various signal processing techniques. In Radio wave propagation Faraday rotation and differential absorption are the method which is used to measure the electron density.

In addition with, this thesis discusses the technique which is used to measure electron density in the lower portion if the ionosphere. The technique combines wave propagation sounding rocket experiment to derive Faraday rotation and Differential absorption.

A method of processing the wave propagation data with the technique of Faraday rotation (Differential phase) based on the generalised Magneto ionic theory for analyzing the Faraday rotation.

1.1 Atmosphere

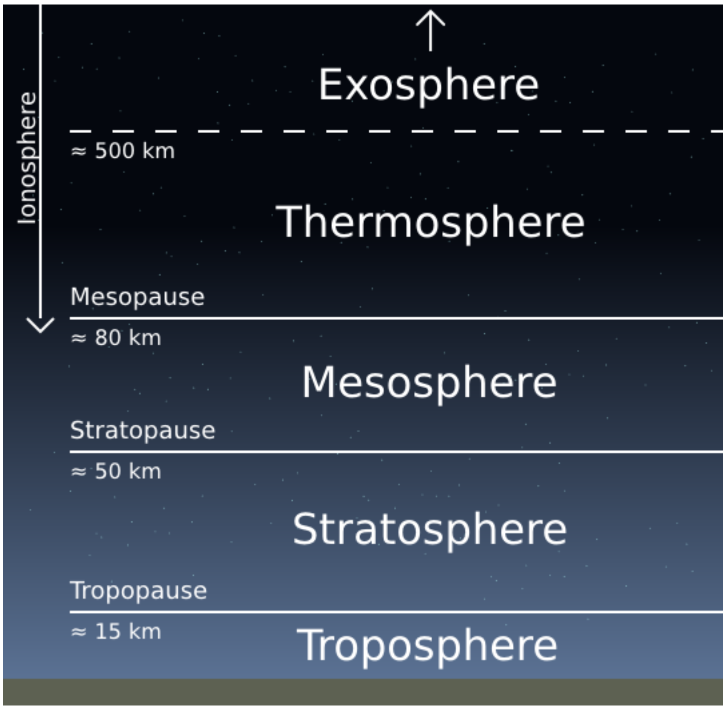

Figure 1.1: Atmospheric Layers.([[1]])

The Atmosphere is divided into layers according to major changes in temperature. (See.fig.1.1)it initiates from 80 km above the surface and extends to 400 km ([[15]]).

The lowest layer of the atmosphere is called troposphere.It ranges in thickness from 8 km at the poles to 16 km over the equator ([[2]]).

The stratosphere defines a layer in which temperature rises with increasing altitude.It occupies the region of atmosphere from about 12 to 50 km.([[2]]).

Temperature in the mesosphere drop with increasing altitude to about 100°C.The mesosphere is the coldest of the atmospheric layers.([[2]]).

The thermosphere,from 80 to 550 km above the Earth's surface. Within the thermosphere temperature rise continually to well beyond 1000°C.([[2]]).

1.2 Ionospheric Regions

The ionosphere is a continually changing area of the atmosphere. Extending from altitudes of around 50 km to more than 600 km it contains ions and free electrons. The free electrons affect the way in which radio waves propagate and in this region they have a denoting effect on HF radio communications([[19]]).

The ionosphere forms because of Solar radiation ionizing to the outer atmosphere.Ultraviolet radiation is most pledged for ionization in the outer atmosphere ([[3]]).

(Fig.1.2) shows that the ionosphere is a charged environment where the air is sufficiently ionized and the ionization is done by both electromagnetic radiations and particles coming from the Sun ([[2]]).

Due to the ionization, the Earth's upper atmosphere (ionosphere) gets consist of free electrons and ions. The reason for the presence of free electrons in the ionosphere is that at these altitudes the density of the Earth's neutral atmosphere is sufficiently low that collisions between particles happen far less frequently than in the lower atmosphere. So, the free electrons live much longer before they got recombined ([[2]]).

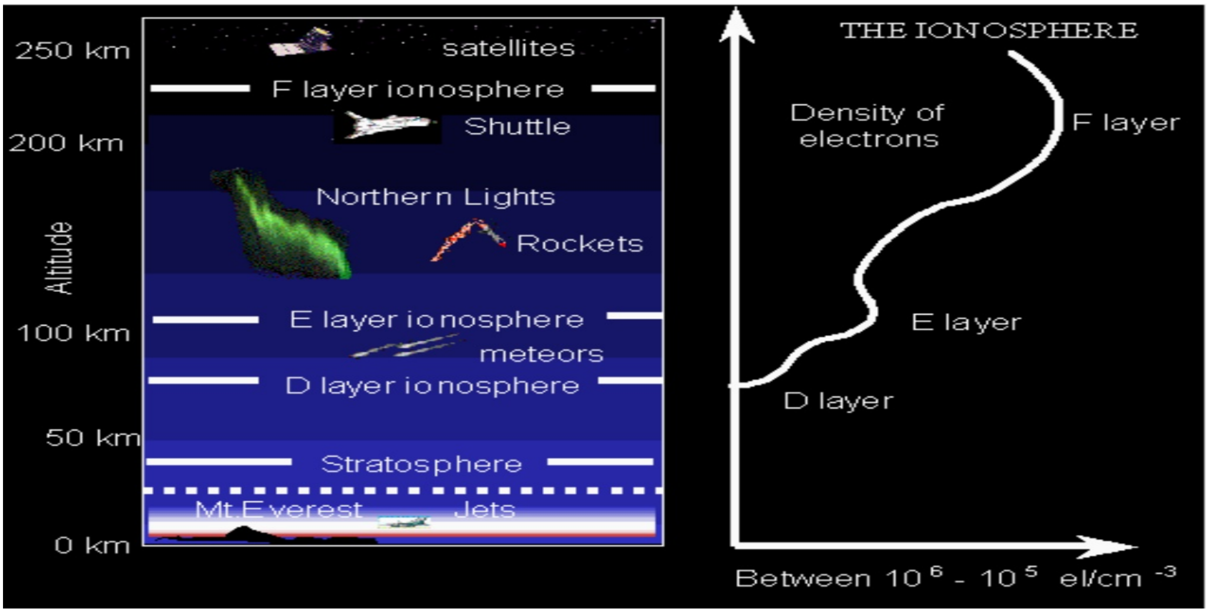

Figure 1.2: Relationship of the atmosphere and ionosphere.([[1]])

1.3 Layers of Ionization

The ionosphere posses varying rate of absorption of EUV (extreme ultra violet) radiations by different atoms/molecules. Resultantly, different ionization layers are formed. which are called as D, E, F1 and F2 layers ([[2]]).

These variations are of two general types:

1. Those which are more or less regular and occur in cycles and, therefore, can be predicted in advance with reasonable accuracy.

2. Those which are irregular as a result of abnormal behavior of the sun and, therefore, cannot be predicted in advance. Both regular and irregular variations have important effects on radio wave propagation ([[4]]).

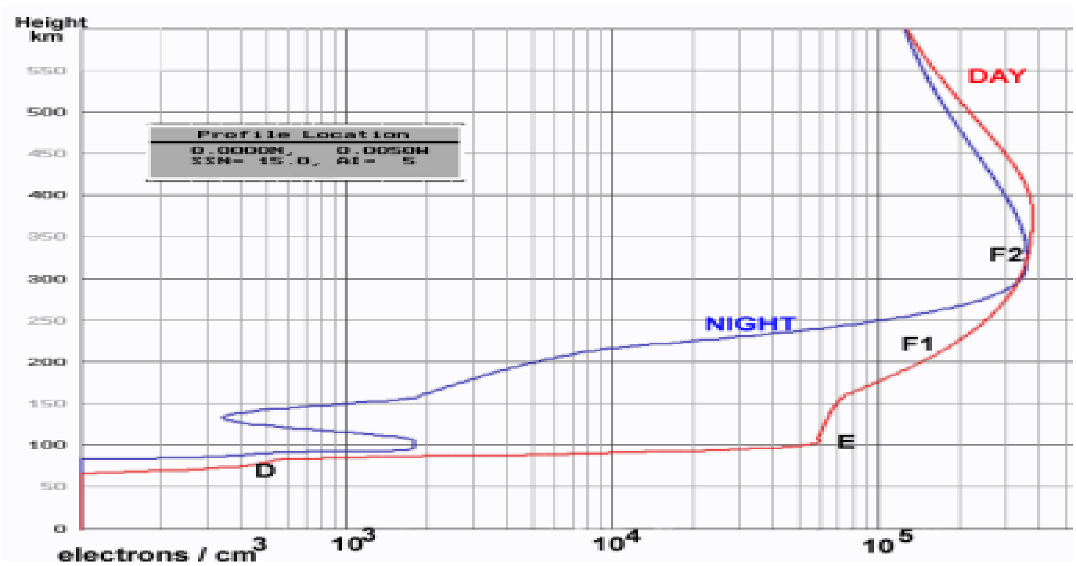

Figure 1.3: Ionospheric Layers during Night and Day.([[1]])

- **D** -Layer: The D- layer is located, lowest among the layers and it does not have any exact starting point. It is characterized by small ion densities and high collision frequencies of electrons and ions with the neutral particles. Hence, it has low values of neutral temperature, ion temperature and electron temperature ([[2]]).

This layer exists mainly during the day and disappears at night which allows radio waves to penetrate into a higher level of ionosphere ([[2]]).

- **E** layer : The E layer is above the D layer. it exists at altitudes between about 100 km and 125 km. This layer can only reflect radio waves having frequencies less than 10 MHz. Despite, during the intense sporadic E events, the layer can reflect frequencies up to 50 MHz. In the E-layer, neutral temperature and ion temperature are nearly the same while the electron temperature starts to deviate to higher values during the day time. At night the E layer begins to disappear because the primary source of ionization is no longer present. This region is also known as the Kennelly - Heaviside layer([[19]]).

- **F** layer : The most important region in the ionosphere for long distance HF radio communications in the F layer. It is 120 Km to 400 Km above the surface of the Earth ([[2]]). It is the top most layer of the ionosphere. During the day time when it received the radiation from the Sun, it divides into two layers: the lower is the F1 and the higher one the F2. F1 layer is found at around 300 Km with the F2 layer above it at 400 Km ([[19]]).

  Although changes happen in the F-layer during day time but still it remains constant relative to other layers and extreme ultra violet radiations absorbed here. The F2 layer is more electron dense than F1 layer. The peak density of electrons in F1 layers is at about 200 km, which is more pronounced in summer and during high Sun spot numbers. The F2 layer exists both at day and night. The F layers are responsible for most of the sky wave propagation of radio waves ([[2]]).

Chapter 2

Theory Background

2.1 Radio and Wave Propagation

Radio propagation is the behavior of radio waves as they travel from one point to another part of the atmosphere. There are various modes in propagation Direct modes,Surface modes and Ionospheric modes ([[14]]).

The ionosphere consists of charged ions and electrons. The ionosphere do not behaves like a pure gas because the number of ionized particles is very large there. hence it is reasonable to consider it as fourth state of matter i.e plasma. Ionospheric plasma is one of the closest naturally occurring plasma. The Ionospheric plasma is defined in terms of four main parameters like electron density, electron temperature, ion temperature and ionic composition ([[2]]).

The theory of radio wave propagation (See fig. 2.1) in a magneto-plasma is characterized by e.g Sen and Wyller(1960) but, a quite more summarized by Friedrich et al. (1991). In both refractive indices the real part regulate the phase velocity and imaginary parts conduct absorption ([[12]]).

The application of the radio propagation technique for rocket experiment was first developed by SEDDON (1953).The use of radio propagation experiments on rockets to study the D region and lower E region of the ionosphere ([[16]]).

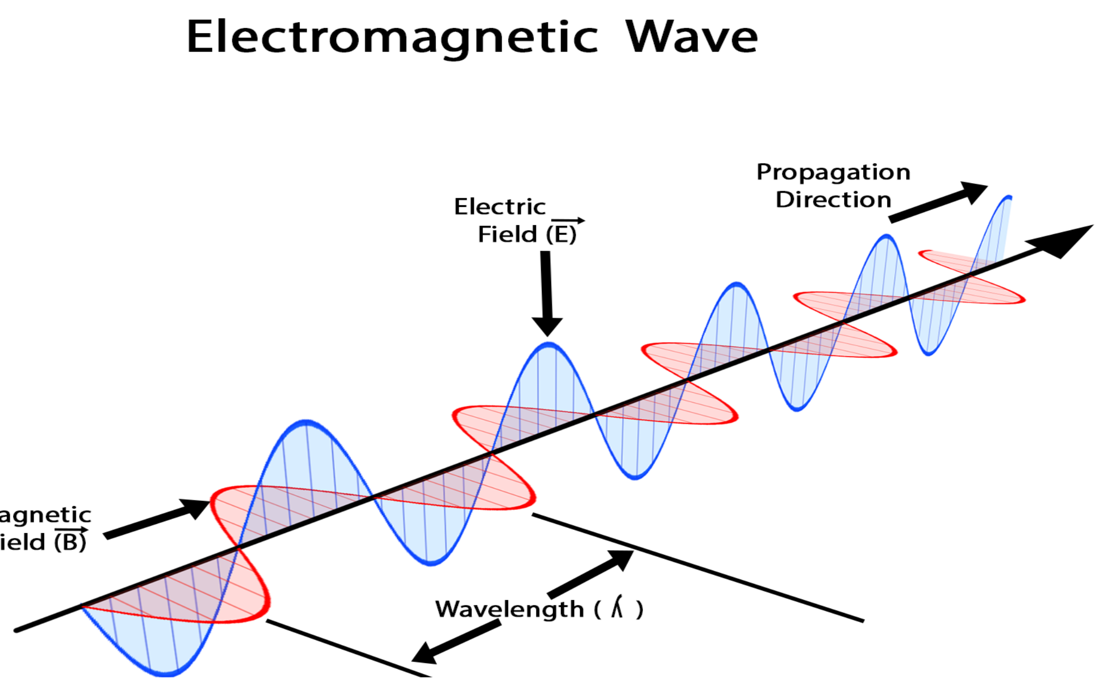

Figure 2.1: Wave Propagation ([[1]]).

They aim to derive absolute electron density at altitudes which are only accessible by sounding rockets. Within these constraints the earliest measurement by a rocket borne radio wave propagation method was in 1947 (Jackson, 1954).

2.2 Different Modes of propagation

There are different modes of wave propagation which take part while passing the electromagnetic wave through the ionosphere.

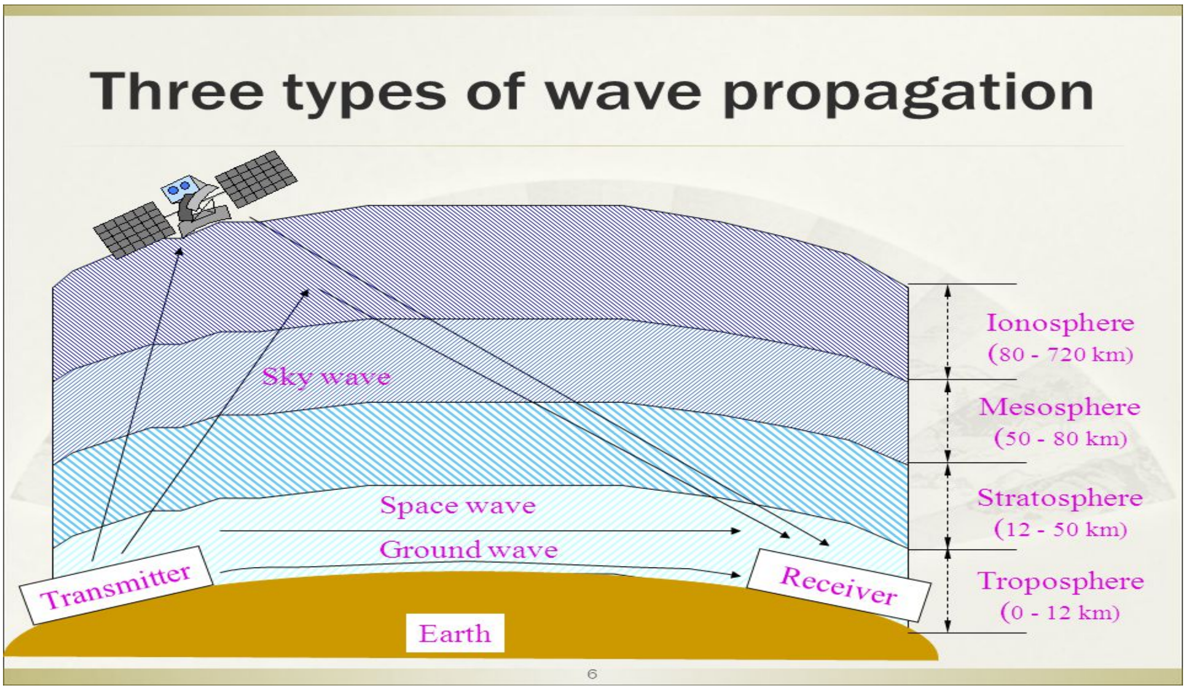

Figure 2.2: Types of Wave Propagation.([[1]])

1. **Direct Modes:** It is a propagation of waves traveling in a straight line.On the earth surface,line of sight propagation is limited by skyline which is (64 Km) ([[20]]). Most of frequencies used are as HF, VHF and UHF. It is mostly used in applications like are Satellite and Mobile communication (See fig:2.2).

2. **Surface Modes:** In this mode it can work on VLF, LF and MF. Because of low frequency vertically polarized waves can travel as surface waves and follow the curve of earth; this is also called ground wave propagation.These frequencies are use for Submarine and Military communication ([[20]]).

3. **Ionosphere Modes:** This is the propagation of radio waves refracted back to Earth's surface by the ionosphere. The HF range can be upto 30 MHz. It is forecasting sky wave so it is used in Microwave link and Radar communication ([[20]]).

