



Determination of the Speed and Source Height of Coronal Shock Waves Using Type II Solar Radio Bursts

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DECLARATION

I certify that this dissertation does not incorporate, without acknowledgment, any material previously submitted for a Degree or Diploma in any university, and to the best of my knowledge and belief, it does not contain any material previously published or written or orally communicated by other people except where due reference is made in the text.

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Sahan Liyanage

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Abstract

This study investigates the determination of shock speed and source height of coronal shock waves using Type II solar radio bursts, focusing specifically on metric-type bursts. A total of 25 datasets were analyzed, sourced from the e-Callisto solar spectrometer network, covering observations from January 2022 to October 2023. Employing Python for a custom-designed noise reduction process, this study isolated bursts using the maximum intensity points on noise-reduced dynamic spectra. The study successfully derived explicit formulas linking shock speed and source height with starting frequency and frequency drift rate, utilizing the plasma oscillation theory and the Newkirk model for solar coronal electron density. These formulas provide a more direct and reliable method for calculating these critical parameters, essential for understanding and predicting solar activity. The research confirmed the calculated shock speed ranged between 343 km/s and 1032 km/s, and the source height values were between $1.317 R_s$ and $1.724 R_s$, agreeing well with previous studies. No correlation was observed between the shock speed and the associated CME speed. The source height was able to be predicted from the best-fit curve $R_s = 7.7f_s^{0.59} + 0.73$ with R -squared value of 0.999 and RMSE value of 0.003. Additionally, the analysis identified that the accuracy of isolating bursts using the second maximum intensity was suboptimal compared to using the first maximum intensity points, influencing the precision of the calculations. This study also highlights the limitation of focusing solely on metric type Type II bursts, recommending the expansion of future datasets to include DH and KM types for a more comprehensive analysis. This study demonstrates that the newly developed noise reduction and burst isolation techniques are effective and that the resulting formulas for determining shock parameters are consistent with existing methodologies. These advancements enhance both the theoretical framework and practical applications in solar physics and astrophysics, particularly in improving the accuracy and reliability of space weather forecasts.

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ABBREVIATIONS

CME	- Coronal Mass Ejections
CALLISTO	- Compound Astronomical Low-frequency Low cost Instrument for Spectroscopy and Transportable Observatory
SOHO	- Solar and Heliospheric Observatory
SDO	- Solar Dynamic Observatory
GPS	- Global Positioning System
SRB	- Solar Radio Bursts
LOFAR	- LOw Frequency ARray
MWA	- Murchison Widefield Array
ISWI	- International Space Weather Initiative
FITS	- Flexible Image Transport System
UT	- Universal Time
LASCO	- Large Angle and Spectrometric Coronagraph
DH	- Decametric
KM	- Kilometric

Chapter 1

INTRODUCTION

The Sun, our closest star, is a complex and dynamic astronomical body that significantly impacts the solar system, particularly Earth. It releases energy through nuclear fusion, a process where hydrogen atoms fuse to form helium, energy, and heavier elements. This release of energy causes the Sun's gases to ionize, forming a plasma that generates strong magnetic fields across the solar surface. Due to the Sun's dynamic nature, these magnetic fields often reconnect, releasing massive amounts of energy in the form of Coronal Mass Ejections (CMEs) or Solar Flares[35, 16].

This thesis aims to refine measurement techniques by addressing two primary research questions: 1) Can the shock speed and source height of coronal shock waves be effectively determined using Type II solar radio bursts(SRBs)? 2) What is the impact of burst intensities on the accuracy of these measurements? Addressing these questions will enhance the methodologies for predicting and understanding the dynamics of solar eruptions.

The solar corona, the Sun's outermost layer, consists of plasma with varying electron densities, described empirically by models such as the Newkirk, Leblanc, and Saito models[25, 31, 15]. Typically, shock waves, often initiated by CMEs or Solar Flares, propagate through the corona, accelerating electrons and inducing plasma oscillations. These phenomena lead to radio emissions, which can be identified as Type II Solar Radio Bursts[24, 33]. By analyzing these bursts, particularly through the e-Callisto network a global network of ground stations it is possible to determine critical shock parameters such as frequency drift rate, shock velocity, and the radial distance of the shock from the Sun's center.