2.2.1 Wave Propagation Losses

There are three types of wave propagation modes which are described in 2.2. But after passing the electromagnetic wave there are also some losses in it. It is called Wave propagation losses.

- **Absorption:** At high frequency, absorption by molecular resonances in the atmosphere is a major factor in radio propagation.
- **Attenuation:** When the distance is double, the signal turns into half less strong. Whereas, receivers are placed in between as a obstacles it has to travel around the earth; thenceforth radio waves lose their energy and forced to bend to follow the earth's angle.
- **Diffraction:** It is the propagation mode where radio waves are bent around the sharp edges it is also called as knife-edge diffraction. A spot located out of sight from a transmitter, but it receives weak transmission because it's signals are bending constantly by diffraction and it can reach to the remote receiver.

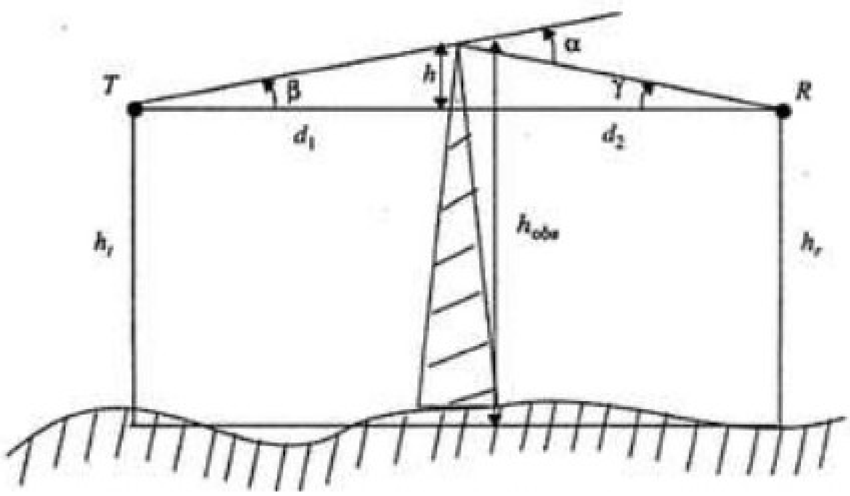

Figure 2.3: Knife-edge diffraction geometry.The point T denotes the transmitter and R denotes the receiver,with an infinite knife-edge obstruction blocking the line-of-sight path.[[[2]])

- **Scattering:** It is a physical process in some form of radiation are forced to fluctuate of reflected radiation from the angle predicted by the specular reflection.([[23]])([[22]])

2.3 Faraday Rotation

Physical interpretation of Faraday effect :

The linear polarized light that is seen to rotate in the Faraday effect can be seen as consisting of the superposition of a right- and a left- circularly polarized beam.

In a circularly polarized light the direction of the electric field rotates at the frequency of the light, either clockwise or counterclockwise (See fig:2.4).

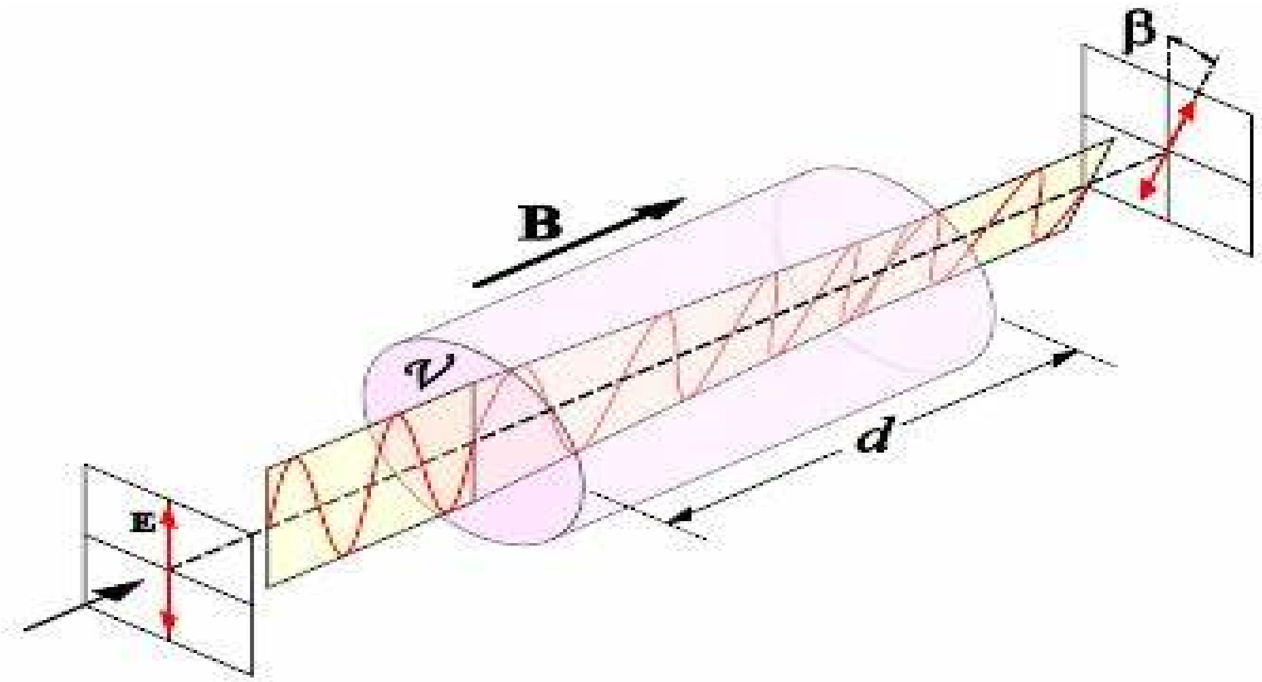

Figure 2.4: Polarization rotation due to Faraday effect.([[1]])

Faraday effect with ordinary and extraordinary waves :

When propagating through ionosphere two waves differ in absorption and the phase velocity. This difference causes the resultant wave which is polarized and it will become elliptically polarized ([[7]]).

Resulting elliptically polarized with the major axis rotates as the wave propagates. This rotation of plane is called Faraday Rotation ([[16]]).

The Faraday rotation angle F is :

$$\frac{dF}{ds} = \frac{\omega}{2c}(\mu_0 - \mu_x) \tag{2.1}$$

$where,\ \omega = is\ the\ angular\ frequency,\ of\ transmitter$

$\mu_0, \mu_x = are\ the\ real\ parts\ of\ the\ ordinary\ and\ extraordinary\ refractive\ indices,$

$s = is\ the\ slant\ range\ from\ the\ ground\ transmitters\ to\ the\ rockets,$

$c = is\ the\ velocity\ of\ light.$

For the low collision frequencies Faraday rotation is proportional to electron density, but for larger collision frequencies the proportionality decreases. ([[10]])

$$\nu_c = \sqrt{\omega^2 - \omega_c^2 cos^2\theta} \tag{2.2}$$

$where\ , \nu_c = collision\ frequency,\ \omega_c = gyro\ frequency.$

$\theta = angle\ between\ magnetic\ field\ \overrightarrow{B}\ and\ propagation\ direction\ \overrightarrow{S}.$

2.3.1 Differential Absorption

Absorption, in wave motion, the transfer of the energy of a wave to matter as the wave passes through it. The energy of an electromagnetic or other wave is proportional to the square of its amplitude.

A technique for the wave propagation experiment, in which transmit the electromagnetic wave into the atmosphere.The upper part shows how higher and lower amplitudes shrink and gives the envelope and obtain differential absorption. But this absorption is happened due to the plasma effect. Whereas we look to the down part of the figure it generates the phase (i.e define sin) during the Faraday rotation.

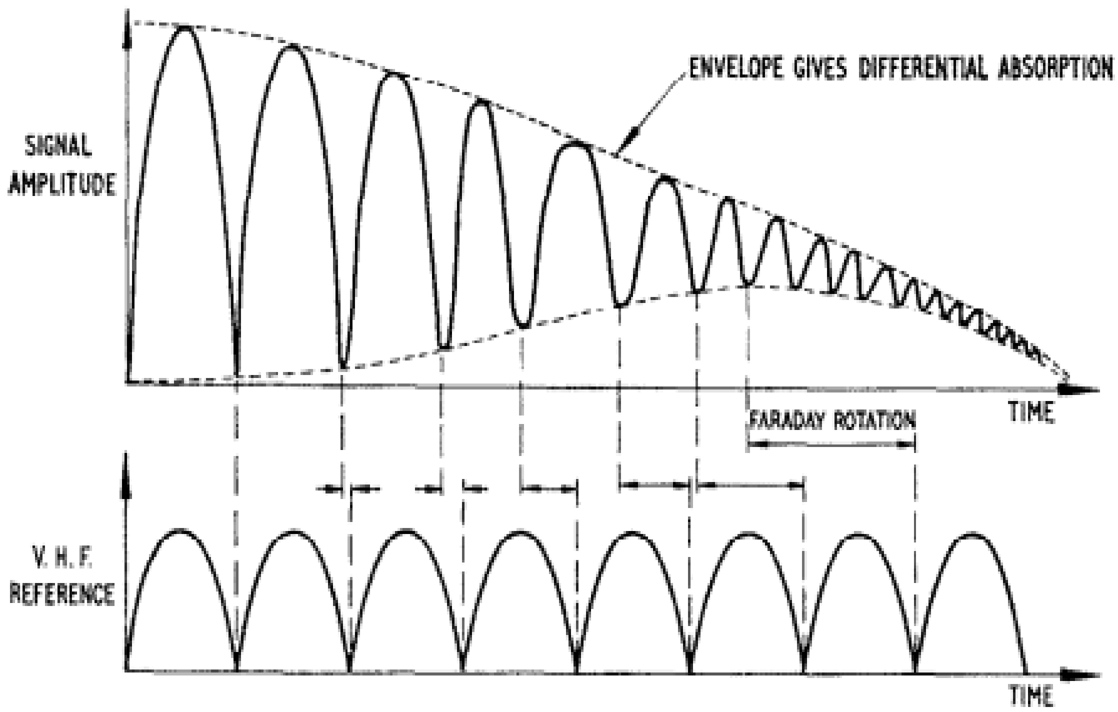

Figure 2.5: received rocket signal emphasize the measurement of Faraday rotation and Differential absorption. ([7])

(Fig:2.5) shows that signal amplitude is changing due to the absorption and the envelope which gives the differential absorption it has changed the amplitude differently that shows one is strong and another one is less stronger.

Hence,the effect on the modulation of the signal received at the spinning rocket is a contraction in the depth of modulation. This event occurs synchronously with the Phase shift of the Faraday rotation.([[16]])

When the amplitude changes respectively and make envelope it shows the absorption and due to the absorption the phase is generated at very high frequency and it shows another technique which is Faraday rotation but there are also other techniques like are phase shift and amplitude difference (with the minimum and maximum points) to measure Electron density.

2.3.2 WADIS 2

The sounding rocket WADIS 2 (Wave Propagation and Dissipation in the Middle Atmosphere) project of the Leibniz Institute for Atmospheric Physics (IAP) in Kühlungsborn with the support of the German Aerospace Center ([[5]]). On 5 March 2015 at 2:44 pm Central European Time, the WADIS-2 sounding rocket from the Andøya Space Center launched nine experiments aboard into the night sky over Norway ([[5]]).

In addition, 13 small, simple "Loki-Dart weather beacons" were launched, measuring pressure and temperature in the days before and after the WADIS launch, to allow for a larger weather environment.

The WADIS 2 rocket weighing a total of 1,550 kilograms reached a height of around 126 kilometers. During the flight, the experiment sensors determined air pressure, temperature, electrical charges as well as density changes in the atmosphere ([[5]]).

These changes in air density, so-called gravity waves, can be measured in terms of temperature, pressure and wind fluctuations. They occur, for example, where wind currents near the ground encounter an obstacle, such as a massif, and these disturbances continue up to a height of 80 kilometers.

WADIS 1 and WADIS 2 both were launched in different period (Summer and Winter). From a scientific point of view, this difference is very important because the atmosphere is then in different states ([[5]]).

There are so many different techniques to measure electron density but only wave propagation experiment will give the absolute values :

This experiment includes different techniques which are,

- **Faraday rotation**
- **Differential absorption**

Chapter 3

Experimental Techniques

3.1 Experiment description

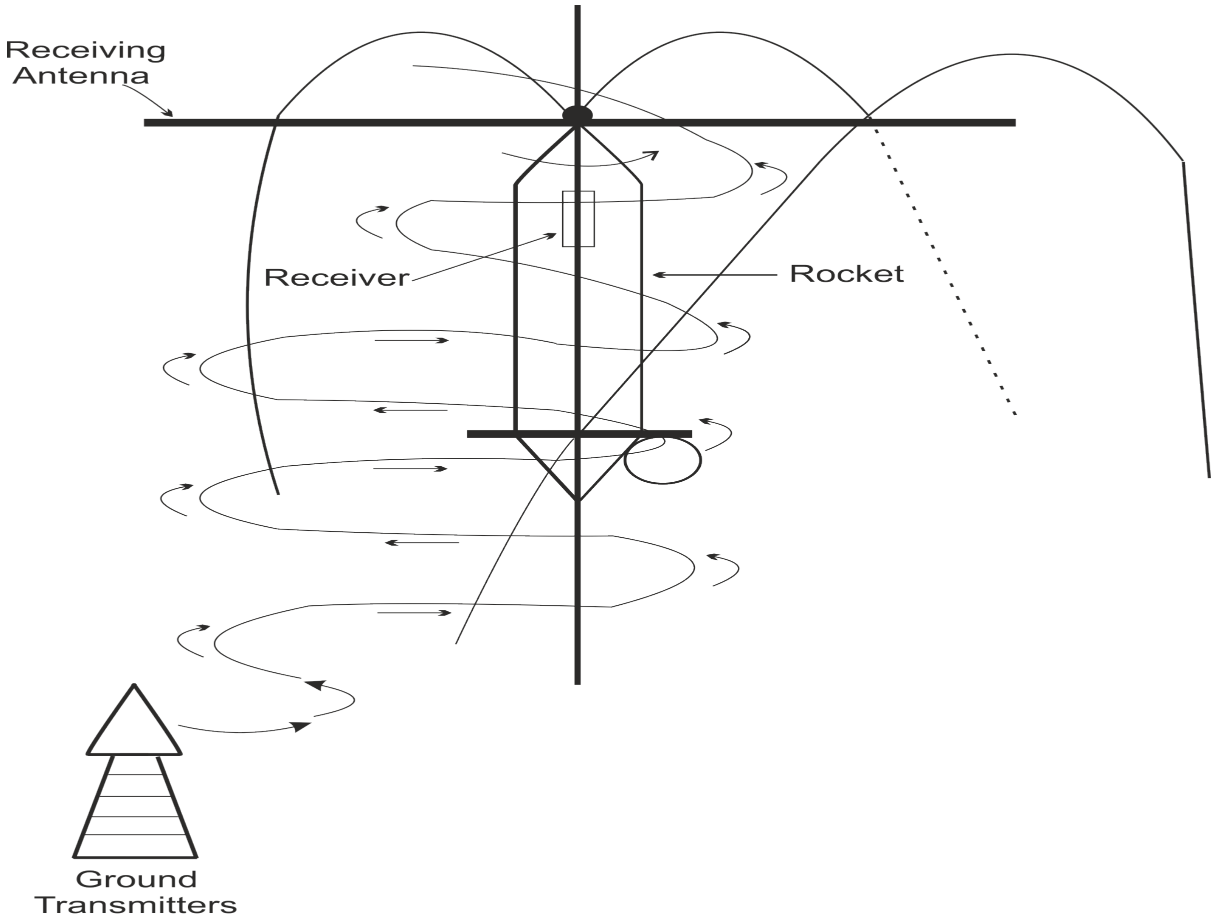

Figure 3.1: Experiment description with the receiving antennas on the board of the sounding rocket.

Fig.(3.1)shows that, an High frequency is distributed via a linearly polarized antenna from the ground to the rocket payload and receiving antenna spins with the rocket, it examines the polarization pattern.

Assume, the receiving antennas has 4 measuring points which are 1A, 1B, 1C, and 1D so the antennas are rotates at 360° (clockwise or anti-clockwise) with point 1A to 1B, 1B to 1C, 1C to 1D and it starts to collect the signal if we consider 1A as a maximum value so the next value which is 1B it will be the minimum value and after that the same action repeat for the other points.

3.2 General principle of absorption

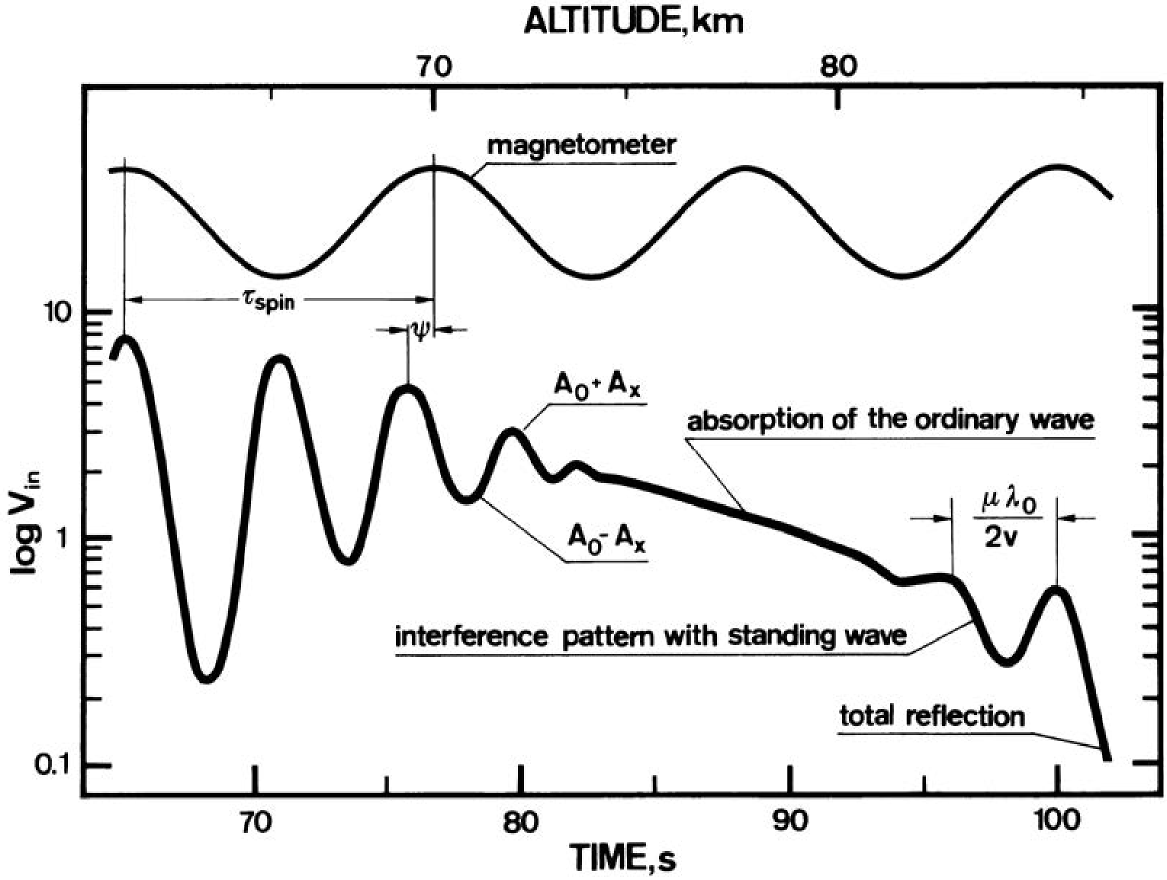

Figure 3.2: Idealized variation of the output of a Faraday receiver (Friedrich and Torkar, 1978).

(Fig.3.2) demonstrates the general measuring principle of absorption. (Fig.3.2) just an example that shows how the absorption works while we transmit electromagnetic wave. In this receiver it has two modes which are O (ordinary) and X (extraordinary). Magnetometer measure the slight fluctuation while receiving antenna spins with the rocket. Whereas, $(A_o - A_x)$ obtain changes in amplitude and suddenly extraordinary component has virtually disappeared and ordinary wave has absorbed totally. Due to the plasma effect it generates interference pattern with standing wave ratio which is superpose the electromagnetic wave.

$$\omega_p = \sqrt{N_\varepsilon . \omega} \tag{3.1}$$

$Where, N\varepsilon = Electron\ \ Density,$

$\omega_p = Plasma\ \ frequency,$

$\omega = Angular\ \ frequency\ \ of\ \ wave.$

3.3 Faraday Raw Data

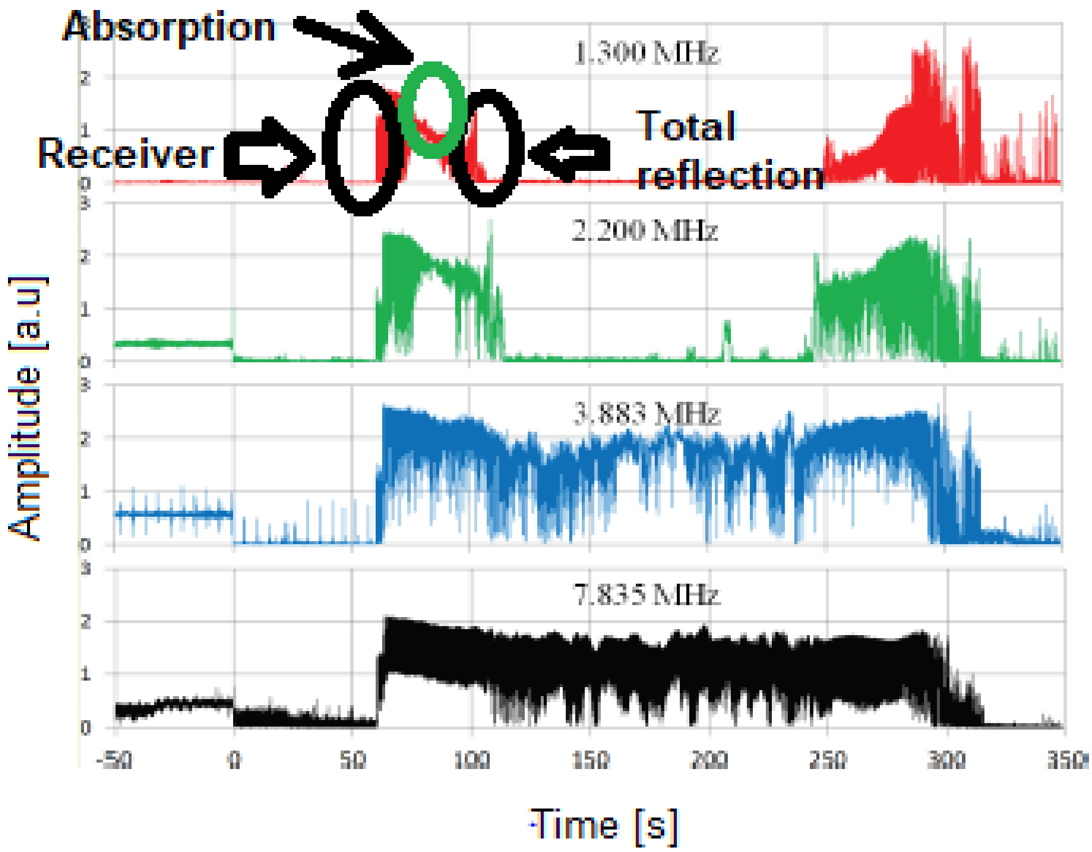

Figure 3.3: WADIS 2 Faraday raw data ([[10]]

Fig.(3.3) shows an example of raw data of the wave propagation experiment conducted during WADIS-2 rocket flight. At about 60 s after lift-off (Which is at 0 s) the receiving antennas on board the sounding rocket are exposed to the atmosphere and start to acquire the signal.

As we can see in Fig.(3.3) there are 4 different frequencies are given here. When we look to the 1.300 MHz we can clearly see that, after receiver started to acquire the signal absorption has taken place for the low frequency we have obtained the total reflection at 110 to 120 sec for 1.300 MHz & 2.200 MHz,respectively.

But, the in the other frequencies like are 3.883 and 7.835 the absorption has taken place after 60 s to 300 sec. The total reflection for higher frequencies, i.e 3.883 & 7.835 MHz takes place at much higher altitudes and is not reached by the rocket. If we compare these two higher frequency with 1.300 & 2.200 MHz it does not show the total reflection as these low frequency showed between 100 to 120 sec and it is only because of the higher altitudes. [Total reflection = Plasma frequency] (ω=ω_p).

3.4 Calibration Data

The calibration data is a property of electronics. The calibration data was measured in laboratory during the pre - flight preparations. It shows how the input signal is attenuated by the measuring electronics. Because there are lot of technical problem occurs i.e soldering of circuit. The actual measured calibration data is in (μV vs.V). It was not linear so we took calibration data to obtain the calibration curve.

Calibration Data Table

Input, μV	Output, V	Output, V	Output, V	Output, V
	1.300 MHz	2.200 MHz	3.883 MHz	7.835 MHz
0.1	0.028	0.047	0.040	0.085
0.3	0.150	0.182	0.194	0.245
0.6	0.400	0.426	0.467	0.466
1.0	0.665	0.650	0.702	0.678
1.5	0.944	0.884	0.940	0.880
2.0	1.143	1.059	1.114	1.034
3.0	1.416	1.300	1.360	1.270
5.0	1.776	1.631	1.685	1.578
7.0	1.989	1.835	1.885	1.776
10.0	2.189	2.027	2.080	1.980
15.0	2.415	2.260	2.316	2.211
20.0	2.560	2.408	2.464	2.366
25.0	2.655	2.504	2.567	2.476
30.0	2.738	2.567	2.654	2.567
35.0	2.804	2.658	2.722	2.639
40.0	2.868	2.727	2.784	2.701
50.0	2.958	2.820	2.878	2.770
100.0	3.218	3.088	3.149	3.087
200.0	3.496	3.365	3.414	3.360
500.0	3.948	3.766	3.799	3.745
1000.0	4.420	4.170	4.202	4.136
2000.0	4.720	4.713	4.731	4.664

Table 3.1: Calibration data from Faraday box 13(b)

As we measured the data from Faraday box 13(b) afterwards we got the values as a input and output in (μV vs. V). But when we plot these values together we obtain the calibration curve as we expected.

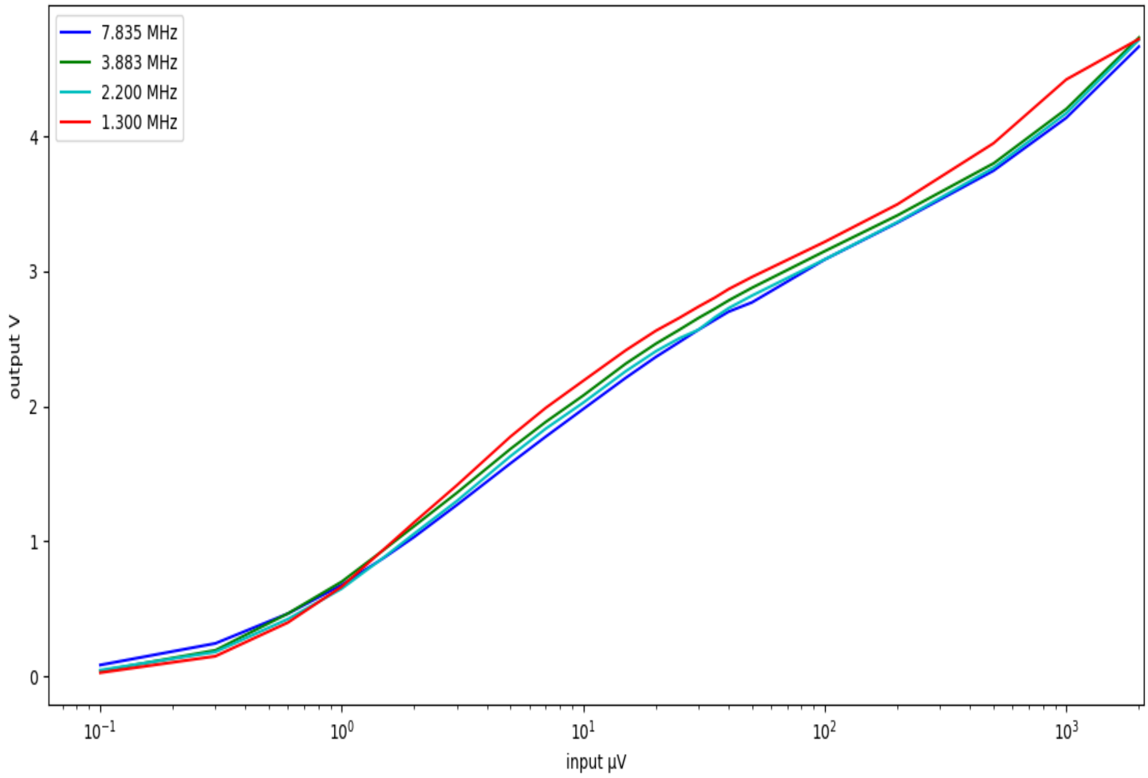

Figure 3.4: Calibration Curve with all the frequencies (μV vs.V)

Fig.(3.4) shows that when calibration input starts from 10^{-1} but when it reaches to 10^{0} we can clearly see that there are some changes in output (V) and frequency 1.300 MHz has modified variations in it's output.

3.5 Signal Processing Techniques

Interpolation

In the field of numerical analysis, interpolation is a method of constructing new data points within the range of a discrete set of known data points. We use interpolation to fill the data gaps between the data ([[18]]).

There are different types of interpolation which are described below.

Types of Interpolation

- **Piecewise constant interpolation**: In the Piecewise interpolation it connects the straight line between data points. Any intermediate value read off from straight line. It can find appropriate sub-interval.([[18]])

- **Linear Interpolation**: It involves the generation of new values based on an existing values.Linear interpolation is achieved by geometrically rendering a straight line between two adjacent points on a graph.([[18]])

- **Polynomial Interpolation**:It is a method of estimating values between known data points.when graphical data contains a gap, but data is available on either side of the gap, an estimate of values within the gap can be made by interpolation.

- **Spline Interpolation**: It is a special function defined Piece wise by polynomials. In interpolating problems, spline interpolation is often preferred to polynomial interpolation because it yields similar results, even when using low degree polynomials.([[18]])

In this thesis we used interpolation technique but there are many types of interpolation which are already described in (3.5). It is totally depending on particular task that which kind of data you have to process and which type of interpolation will be suited to the data set.

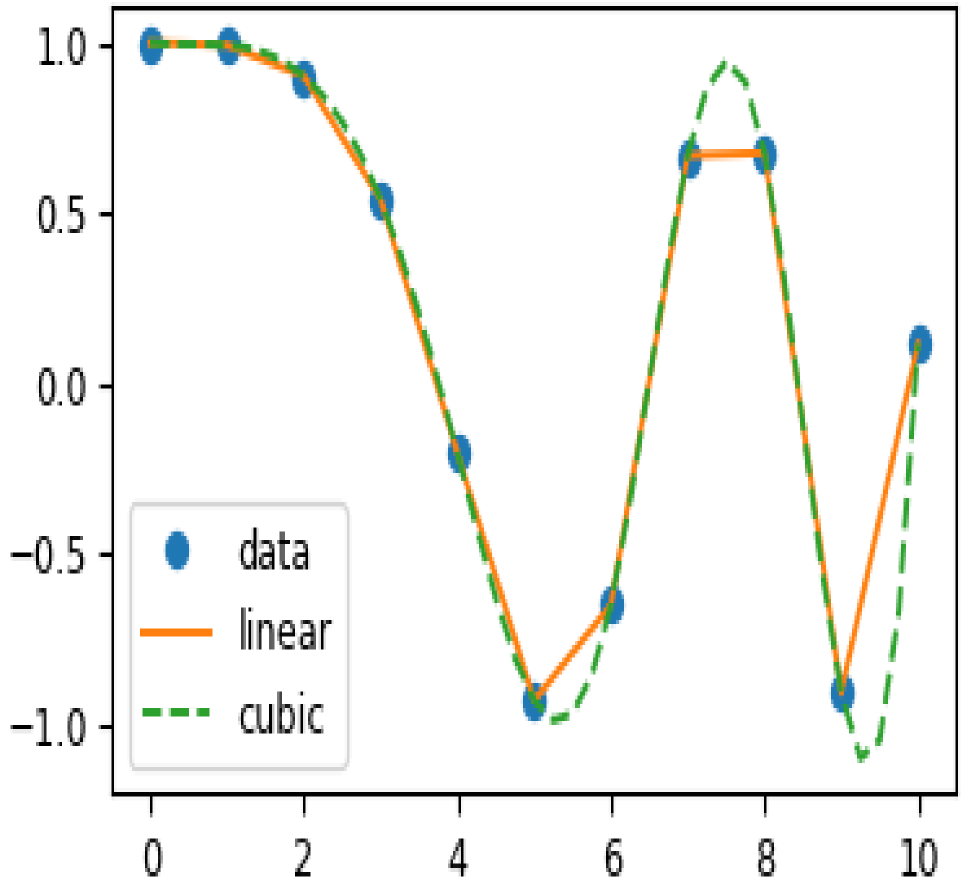

Figure 3.5: Implementation with different types of interpolation.

Fig.(3.5) exhibits that there is a data set and there are two types of interpolation used. But when we observe the actual data and after the interpolation with two different types of interpolation the linear interpolation gives the same fit as the data fit itself.

Whereas, cubic spline interpolation fits the data perfectly and also gives the lower degree polynomial which can fit the data easily. That is the main reason that cubic spline interpolation is being used in this thesis because we need minimum and maximum points for the Phase shift.

3.6 Data Before Interpolation for (frequency 4 = 7.835 MHz)

Fig.(3.6) shows an example of raw data in the time interval between 72 to 76 sec.

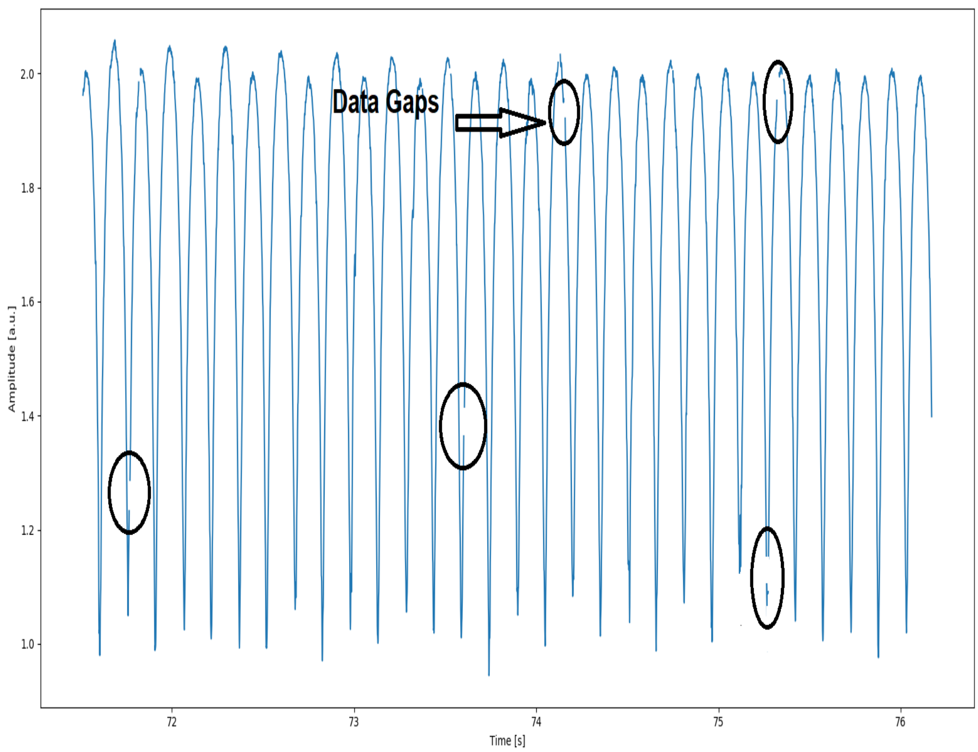

Figure 3.6: Data from 72 to 76 (sec) of Frequency 4 = 7.835 MHz without interpolation with large data gaps.