The objective of this study is to improve the understanding and predictive accuracy of space weather forecasting by determining the shock speed and source height of shock waves generated by solar flares and CMEs. This research involves collecting and preprocessing 25 datasets of metric-type Type II solar radio bursts from the e-Callisto network. It applies the Newkirk density

model to analyze solar corona and plasma oscillations and derives expressions for shock speed and source height. A comparative analysis will then assess the efficacy and accuracy of these measurements against those obtained from alternative methods and models. This research will elucidate the broader implications of these refined shock speed determinations for space weather forecasting, particularly their potential to improve the accuracy of predictions concerning the timing and impact of solar flares and CMEs on Earth's space environment.

In most past studies, burst noise reduction and burst isolation processes have utilized apparent methods and image processing techniques. Furthermore, the calculation of shock parameters has often directly applied empirical data for electron density in the solar corona[33]. This study proposes an approach to reduce background noise in the raw data, isolate the burst using a manual method, and calculate shock speed and source height using explicit formulas that combine the theory of plasma oscillations with the solar coronal density model (Newkirk Density Model). Thus, this research will make a significant contribution to the field of solar physics by enhancing the precision and reliability of measurements obtained from Type II solar radio bursts. The improved methodologies will aid in accurately forecasting space weather conditions, potentially mitigating the adverse effects of solar activity on Earth's technological systems.

The structure of the thesis is organized as follows: Chapter 1 introduces the study, outlining the problem, research questions, and significance. Chapter 2 reviews existing literature, discussing previous research and methodologies related to solar radio bursts. Chapter 3 integrates the theory of plasma oscillations with the Newkirk density model and derives explicit formulas for shock speed and source height for coronal shocks. Chapter 4 details the data collection methods and analytical techniques employed in this study. Chapter 5 presents the results and discusses their implications for predicting space weather conditions. Finally, Chapter 6 concludes the research and offers recommendations for future studies in this area.

Chapter 2

LITERATURE REVIEW

2.1 Solar Coronal Electron Density

The study of solar coronal electron density is pivotal for understanding solar phenomena, predicting space weather, and its impact on Earth's communication systems. Empirical electron density models, including the Newkirk, Saito, and Leblanc models, play a crucial role in this domain. These models offer a framework to estimate the electron density in the solar corona, which is essential for analyzing solar activities such as coronal mass ejections (CMEs) and solar flares, and for estimating the shock speed of magnetohydrodynamic shocks that are generated by solar eruptive events such as CMEs and solar flares.

The Newkirk model, proposed by G Newkirk Jr in 1961, was one of the first to offer an empirical formula for electron density distribution in the corona, suggesting a radial density distribution that increases exponentially with height above the photosphere. This model was primarily based on observation of the solar corona during solar eclipses and was a significant step forward in coronal studies[25].

The Saito model, developed by K. Saito in 1977 extended the understanding of coronal electron density by providing a more detailed latitudinal structure of the corona. This model was derived from observations of K-coronameter data and introduced a significant improvement over the Newkirk model by accounting for the solar cycle's effects on electron density[31].

Leblanc, Dulk, and Bougeret introduced the Leblanc model in 1998, which offered a two-fold radial density distribution that better matched in-situ observation from spacecraft. This model was particularly useful for studying the dynamics of solar wind and provided a more accurate estimation of electron density at various distances from the sun[15].

Recent studies have tested the validity of these models against observations from modern instruments like the Solar and Heliospheric Observatory (SOHO) and the Solar Dynamics Observatory (SDO). For instance, [18] have used observation of type II radio bursts to evaluate

electron density models, finding that while these models provide a good first approximation, discrepancies arise due to the dynamic nature of solar corona and the influence of solar activity on electron densities.

2.2 Solar Flares and Coronal Mass Ejections(CME)

Solar flares are intense bursts of radiation emitted from releasing magnetic energy in the Sun's atmosphere, primarily observed in the X-ray and extreme ultraviolet wavelengths[28]. Coronal Mass Ejections(CMEs), on the other hand, are large expulsions of plasma and magnetic field from the solar corona into space, capable of releasing billions of tons of coronal material such as plasma[35]. Although these phenomena are primarily observed in the X-ray and extreme ultraviolet wavelengths, radio emissions can also be used to study them[9]. The origin of both phenomena is closely tied to the Sun's magnetic field. Solar flares typically occur in active regions around sunspots, where magnetic fields are highly concentrated and complex[2]. CMEs can be associated with solar flares but can also occur independently. They are often linked to the eruption of magnetic flux ropes, structures in the corona twisted by the Sun's differential rotation, and convective motion[6].