- It is clearly seen from the Fig.(3.6) that the data contains data gaps. To fill these data gaps we need to use interpolation technique which is defined in [3.5] and also why we used cubic spline interpolation.

3.7 Data After Interpolation for (frequency 4 = 7.835 MHz)

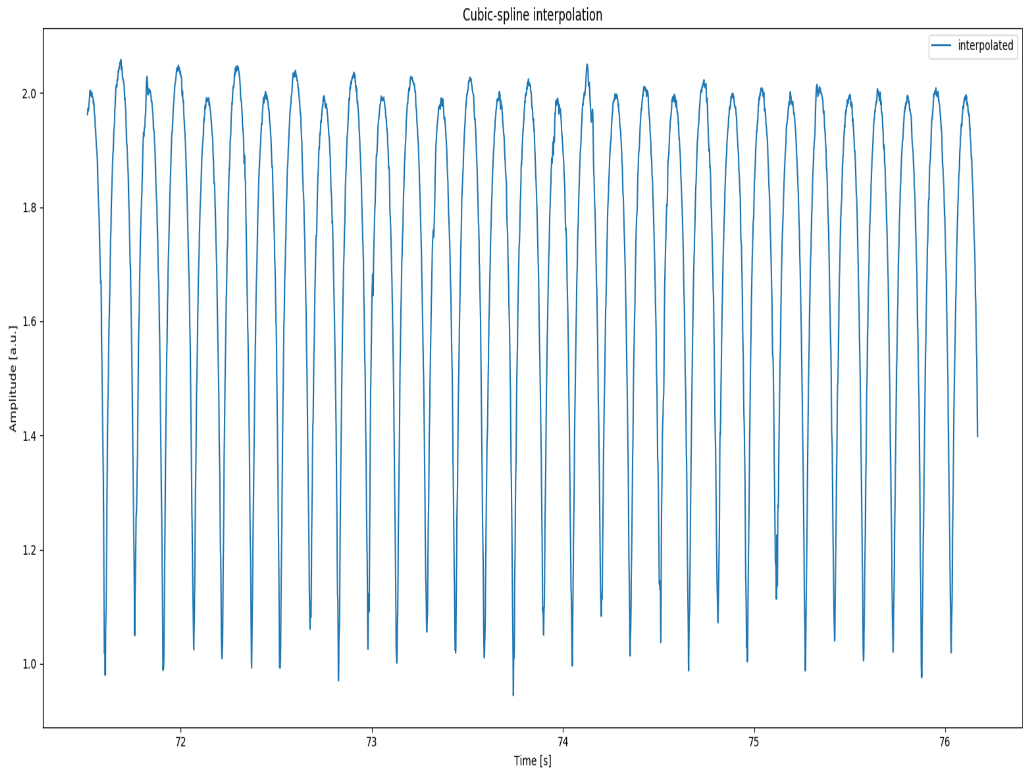

Figure 3.7: Data from 72 to 76 (sec) of Frequency 4 = 7.835 MHz after interpolation.

- If we compare the fig.(3.6) and fig.(3.7) we can undoubtedly identify that after using "Cubic Spline interpolation" the data gaps has been completely filled and in upcoming conversions we can use lower polynomial degrees as per our requirement.

3.8 Spin Frequency (3.27 Hz)

As shown in the (Fig:3.8) it is just spin around the roll axis to stabilize the flight during the phase. In this thesis the given Spin frequency is 3.27 Hz.

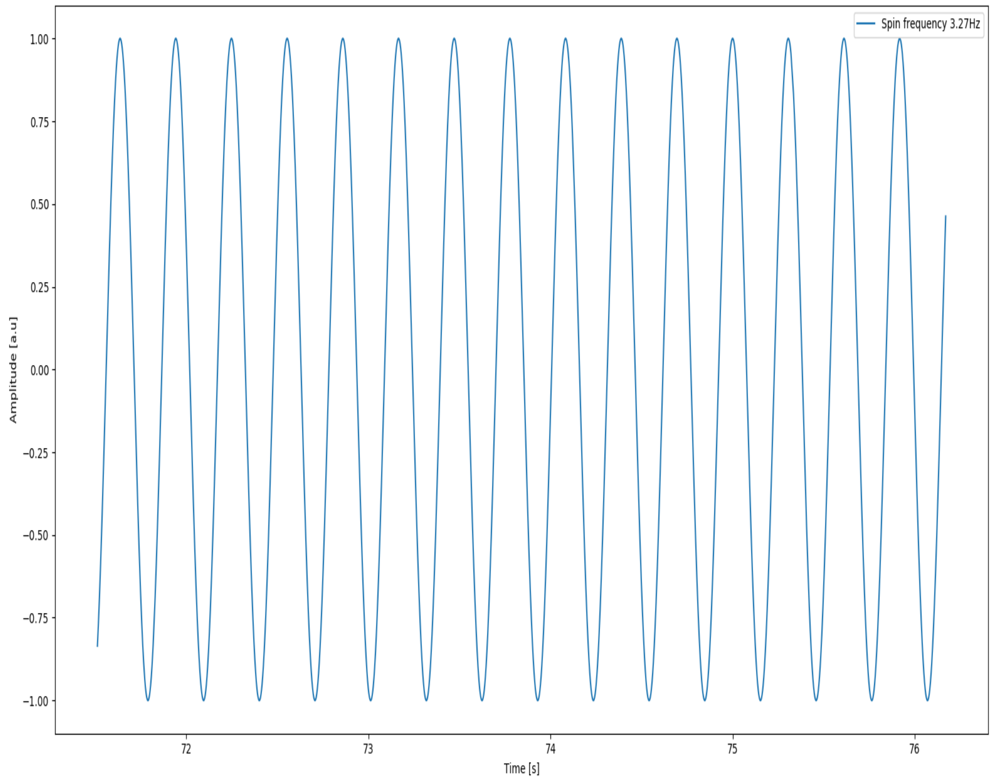

Figure 3.8: Spin Frequency (3.27 Hz)

Many sounding rockets, constructed for ballistic flights,build up a spin around the roll axis to stabilize the flight vector during the ascent phase. Where sin- curve in blue is the known phase of the rocket due to spin.

The final spin frequency depends on the type of rocket. Spin rates in the range of several Hz are obtained. The spin rate can be reduced by a yo-yo system. The dimension of the yo-yo system depends on the inertia of the roll axis and the diameter of the payload ([[9]]).

3.9 Polynomial Function Fitting

It is the process of constructing a curve, that has the best fit to a series of data.

As we have calibration data points which are shown in fig.(3.9) and we are applying here curve fitting method we used polynomial function so it gives the Polynomial orders which can provide the connection between two points in a order of Polynomial degree and we have generated the coefficients for the polynomial function. It is called "Polyfit" function.

Polynomial Function Fitting of (frequency 4 = 7.835 MHz)

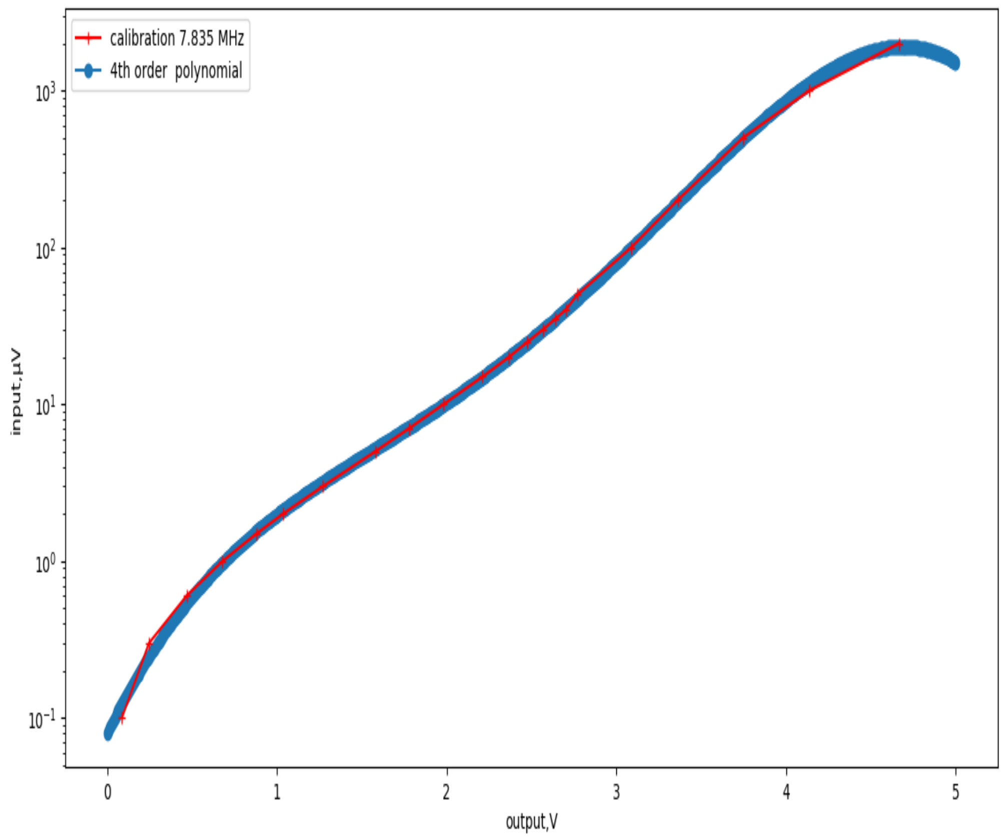

Figure 3.9: Polyfit function of Frequency 4 = 7.835 MHz (4th order)

We have to chose Polynomial order sharply that can cover maximum points so it will fit the data perfectly and gives the perfect curve with polynomial order.

Polynomial Function Over Fitting

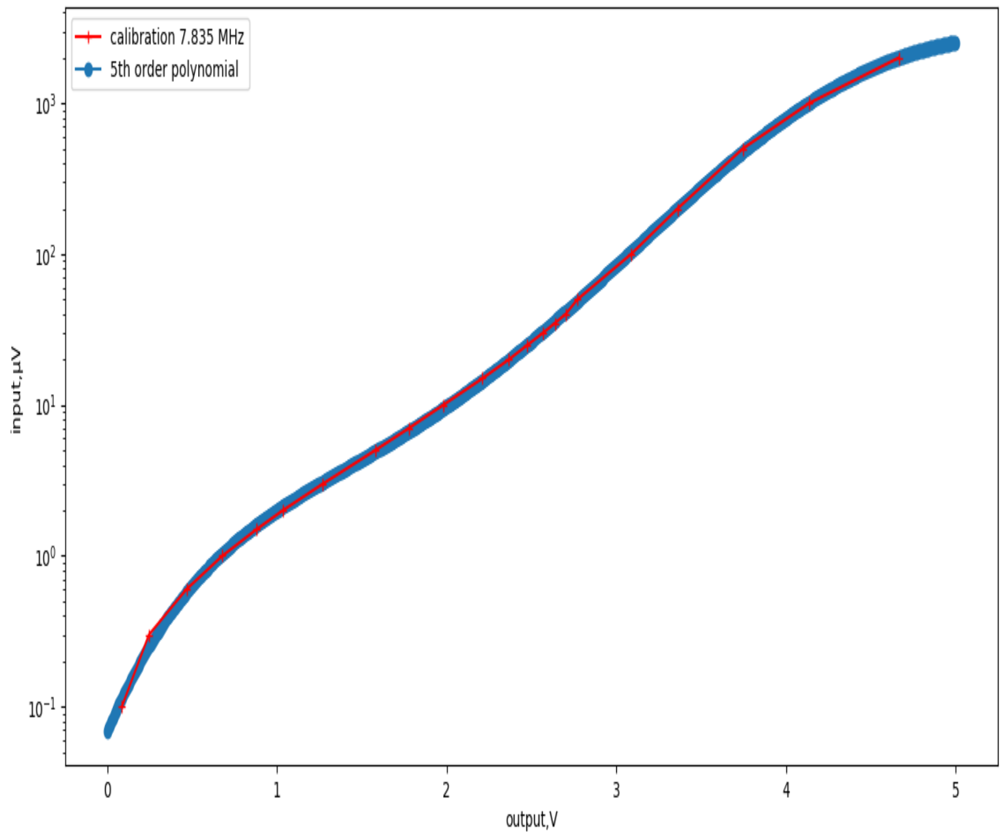

Figure 3.10: Polyfit function with Over fitting (non - generic).

As (fig.3.10) shows the calibration data points are perfectly fit in this polyfit function. If, an polynomial order can cover whole points we would not take this type of polynomial orders because it will non - generic and it is called "over fitting".

Chapter 4

Data Analysis

4.1 Spin frequency (3.27 Hz) vs. Interpolated Data

As earlier described Spin Frequency in [Section.3.8] and interpolated data in [Section.3.7] this is a comparison between both. But, the spin frequency is now twice as compared to the fig.(3.8) we can clearly see the difference between original spin frequency and after twice the spin frequency.

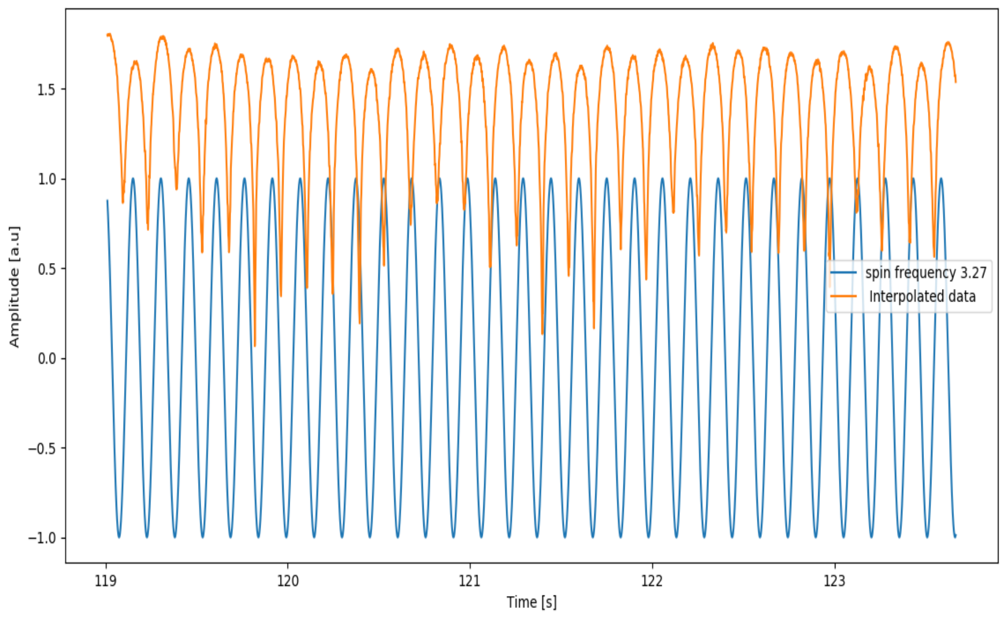

Figure 4.1: Spin frequency 3.27 Hz (blue) vs. Interpolated Data (Orange)

Fig.(4.1) shows the minimum amplitude and maximum amplitude of spin frequency and interpolated data. Now, we can find the minimum and maximum points according to it's amplitude.

4.2 Savitzky - Golay filter (Savgol filter)

A Savitzky - Golay filter is a digital filter that can be applied to set of digital data points for the purpose of smoothing the data , that is , to increase the precision of the data without distorting the signal tendency ([[21]])([[17]]).

Savitzky and Golay proposed a method of data smoothing based on local least-squares polynomial approximation. They showed that fitting a polynomial to a set of input samples and then evaluating the resulting polynomial at a single point within the approximation interval is equivalent to discrete convolution with a fixed impulse response. The lowpass filters obtained by this method are widely known (in some sectors) as Savitzky-Golay filters. Savitzky and Golay were interested in smoothing noisy data.([[6]]).

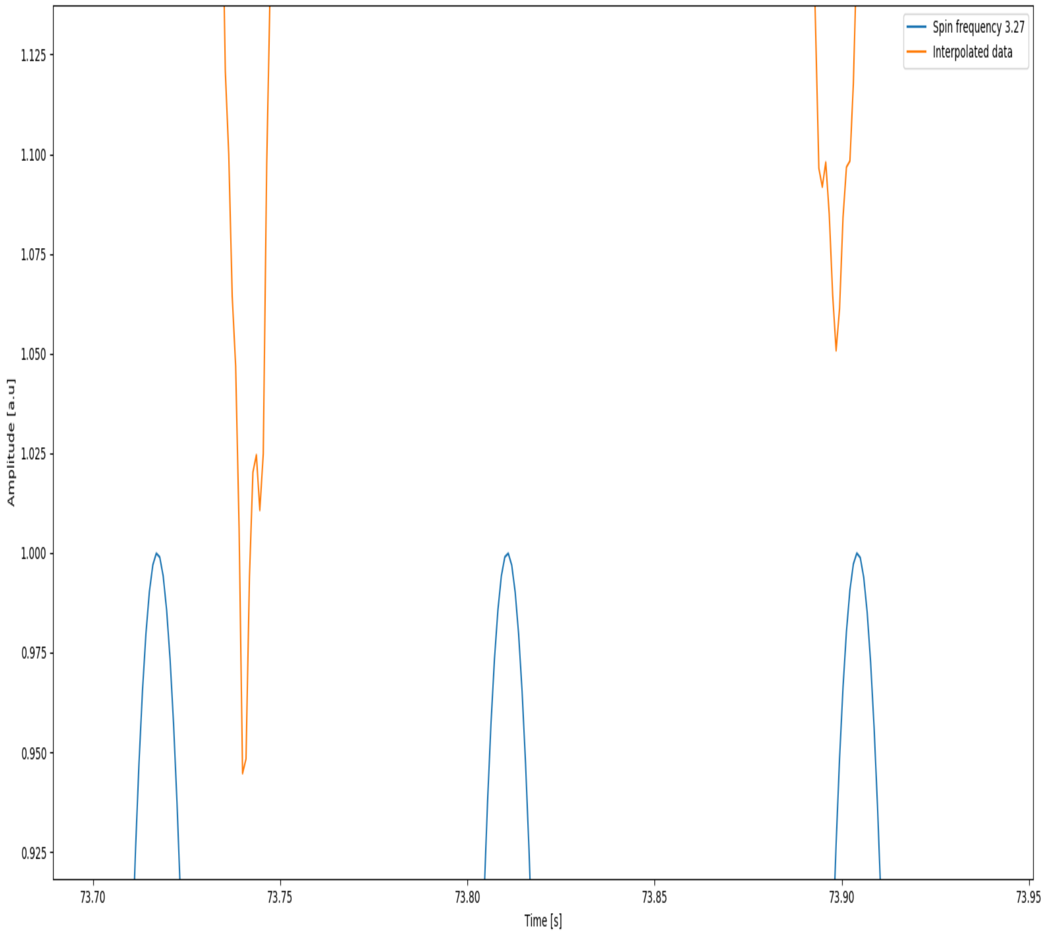

Figure 4.2: Data quality is not so good

On the other hand when we observe the (fig:4.2). It is clearly noticed that we can't find the minimum and maximum points due to the poor data quality. So, to improve the data quality and to remove the unwanted features from the signal we regulated Savitzky - Golay filter.

4.3 Minimum Points

After applying Savitzky - Golay filter we have able to improve the data quality and find the minimum points with their respective minimum amplitudes of interpolated data.

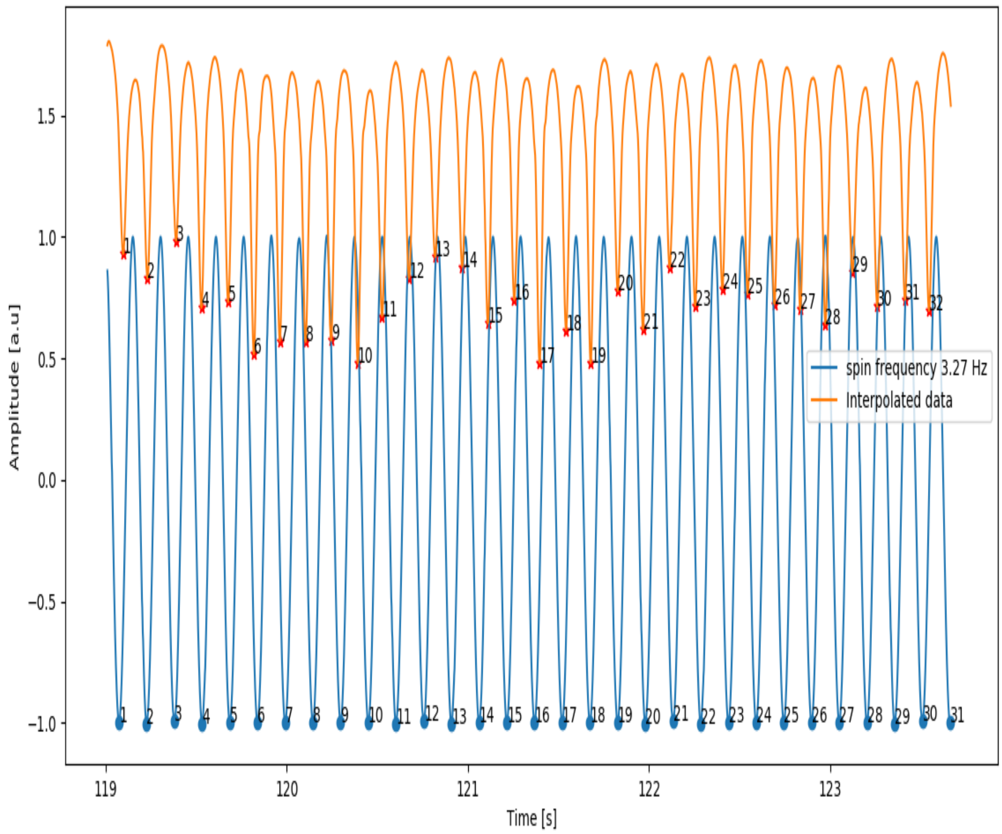

Figure 4.3: Minimum points of spin frequency 3.27 Hz and interpolated data.

After obtained minimum and maximum points we had taken the minimum amplitude difference with minimum time and maximum amplitude difference with maximum time. Consequently, the phase shift has received between these two points.

For amplitude difference we have adopted the same logic but in that we had applied the time difference to measure minimum and maximum amplitude difference of the data.

4.4 Maximum Points

The procedure is same as previously shown in [Section. 4.3] for the maximum points also. There is only a change in amplitudes in minimum point we took the minimum amplitude but here we had taken maximum amplitude of spin frequency and interpolated data.

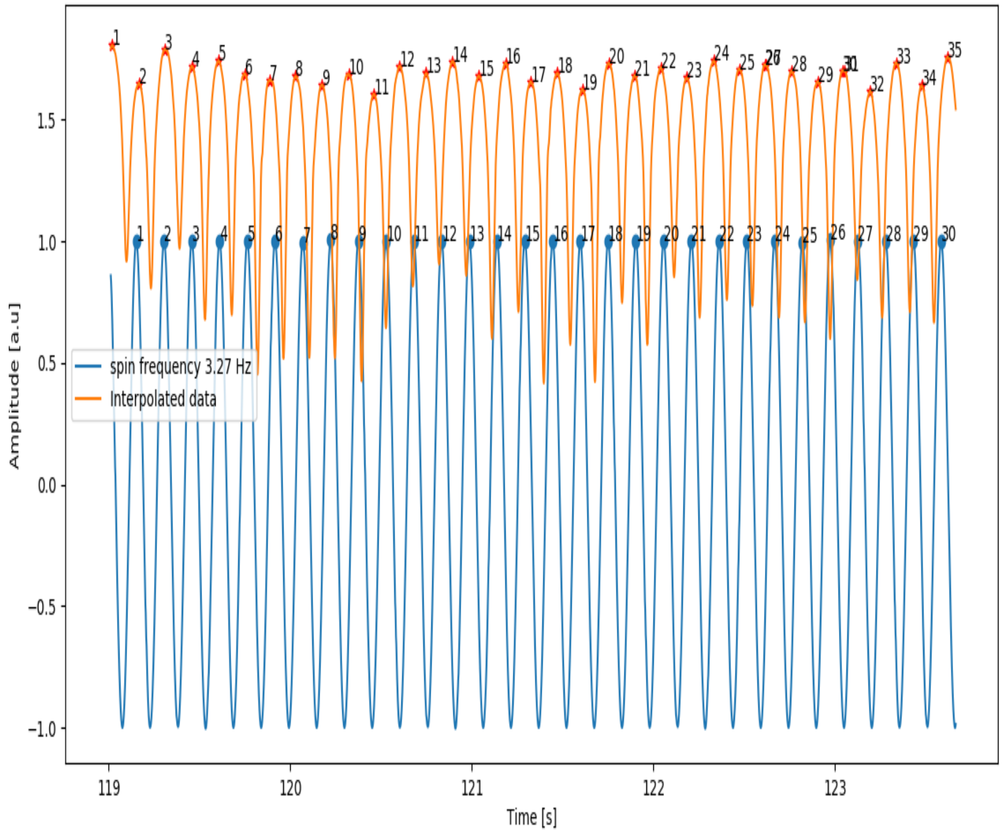

Figure 4.4: Maximum points of spin frequency 3.27 Hz and interpolated data.

4.5 Results

As (fig:4.5) shows that frequency 4 = 7.835 MHz which is the highest frequency among these all given frequency and we can see that it rotates very slowly and here we are using 4 different frequencies due to the redundancy.From these results we can clearly uphold that when we are passing electromagnetic waves it is totally depends on the ionospheric condition.

Result 1 : Phase Shifts

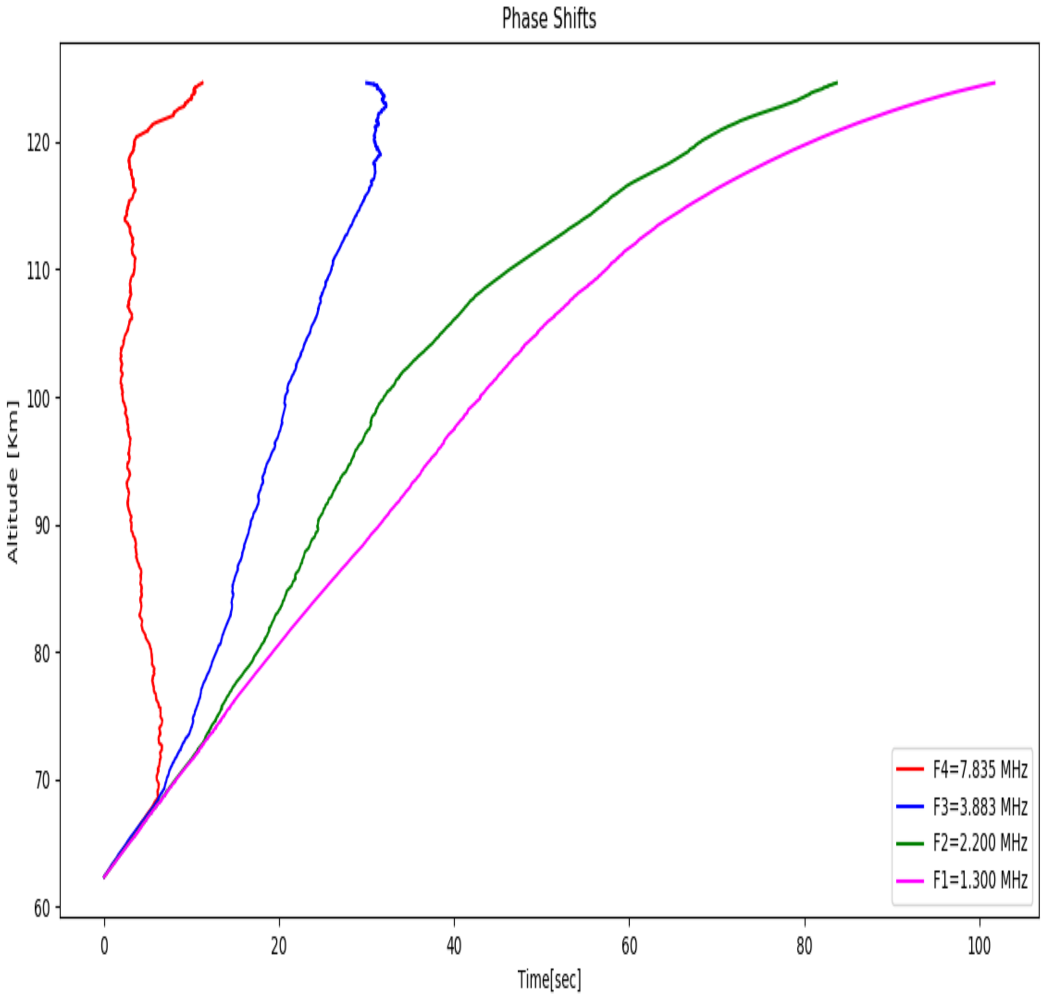

Figure 4.5: Phase Shifts of all frequencies.

- We can clearly see that radio wave with frequency of 7.835 MHz experiences almost no Faraday rotation effect. This is consist with expectations from theory of the wave propagation in the ionosphere. This also implies that this frequency (or higher frequencies) may be used as a reference frequency instead of the spin frequency of the rocket measured by e.g. on board magnetometer in case it fails.

- It is seen from (fig:4.5) that the Faraday rotation effect is stronger for lower frequency. This implies, that the lower frequencies are more sensitive to the change of Nε, and therefore they are better suitable for electron density measurements.

$$N\varepsilon = \begin{cases} f_1 = N\varepsilon_1 \\ f_2 = N\varepsilon_2 \\ f_3 = N\varepsilon_3 \\ f_4 = N\varepsilon_4 \end{cases}$$

$$N\varepsilon = f(\Delta\Phi) \tag{4.1}$$

$Where,\ \ N\varepsilon = Electron\ \ Density, \qquad \Delta\Phi = Phase\ \ shift$

Result 2 : Amplitude Difference

The amplitude difference is used to derive electron densities based on the differential absorption technique.

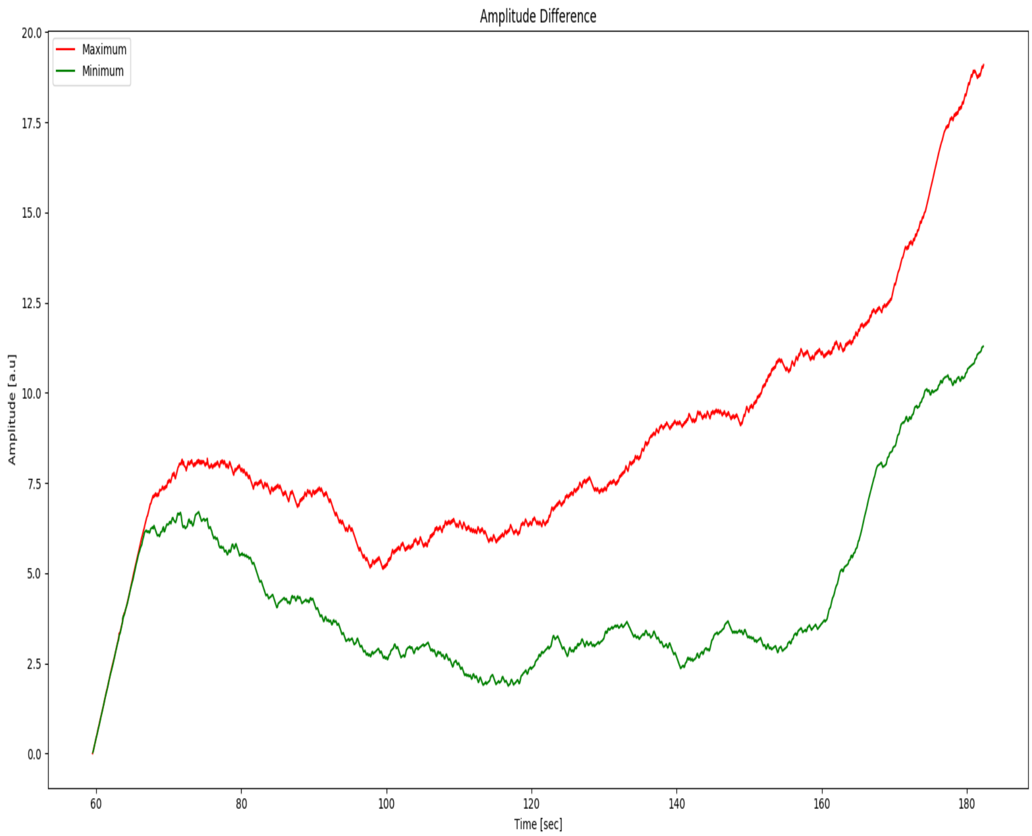

Figure 4.6: Amplitude Difference of Frequency 4 = 7.835 MHz.

(Fig.4.6) shows the amplitude difference of the signal (i.e max and min value per revolution). As we can see in (Fig.4.6) at about 60 s after lift-off (which is at 0 s) where minimum amplitudes are declining and maximum amplitudes are at the apex, from 7.0 km until 175 sec.

This is an another technique to measure electron density with minimum and maximum points.

$$N\varepsilon = f(\Delta A) \tag{4.2}$$

$$Where,\ \ N\varepsilon = Electron\ \ Density, \qquad\qquad \Delta A = Amplitude\ \ Difference$$

Chapter 5

Outcome

5.1 Summary

- In the chapter 1 an introduction about atmosphere along with the lower ionosphere and a little description about ionospheric regions with different layers of ionization are demonstrated.

- Chapter 2 contained the theory background of this thesis which represent the detailed description about wave propagation method along with different modes of wave propagation. The major techniques of this experiment which are Faraday Rotation and differential absorption are expound with it's definition. The information about the sounding rocket is involve in WADIS-2.

- The experimental techniques has a description about this thesis and general principle of absorption.On the other hand, Faraday raw data and calibration curve demonstrated precisely. Additionally, the signal processing techniques which are used in this thesis are rationalized and alongside it's shown the resultant figures which were generated with the help of this signal processing techniques. A spin frequency is also played a crucial role in this project.

- The comparison between spin frequency and interpolated data is shown in chapter 4 (Data Analysis). It has also shown the minimum points and maximum points (values) but before obtaining these points we used the Savitzky - Golay filter to remove the unwanted noise and smooth the data. The final plots (results) are also included.

- This chapter consist a conclusion of this thesis along with the future scope.

5.2 Conclusion

Main objective of this thesis is to measure electron density with the wave propagation experiment but to measure electron density there are various techniques.

Thus, we have applied Faraday Rotation and differential absorption techniques and the main reason for using these technique is, it will give the absolute values. However we conclude that there is no Faraday rotation effect on high frequency (frequency 4 = 7.835 MHz) and lower frequencies like are 1.300 & 2.200 MHz are more sensitive to the change in electron density

As Prof. Martin Friedrich described various techniques to measure electron density in his book ([[10]]). But, it was just a best guess among the all techniques for all different frequencies.