Solar flares and CMEs have profound implications for Earth and its near-space environment. The radiation from a solar flare can ionize the Earth's upper atmosphere, disrupting radio communications and causing navigation errors in GPS systems[11]. CMEs, with their powerful magnetic fields and embedded plasma, can interact with the Earth's magnetosphere, potentially leading to geomagnetic storms. These storms can induce electric currents in power lines, leading to transformer damage and power outages, and enhance the degradation of satellite components[5].

Recent research has focused on improving the predictability of solar flares and CMEs. Studies utilizing advanced solar observation satellites, such as the Solar Dynamic Observatory(SDO) and the Solar and Heliospheric Observatory(SOHO), have provided valuable data for understanding the precursors to these events[27]. Machine learning and artificial intelligence have been increasingly applied to this data to predict solar flares and CMEs, showing promise in forecasting space weather with greater accuracy[4]. In this study, we will try to get those

characteristics, such as the speed of the Magnetohydrodynamic(MHD) Shock and its source height of Solar flares and CMEs, using radio emissions from the sun.

2.3 Magnetohydrodynamic(MHD) Shock Waves

MHD shock waves are large-scale disturbances in the plasma of the solar corona, driven by sudden releases of magnetic energy. These waves propagate through the corona and can accelerate particles to high energy, leading to various solar phenomena, including solar radio bursts[33]. They are often associated with solar flares and coronal mass ejections(CMEs), which can launch shock waves through the corona and into the heliosphere. The propagation of these shock waves is influenced by the coronal magnetic field structure and the ambient plasma conditions, making their study complex and multifaceted.

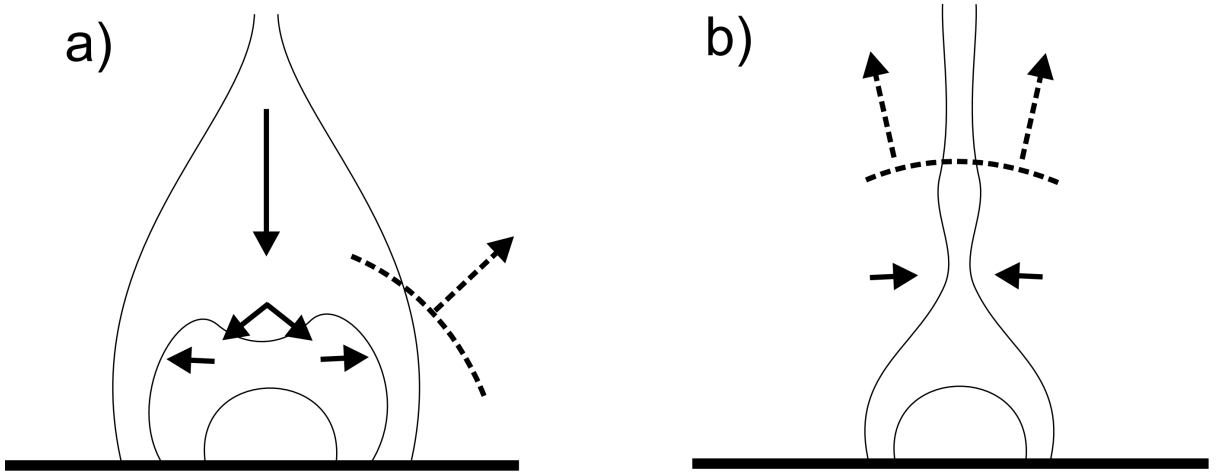


Figure 2.1: (a) Magnetic pressure pulse caused by the formation of the reconnection outflow and the associated deformation of low-lying loops. (b) Outward moving perturbation is created by the changing reconnection rate. Shock waves are depicted by dashed arcs, plasma flows by bold arrows, and field lines by thin solid lines [33].

The speed of MHD shock waves is a critical parameter for understanding their impact on the solar corona and interplanetary space. Shock speeds can vary significantly, typically ranging from a few hundred to several thousand kilometers per second, depending on the driving mechanism and the local coronal conditions[17]. Observational techniques to measure shock speeds include radio imaging, ultraviolet and X-ray observations, and in-situ spacecraft measurements. These methods have provided valuable data for validating theoretical models and improving our understanding of shock dynamics[8].

Empirical studies have significantly advanced our understanding of MHD shock waves and their relation to solar radio bursts. Observations from the SOHO and SDO have been instrumental in tracking shock waves and associated phenomena. Theoretical models, including numerical simulations, have been developed to describe MHD shocks' formation, propagation, and effects, integrating observations with fundamental physical principles[34].