During this thesis we have used these two techniques on a WADIS-2 Faraday raw data but we already enforced the signal processing techniques electronically to measure the phase shifts for every revolution of the payload and amplitude difference of the signal(i.e max and min value per revolution).

5.3 Future Scope

In this thesis we have described only two techniques to measure Electron density. However, future work on this ionosphere topic would be, to measure Electron density contrast altitude but Electronically. As Prof. Martin Friedrich illustrated in his book ([[10]]). He described all the techniques to measure electron density but he has done manually which he called the best guess among all the frequencies and used techniques.

Appendix A

Figures and Tables

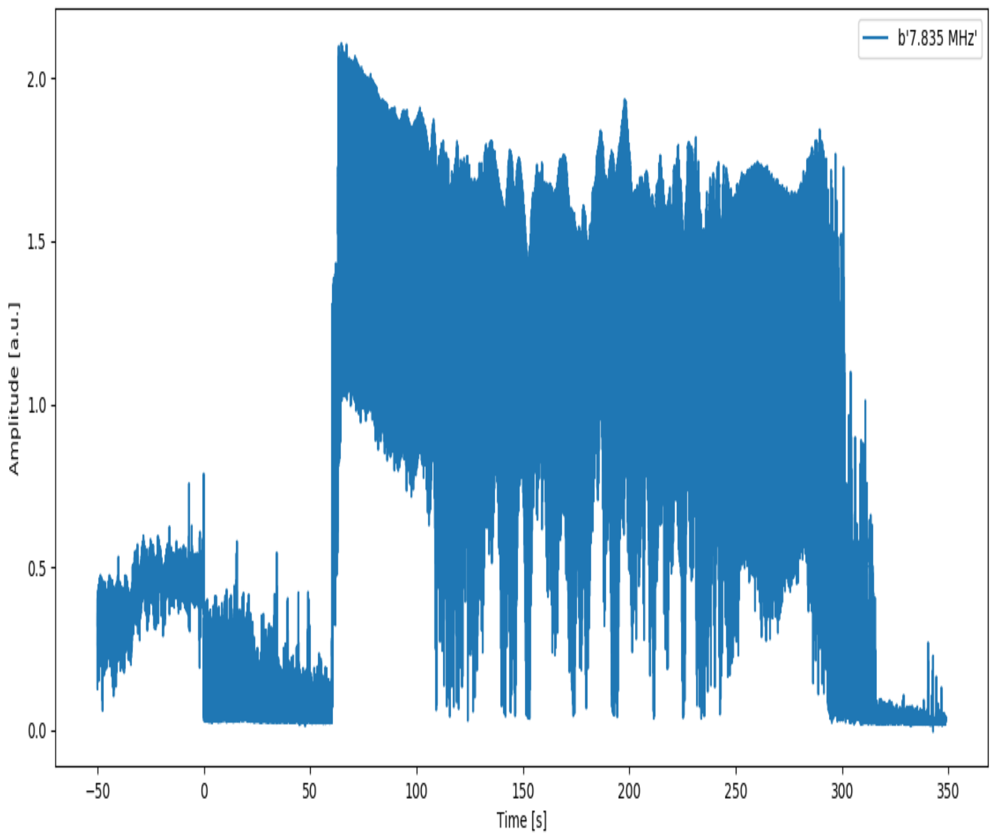

Figure A.1: Full Window of the frequency 4 = 7.835 MHz from -50 to 350 (sec)

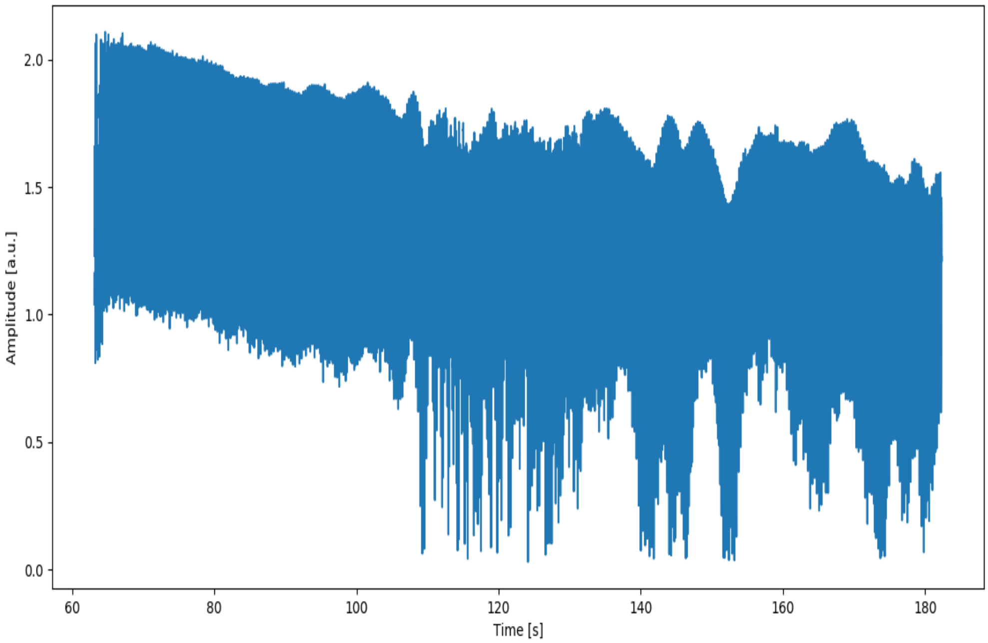

Figure A.2: Window Cutting upto 175 (sec) in t42 (Time).

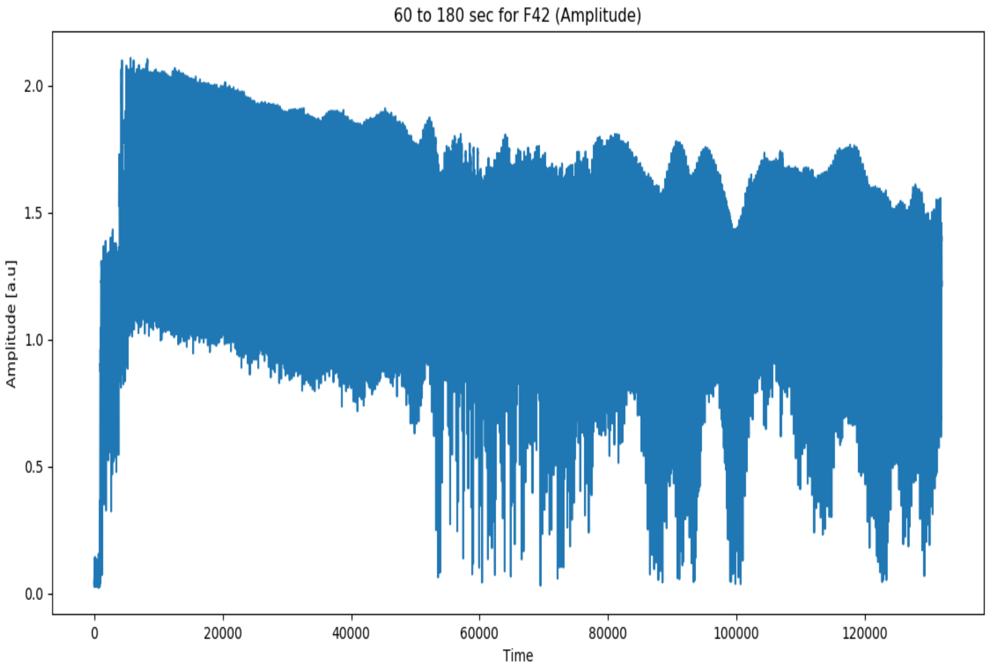

Figure A.3: Time interval 60 to 180 (sec) of f42 (Amplitude).

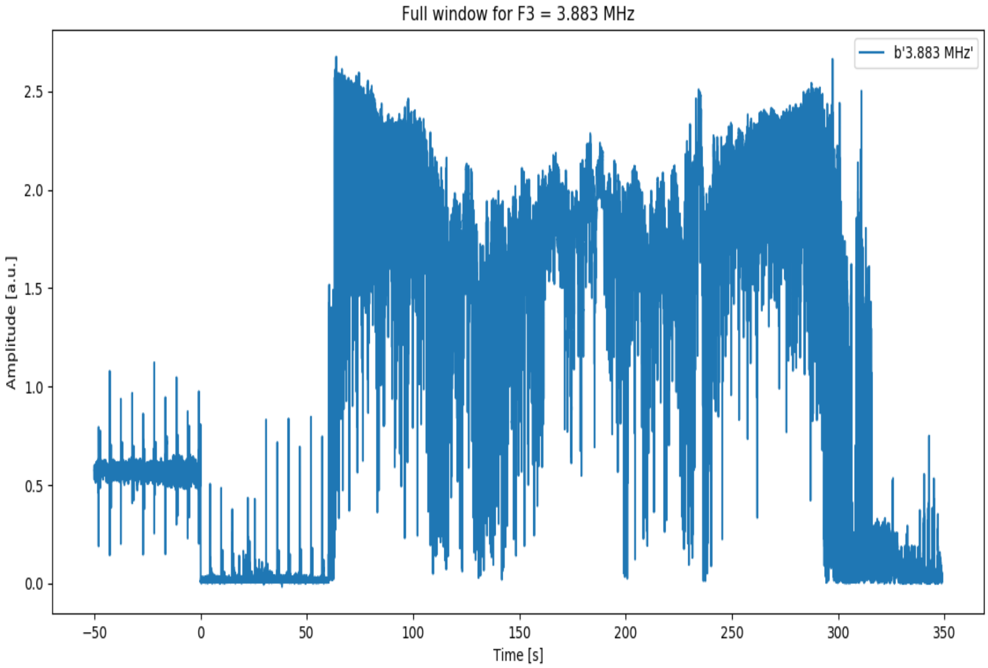

Figure A.4: Full window of frequency 3 = 3.883 MHz

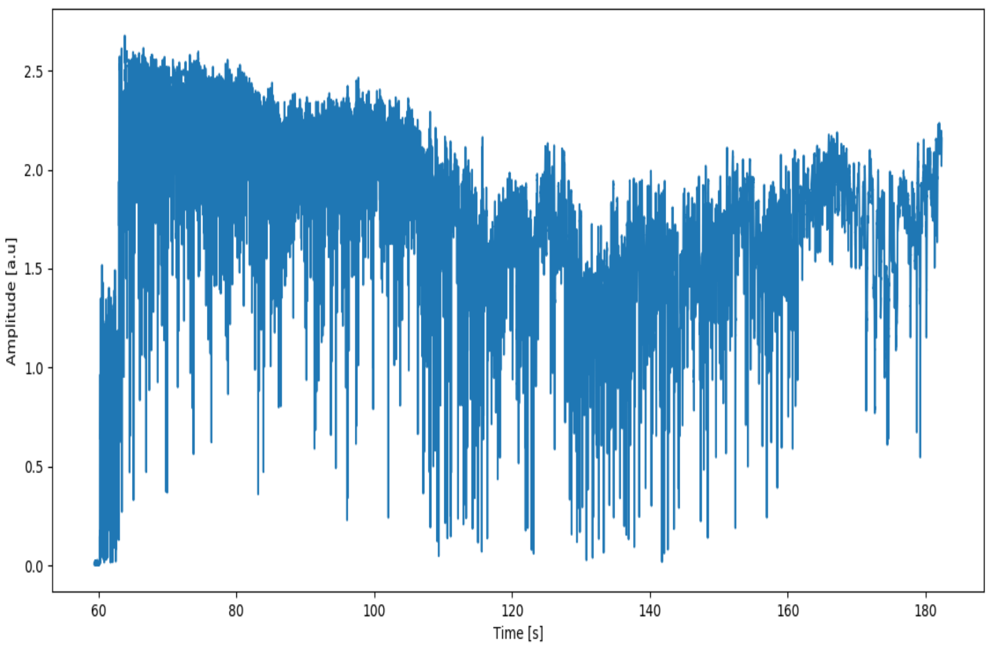

Figure A.5: Window cutting in t32 (Time)

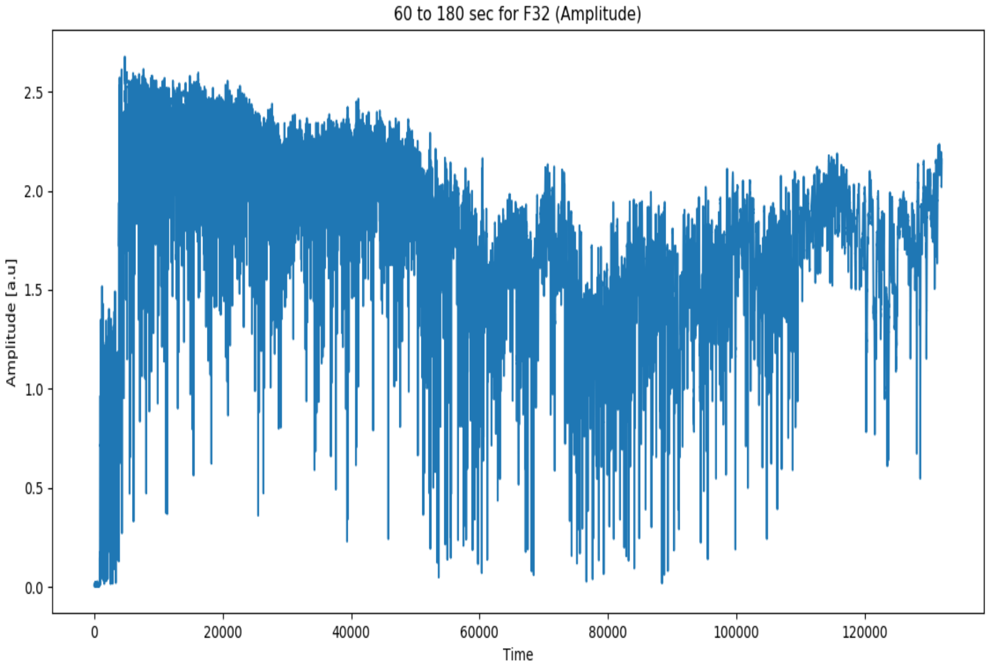

Figure A.6: Time interval 60 to 180 (sec) of f32 (Amplitude)

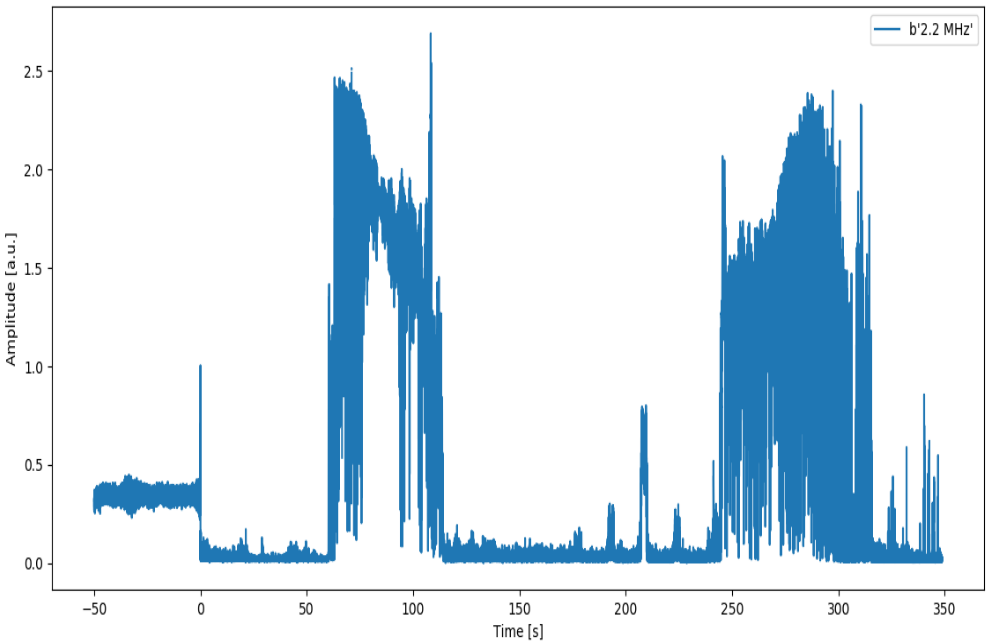

Figure A.7: Full window for the frequency 2 = 2.200 MHz

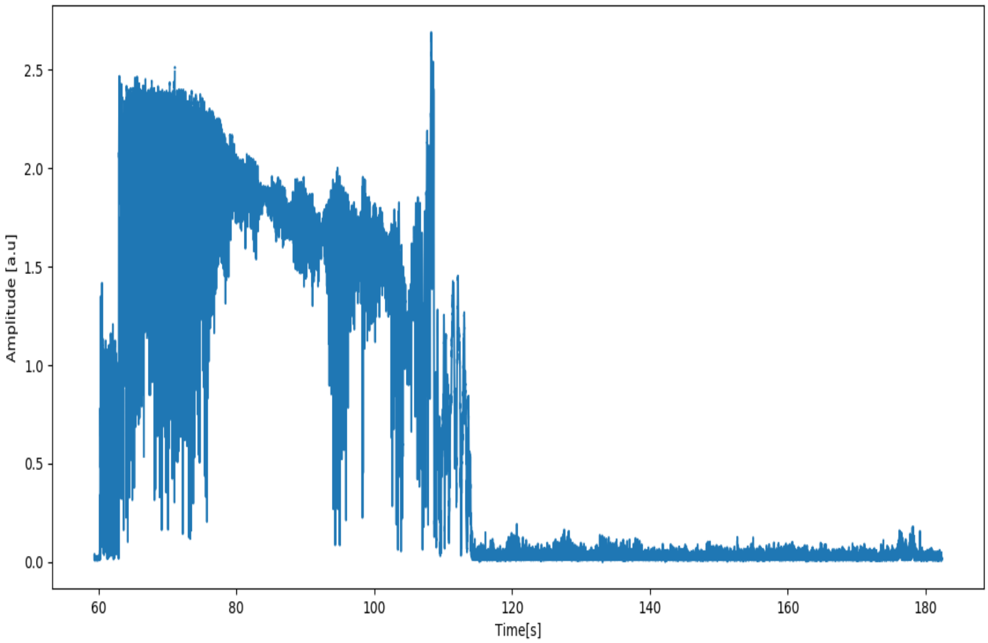

Figure A.8: Window cutting in t22 (Time)

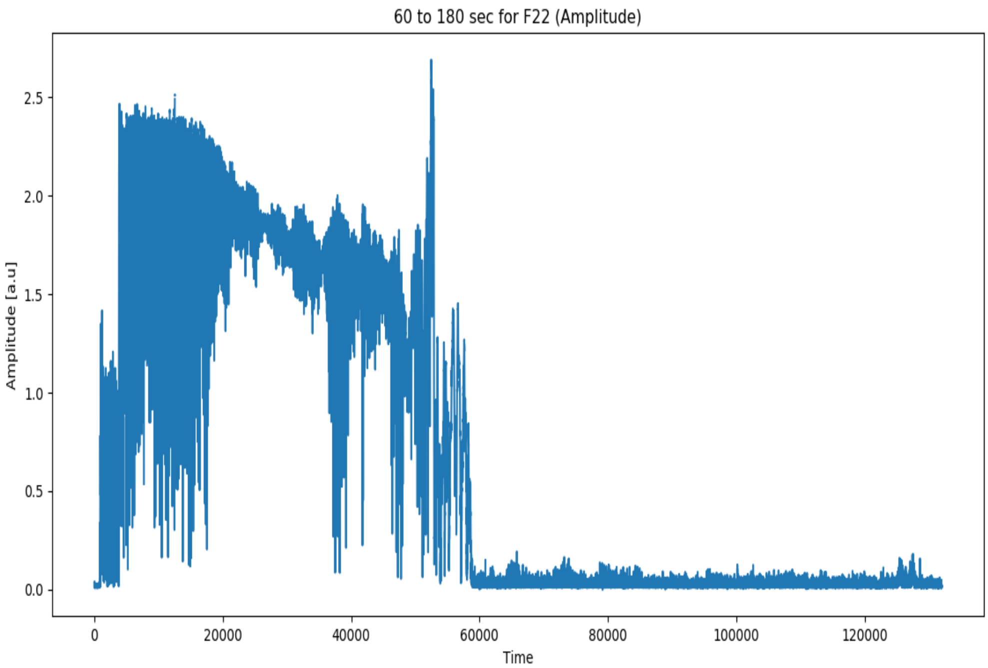

Figure A.9: Time interval 60 to 180 (sec) of f22 (Amplitude)

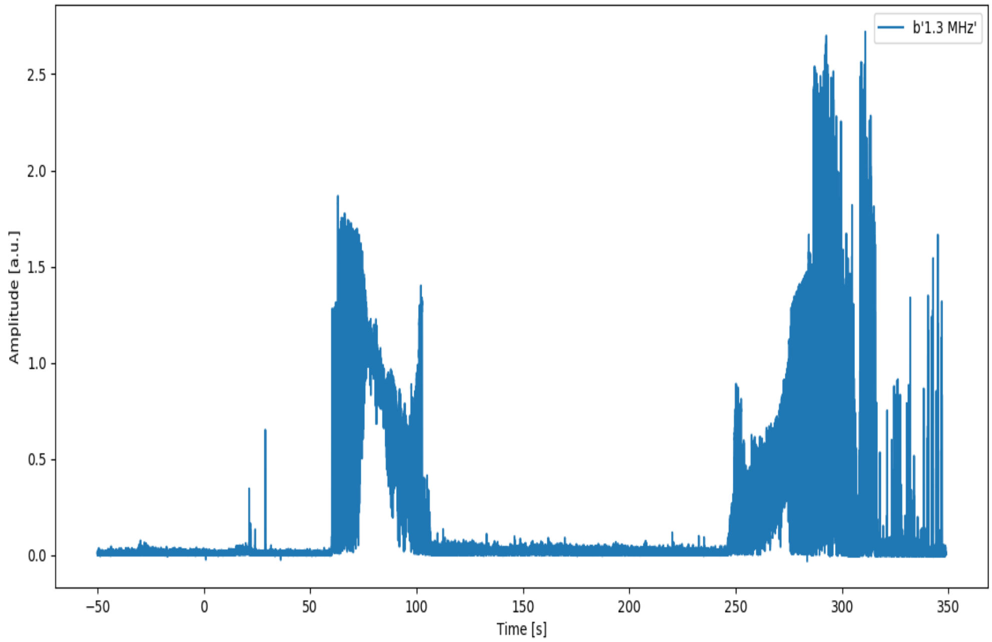

Figure A.10: Full window for the frequency 1 = 1.300 MHz

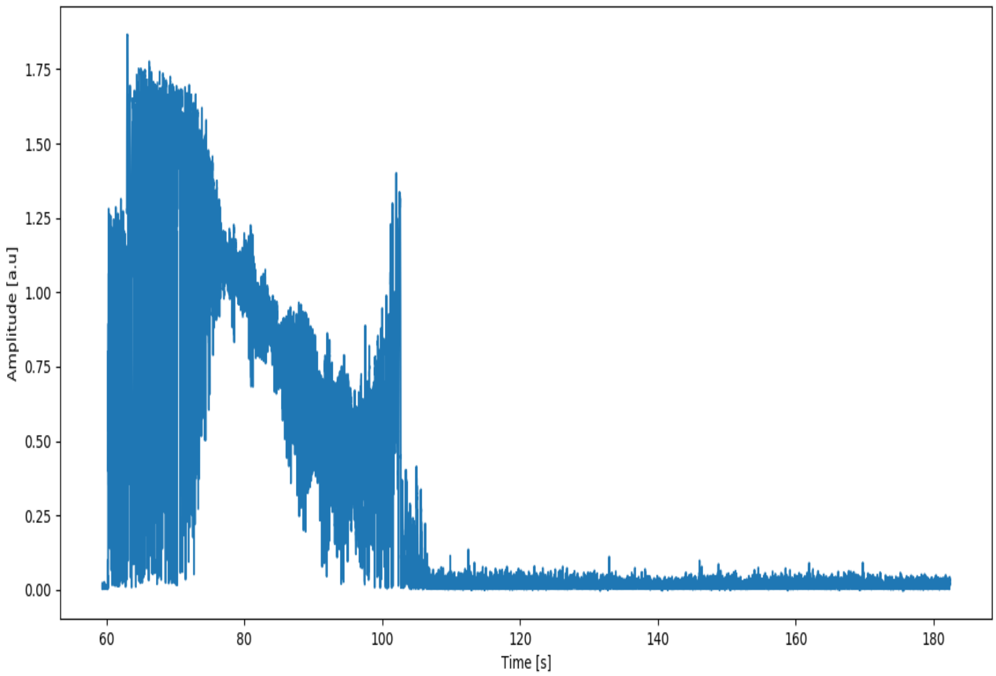

Figure A.11: Window cutting in t11 (Time)

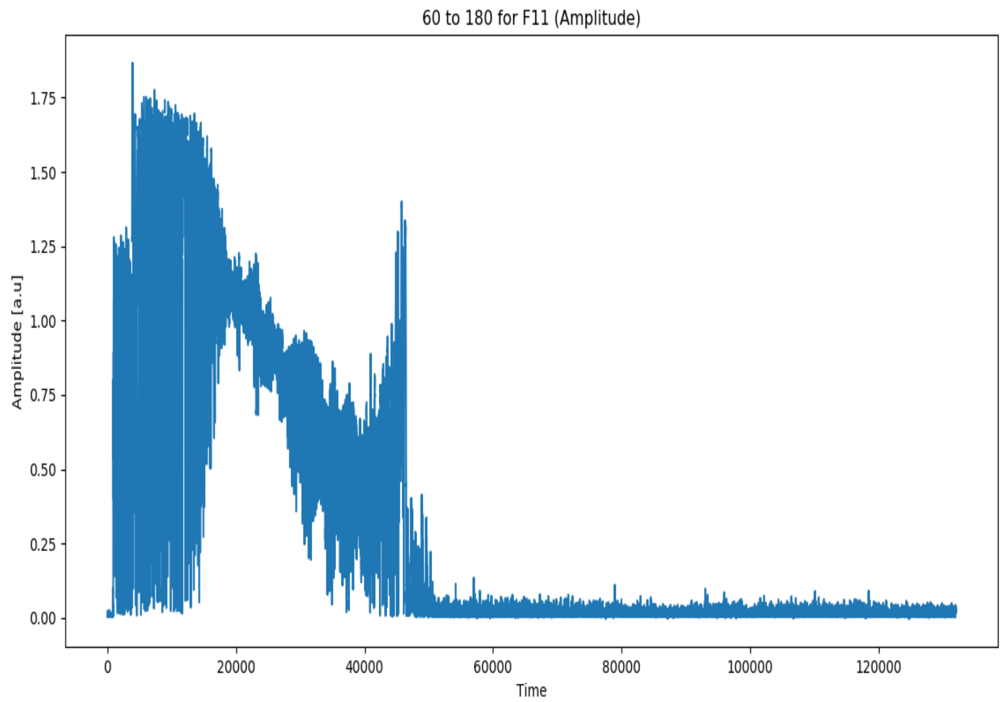

Figure A.12: Time interval 60 to 180 (sec) of f11 (Amplitude)

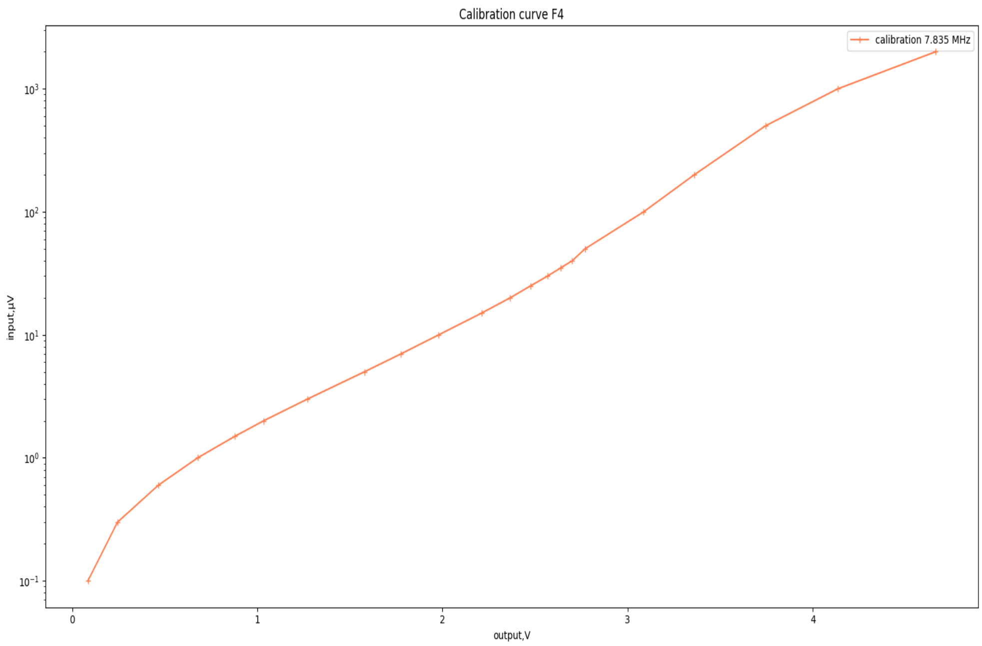

Figure A.13: Calibration Curve (V vs. μV) for frequency 4 = 7.835 MHz

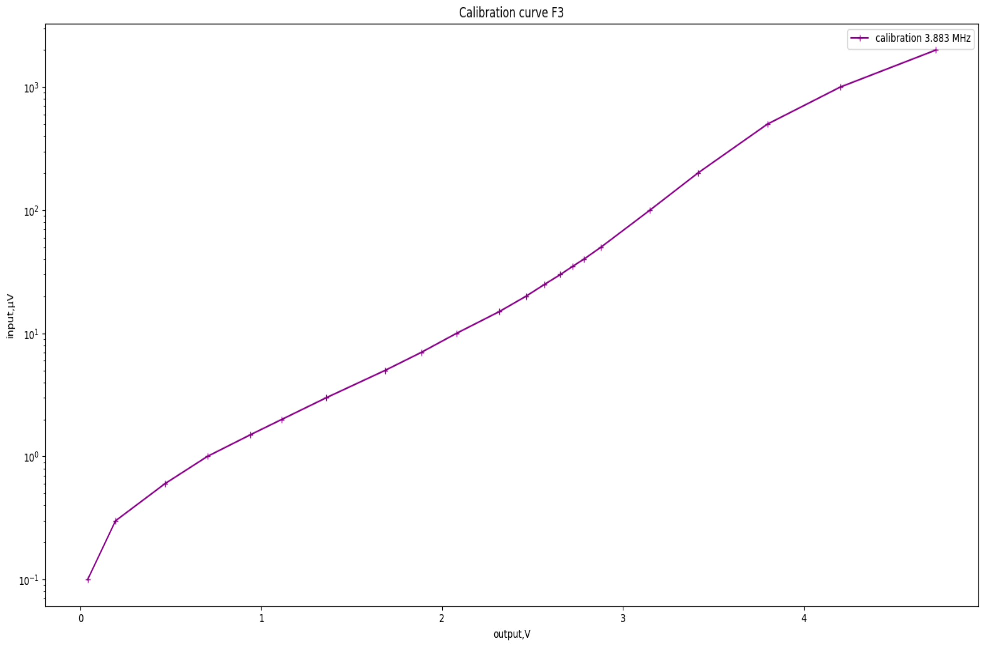

Figure A.14: Calibration Curve (V vs. μV) for frequency 3 = 3.883 MHz

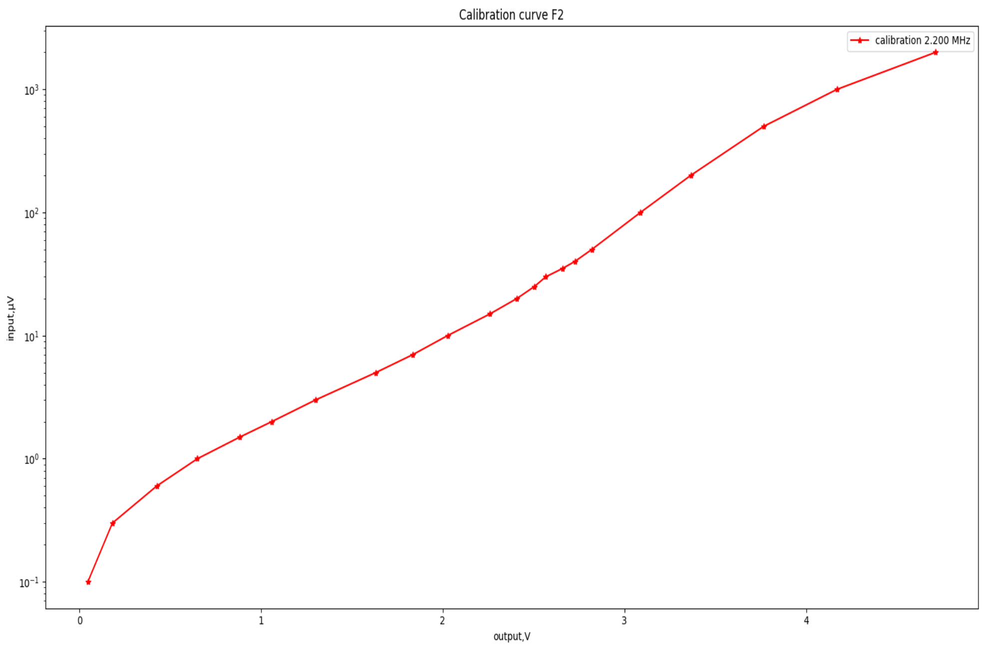

Figure A.15: Calibration Curve (V vs. μV) for frequency 2 = 2.200 MHz

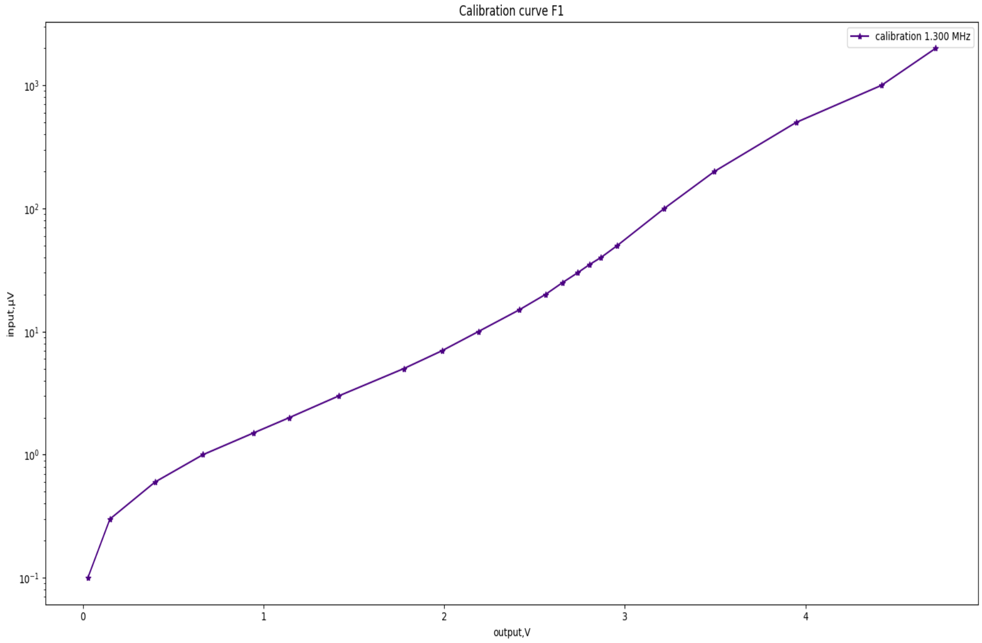

Figure A.16: Calibration Curve (V vs. μV) for frequency 1 = 1.300 MHz

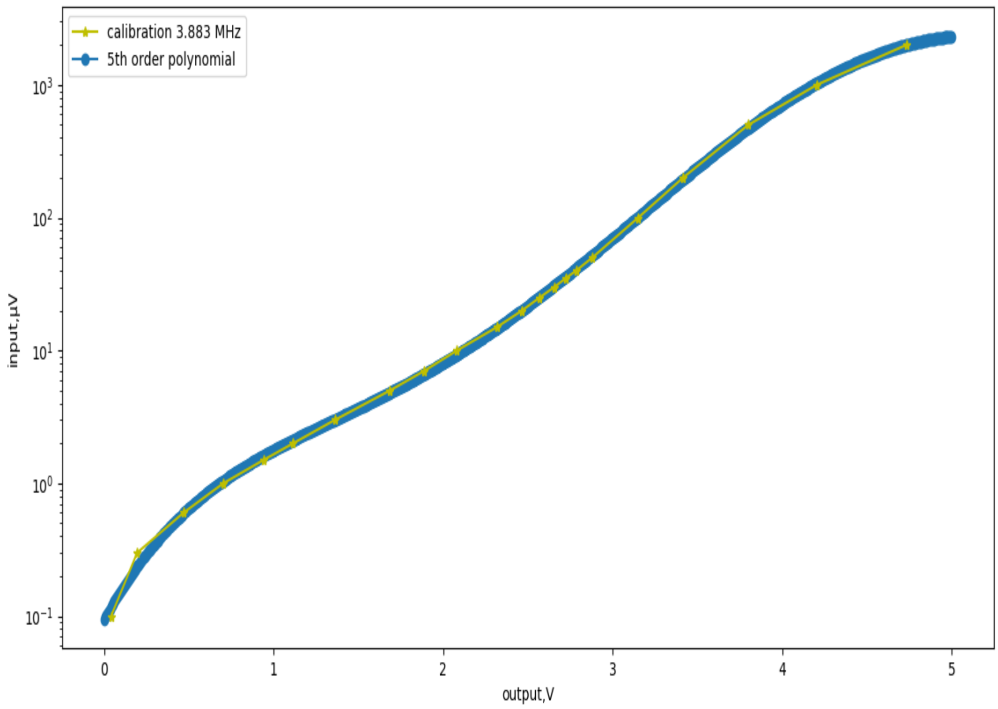

Figure A.17: Calibration data: Polyfit function of frequency3 = 3.883 MHz (5th order)