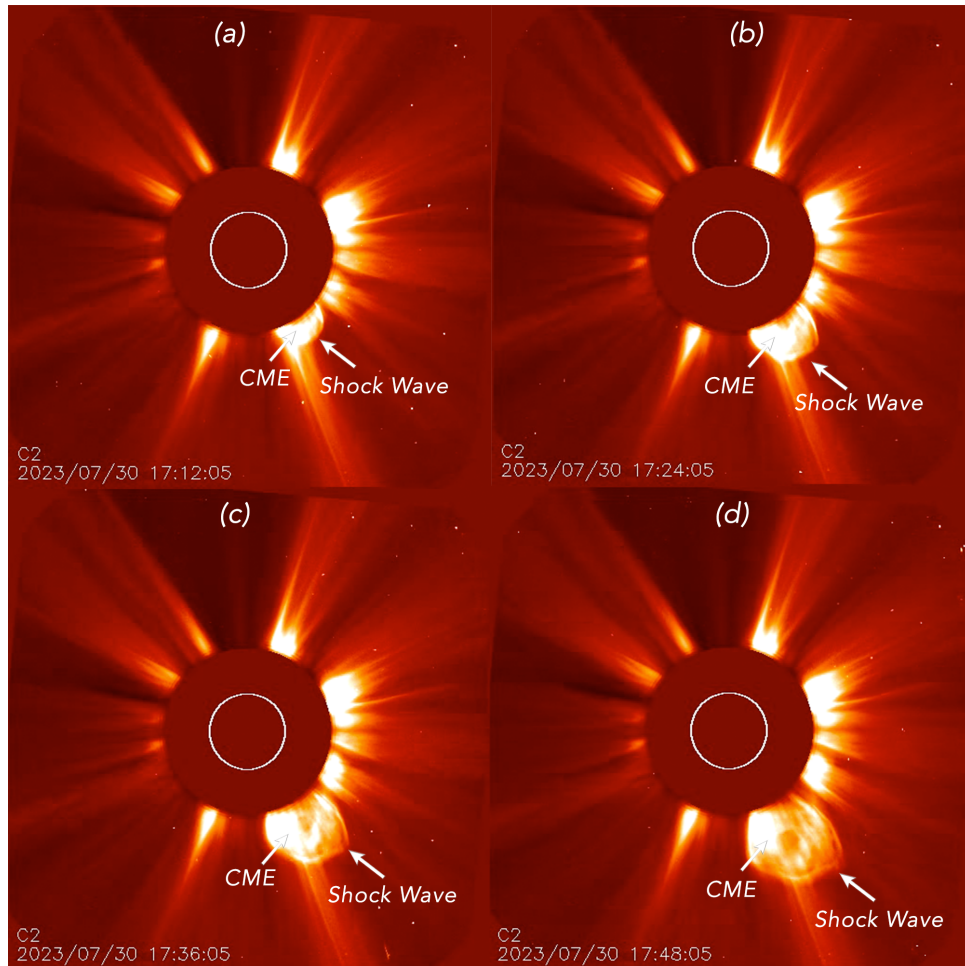


Figure 2.2: A Coronal Mass Ejection observed by the LASCO C2 from the SOHO spacecraft on 30/07/2023 at 17:12:05 UT. (a) The starting point of the CME the shock wave front and the CME is shown in the picture. Figures (b), (c), and (d) are showing the propagation of the CME and the Shock wave in consecutive 12 minutes time intervals.

Recent studies have focused on the interaction between shock waves and the solar corona's magnetic structure, exploring how these interactions influence shock speed and the generation of radio bursts[14]. Additionally, the role of shock waves in accelerating particles to high energies and the subsequent production of solar energetic particle events have been subjects of intense research, linking the dynamics of the corona to observable space weather effects at

Earth[29].

2.4 Solar Radio Bursts

Solar radio bursts represent a class of solar phenomena characterized by the sudden, temporary enhancement of solar radio emission, typically associated with solar flares, CMEs, and other forms of solar magnetic activity. These bursts are classified into five main types (I-V), each with distinct characteristics related to different aspects of solar activity and plasma physics.