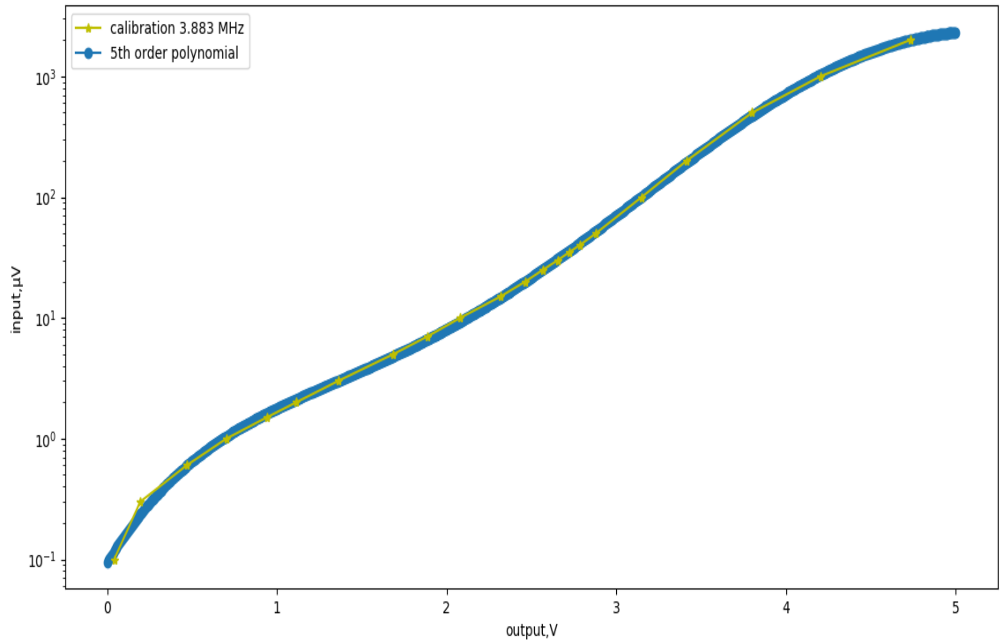

Figure A.18: Calibration data: Polyfit function of frequency2 = 2.200 MHz (5th order)

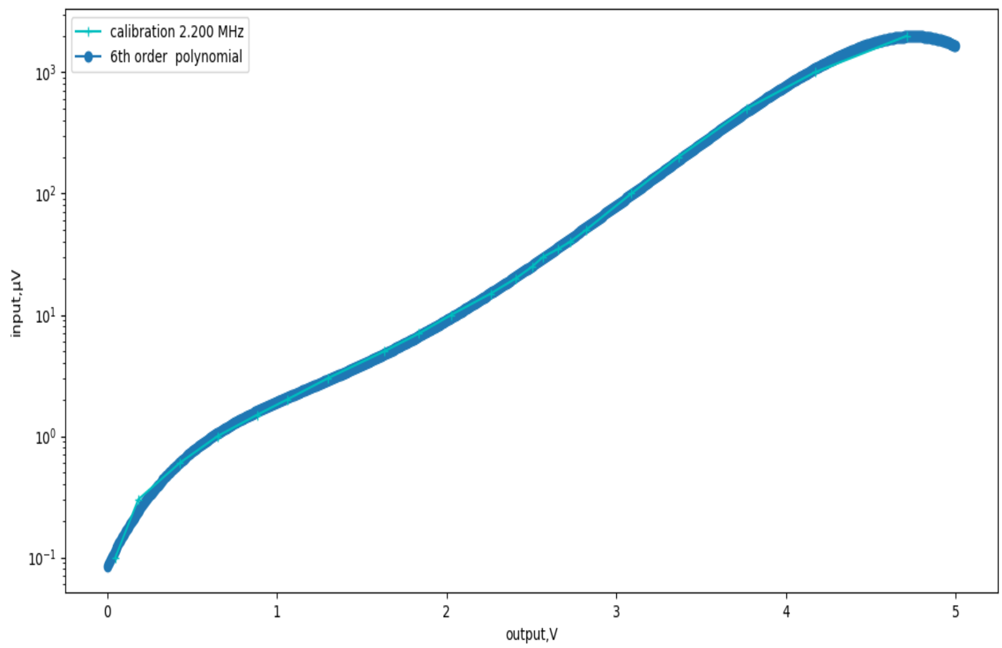

Figure A.19: Calibration data: Polyfit function for frequency 1 = 1.300 MHz (6th order)

(f42 , t42)	Time (sec)
118000 : 122000	60 to 63
123576 : 130000	65 to 70
131000 : 136000	72 to 76
138000 : 140000	78 to 79.75
142000 : 146000	82 to 85.5
148000 : 152000	87 to 91
155000 : 159000	94 to 97.5
172000 : 180000	110 to 117
182000 : 187000	119 to 123
188000 : 191000	124 to 127
192000 : 204000	128 to 140
206000 : 212000	142 to 147
214000 : 219000	149 to 152
220000 : 223000	154 to 157
224000 : 232000	158 to 165
234000 : 238000	167 to 171
239000 : 242000	172 to 175

Table A.1: Windows scarification table of frequency 4 = 7.835 MHz

(f32 , t32)	Time (sec)
118000 : 122000	60 to 63
123550 : 130000	65 to 70
131000 : 136000	72 to 76
137000 : 140000	77 to 80
141000 : 146000	81 to 85
147000 : 152000	87 to 91
153000 : 159000	92 to 97
160000 : 170000	100 to 108
172000 : 180000	110 to 117
181000 : 187000	118 to 123
188000 : 191000	124.5 to 127
192000 : 204000	128 to 140
206000 : 212000	142 to 147
214000 : 219000	149 to 153
220000 : 223000	154.5 to 157
224000 : 232000	158 to 165
234000 : 238000	167.5 to 171
239000 : 242000	172 to 175

Table A.2: Windows scarification table of frequency 3 = 3.883 MHz

(f22 , t22)	Time (sec)
118000 : 122000	60 to 63
123550 : 130000	65 to 70
130500 : 136000	71 to 76
137000 : 140000	77 to 80
141000 : 146000	81 to 85
147000 : 152000	87 to 91
153000 : 159000	92 to 97
160000 : 170000	100 to 108
172000 : 180000	110 to 117
181000 : 187000	118 to 123
188000 : 191000	124.5 to 127
192000 : 204000	128 to 140
206000 : 212000	142 to 147
217000 : 223000	152 to 157
226000 : 232000	160 to 165
234000 : 238000	167.5 to 171
239500 : 242000	172 to 175

Table A.3: Windows scarification table of frequency 2 = 2.200 MHz

(f11 , t11)	Time (sec)
118000 : 122000	60 to 63
123550 : 130000	65 to 70
130500 : 136000	71 to 76
137000 : 140000	77 to 80
141000 : 146000	81 to 85
147000 : 152000	87 to 91
153000 : 159000	92 to 97
160000 : 170000	100 to 108
172000 : 180000	110 to 117
182000 : 187000	119 to 123
188000 : 191000	124.5 to 127
192000 : 204000	128 to 140
206000 : 212000	142 to 147
217000 : 223000	152 to 157
224000 : 232000	158 to 165
234000 : 238000	167.5 to 171
239500 : 242000	172 to 175

Table A.4: Windows scarification table of frequency 1 = 1.300 MHz

List of Figures

List of Tables

List of Abbreviations

CF	**Collision Frequency**
DA	**Differential Absorption**
EM	**Electromagnetic Waves**
HF	**High Frequency**
LF	**Low Frequency**
MF	**Medium Frequency**
MLT	**Mesosphere and Lower Thermosphere**
UHF	**Ultra High Frequency**
VHF	**Very High Frequency**
VLF	**Very Low Frequency**

WADIS	**Wave Propagation and Dissipation**
WP	**Wave Propagation**

Physical Symbols

$\Delta A = Amplitude$

$\omega = Angular\ \ Frequency$

$\vartheta_c = Collision\ \ Frequency$

$\mathrm{N}\epsilon = Electron\ \ Density$

$\omega_c = Gyro\ \ Frequency$

$\omega_p = Plasma\ \ Frequency$

$\Delta \Phi = Phase\ \ shift$

$\vartheta = Phase\ \ Velocity$

$\mu = Real\ \ Part\ \ in\ \ Refractive\ \ Index$

$\mu_0, \mu_x = Real\ \ part\ \ of\ \ the\ \ ordinary\ \ and\ \ extraordinary\ \ indices.$

List of Definitions

- **Altitude :** The apparent height of celestial object above the horizon,measured in angular distance.

- **Amplitude :** The amplitude of a periodic variable is a measure of its change over a single period.

- **Apogee :** When a satellite follows a non-circular orbit around the earth, the satellite's path is an ellipse with the center of the earth at one focus.Such a satellite has variable altitude and variable orbital speed. The point of highest altitude is called apogee.

- **Charged Particle :** A charged particle is a particle with an electric charge. It may be an ion, such as a molecule or atom with a surplus or deficit of electrons relative to protons.

- **Electron Density :** It is the meaure of the probability of an electron being present at specific location.

- **Ionosphere :** The ionosphere is the ionized part of Earth's upper atmosphere, from about 60 km to 1,000 km altitude, a region that includes the thermosphere and parts of the mesosphere and exosphere. The ionosphere is ionized by solar radiation.

- **LOKI-DART-BEACONS :** The Loki-Dart was the sounding rocket version of the Loki surface-to-air spin-stabilized missile briefly used as a barrage weapon by the U.S. Army in 1949.

- **Phase Velocity :** The phase velocity of a wave is the rate at which the phase of the wave propagates in space. This is the velocity at which the phase of any one frequency component of the wave travels. For such a component, any given phase of the wave will appear to travel at the phase velocity.

- **Spin Frequency :** Sounding rockets are constructed for ballistic flights, build up a spin around the roll axis to stabilize the flight vector during the ascent phase. The final spin frequency depends on the type of rocket. Spin rates in the range of several Hz are obtained.

- **Yo - yo system :** A Yo- yo de-spin mechanism is a device used to reduce the spin of satellites, typically soon after launch. The cables are wrapped around the final stage and /or satellite, in the manner of a double yo-yo. When the weights are released, the spin of the rocket flings them away from the spin axis.

Bibliography

[1] all images Homepage.https://www.bing.com/.

[2] Slideshare.net homepage.https://www.slideshare.net/.

[3] AGU,Advance earth and space science https://agupubs.onlinelibrary.wiley.com/action/doSearch?AllField=farday+rotation+&SeriesKey=1944799x.

[4] day and night structure of F layer.http://www.idc-online.com/technical_references/pdfs/electronic_engineering/Day_and_night_structure_of_ionosphere.pdf.

[5] DLR.de homepage. https://www.dlr.de/DE/Home/home_node.html;jsessionid=03D46BB50C417275A2BCE7811FAD426F.delivery-replication2.

[6] Savitzky - Golay filter.https://c.mql5.com/forextsd/forum/147/sgfilter.pdf.

[7] FDG Bennett, JE Hall, and PHG Dickinson. "D-region electron densities and collision frequencies from Faraday rotation and differential absorption measurements". In: *Journal of Atmospheric and Terrestrial Physics* 34.8 (1972), pp. 1321–1335.

[8] Martin Eberhart et al. "Atomic oxygen number densities in the mesosphere–lower thermosphere region measured by solid electrolyte sensors on WADIS-2". In: *Atmospheric Measurement Techniques* 12.4 (2019), pp. 2445–2461.

[9] Josef Ettl and Johann Pfänder. "Rate Control System for Sounding Rockets". In: *19th Symposium on European Rocket and Balloon Programmes and Related Research*. Sept. 2009. URL: https://elib.dlr.de/82067/.

[10] Martin Friedrich. *Handbook of the Lower Ionosphere*. 2016.

[11] Martin Friedrich, C Pock, and K Torkar. "Long-term trends in the D-and E-region based on rocket-borne measurements". In: *Journal of atmospheric and solar-terrestrial physics* 163 (2017), pp. 78–84.

[12] Martin Friedrich et al. "Multi-instrument comparisons of D-region plasma measurements". In: *Annales Geophysicae*. Vol. 31. European Geosciences Union. 2013, p. 135.

[13] Qiang Li et al. "Active falling sphere for high-resolution measurements of density, temperature, and horizontal winds in the middle atmosphere". In: *European Space Agency, (Special Publication) ESA SP* 721 (Jan. 2013), pp. 361–366.

[14] Ken-ichi Maeda. "Radio propagation effects used on rockets in probing the ionosphere". In: *Journal of Atmospheric and Terrestrial Physics* 32.4 (1970), pp. 647–661.

[15] Scott Robertson et al. "Mass analysis of charged aerosol particles in NLC and PMSE during the ECOMA/MASS campaign". In: (2009).

[16] LG Smith. "Electron density measurements in the middle atmosphere by radio propagation techniques". In: *In International Council of Scientific Unions Handbook for MAP, Vol. 19 15 p (SEE N86-26725 17-46)*. Vol. 19. 1986.

[17] Wikipedia contributors. *Filter (signal processing)*. `https://en.wikipedia.org/w/index.php?title=Filter_(signal_processing)&oldid=918000725`. [Online; accessed 15-October-2019]. 2019.

[18] Wikipedia contributors. *Interpolation*. `https://en.wikipedia.org/w/index.php?title=Interpolation&oldid=920371919`. [Online; accessed 15-October-2019]. 2019.

[19] Wikipedia contributors. *Ionosphere*. `https://en.wikipedia.org/w/index.php?title=Ionosphere&oldid=917206272`. [Online; accessed 15-October-2019]. 2019.

[20] Wikipedia contributors. *Radio propagation*. `https://en.wikipedia.org/w/index.php?title=Radio_propagation&oldid=888140273`. [Online; accessed 15-October-2019]. 2019.

[21] Wikipedia contributors. *Savitzky–Golay filter — Wikipedia, The Free Encyclopedia.* `https://en.wikipedia.org/w/index.php?title=Savitzky`. [Online; accessed 1-November-2019]. 2019.

[22] Wikipedia contributors. *Scattering — Wikipedia, The Free Encyclopedia.* `https://en.wikipedia.org/w/index.php?title=Scattering&oldid=919026908`. [Online; accessed 1-November-2019]. 2019.

[23] Wikipedia contributors. *Skip zone — Wikipedia, The Free Encyclopedia.* `https://en.wikipedia.org/w/index.php?title=Skip_zone&oldid=912584522`. [Online; accessed 16-October-2019]. 2019.

Acknowledgement

Essentially i would like to express my inmost requital to all those who helped me to accomplished this M. Sc. thesis.

I would like to express my appreciativeness to Prof. Dr.-ing. habil Andreas Ahrens for providing me research possibility by being my objective supervisor at Hochschule Wismar. As a result of his continuous support throughout my Master Thesis i enact my thesis goal.

Additionally my whole hearted thanks to Dr. Boris Strelnikov by being my supervisor at Leibniz Institute of Atmospheric Physics for his exceptional guidance, patience and providing me an comfortable surroundings to transact this M. Sc. thesis at IAP as well as for his immense supervision and perpetual support during the learning process of this thesis.

Furthermore my sincere benediction goes to Dr.-ing. Toralf Renkwitz who offered me this opportunity to work at IAP.

Finally i express my gramercy towards my family and friends for their love, encouragement, support and motivation to consummate my mark.