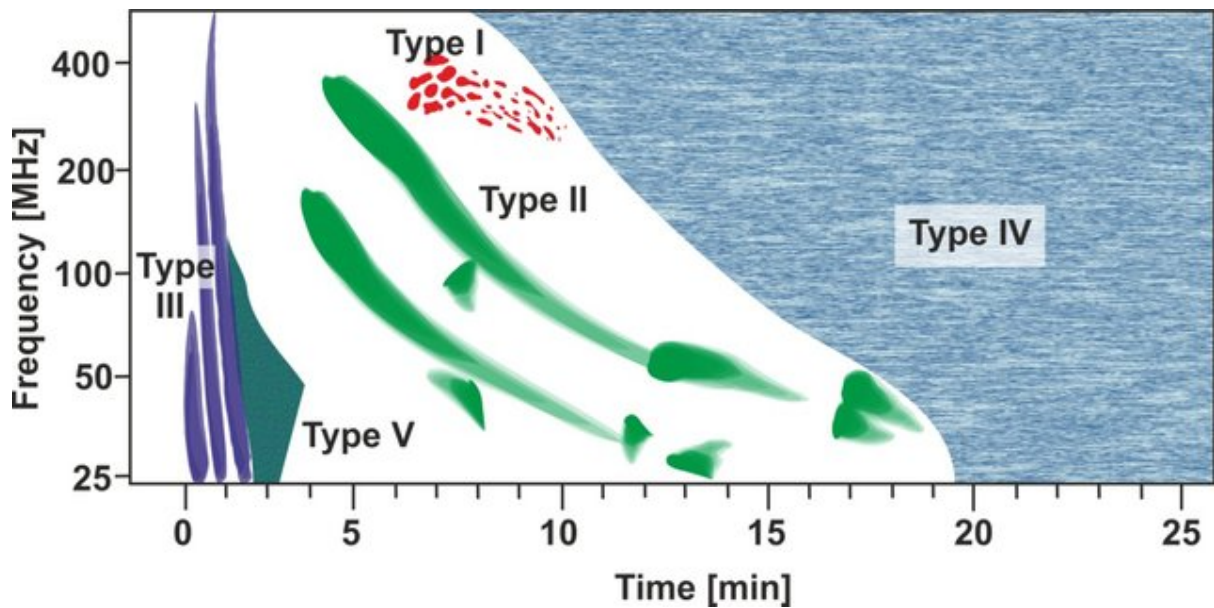


Figure 2.3: Schematic diagram shows the basic classification of solar radio bursts in the frequency range 25-400 MHz based on Ganse et al. 2012 [7].

The classification system for solar radio bursts was first introduced by Wild and McCready in 1950, who categorized them into types I-V based on their spectral features observed in dynamic spectra. Type I bursts are associated with solar flares and active regions, Type II and Type III bursts with shock waves and streams of accelerated electrons, respectively, while Type IV bursts are related to moving magnetic structures in the corona, and Type V bursts are thought to be an extension of Type III bursts[36, 19].

Recent advancements in solar observation and modeling have provided new insights into the mechanisms behind solar radio bursts. High-resolution observations from spacecraft like the SDO is revealing the fine structure of radio bursts in unprecedented detail, offering new opportunities to understand the complex interplay between solar magnetic activity, particle

acceleration, and plasma processes in the solar atmosphere[13].

2.4.1 Type II Solar Radio Bursts

Type II solar radio bursts represent a critical diagnostic tool in the study of magnetohydrodynamic (MHD) shocks in the solar corona, providing valuable insights into the dynamics of solar eruptions and the propagation of shock waves through the solar atmosphere and interplanetary space. In this study, we will focus on Type II solar radio bursts.

Type II solar radio bursts are characterized by their slow frequency drift from high to low frequencies in radio dynamic spectra. This drift is interpreted as the signature of a shock wave moving through the solar corona and into the interplanetary medium, encountering plasmas of progressively decreasing density. These bursts are often associated with solar flares, coronal, mass ejections(CMEs), and other forms of solar magnetic activity that are capable of driving shock waves through the solar atmosphere[24, 33].

The association between type II bursts and MHD shock waves arises from the understanding that these bursts are generated by the interaction of shock waves with the solar corona's plasma. As the shock wave propagates, it accelerates electrons, which then produce radio emission through plasma radiation mechanisms. The frequency of the emitted radiation corresponds to the local plasma frequency, which is directly related to the electron density of the medium through which the shock is traveling. Thus, the observed frequency drift of Type II bursts can be used to trace the shock's path and estimate its speed[18, 8].

The speed of the MHD shock wave is a fundamental parameter for understanding the dynamics of solar eruptions and their potential impact on space weather. It can be estimated from Type II radio bursts by analyzing the rate of frequency drift in the dynamic spectrum. This method relies on models of the solar corona's electron density distribution to convert frequency drift rates into velocity estimates. Various empirical models, such as the Newkirk model, Saito model, and Leblanc model have been employed for this purpose, allowing researchers to infer shock speeds from observed Type II bursts[25, 31, 15].

Recent advancements in radio astronomy instrumentation have provided high-resolution observations of Type II solar radio bursts, leading to more accurate estimates of shock speeds

and a better understanding of the relationship between Type II bursts and MHD shock waves. For instance, studies utilizing data from the LOw Frequency ARray(LOFAR) and Murchison Widefield Array(MWA) have revealed detailed structures within Type II bursts, offering insights into the fine-scale processes occurring at the shock front[22].

Moreover, theoretical and simulation studies have complemented observational efforts, helping to elucidate the mechanisms of shock wave propagation and electron acceleration responsible for Type II bursts. These studies have also explored the impact of coronal and interplanetary conditions on the characteristics of Type II bursts and the associated shock waves[12].

2.5 e-Callisto Solar Spectrometer

The e-Callisto solar spectrometer network represents a significant advancement in the field of solar radio astronomy, offering a global, ground-based system dedicated to monitoring solar radio emissions, particularly during solar flares, CMEs, and other solar eruptive events.

Developed under the auspices of the International Space Weather Initiative (ISWI), the e-Callisto network aims to provide continuous, 24/7 monitoring of the solar radio spectrum in the frequency range of approximately 45 MHz to 870 MHz. The initiative was spearheaded by Christian Monstein and colleagues at the Institute for Astronomy, ETH Zurich, Switzerland, to expand global coverage of solar radio observations and facilitate access to solar radio data for researchers worldwide[20].

The e-Callisto network is composed of a series of ground-based radio spectrometers, distributed across various locations around the globe to achieve continuous observation of the Sun across different time zones. Each station in the network employs a relatively simple and cost-effective setup, including a broadband log-periodic or Yagi antenna, a low-noise amplifier, and a software-defined radio receiver connected to a computer running the Callisto spectrometer software. This design enables the network to be expanded easily by adding new stations, fostering collaboration among institutions in different countries[3].

The e-Callisto network has made significant contributions to solar physics and space weather research by providing high-temporal and spectral resolution observations of a wide range of solar phenomena, including Type II and Type III solar radio bursts, noise storms, and

other transient events associated with solar flares and CMEs. These observations have been instrumental in studying the dynamics of solar eruptions, the acceleration of solar energetic particles, and the propagation of shock waves in the solar corona and interplanetary space[3].

Chapter 3

THEORY

3.1 Solar Coronal Electron Density

3.1.1 Newkirk Density Model

The Newkirk density model, introduced by Gordon Newkirk, Jr. in 1961, is a semi-empirical model designed to describe the electron density distribution in the solar corona. This model was developed in the early era of solar radio astronomy and has been extensively used to interpret solar radio emissions, particularly for understanding the propagation of radio waves in the corona and for estimating the coronal density at various radial distances from the Sun's surface. The model is especially relevant for studies related to solar radio bursts, such as Type II and Type III bursts, which are influenced by the density of the corona through which they propagate.

The Newkirk density model assumes a spherically symmetric corona, where the electron density n_e decreases as a function of the radial distance, r , from the solar center. The model provides an empirical formula to estimate the electron density as a function of height above the photosphere. The formula for the electron density n_e at a distance R from the Sun's center is given by:

$$n_e(R) = n_0 \beta \times 10^{\alpha \frac{R_0}{R}} \quad (3.1)$$

Where n_0 is the electron density near at the base of the corona(close to the solar surface) and its value is approximately considered in the Newkirk model as $4.2 \times 10^{-4} cm^{-3}$. R_0 is the solar radius and R is the radial distance which is measured from the center of the Sun. α is a constant which is equal to 4.32. β is an enhancement factor holds $1 \leq \beta \leq 4$ in quiet Sun.

The Newkirk model was derived from observations of the solar corona's radio brightness, which is directly related to the electron density. By analyzing radio occupation and white-light

observations, Newkirk was able to estimate the value of n_0 and R that best fit the observed data. The model successfully explained the observed radial gradient of electron density in the corona and has been used to estimate the density at various heights, crucial for understanding the propagation of radio waves and dynamic solar eruptions.

The Newkirk model has been foundational in solar physics, providing a basis for subsequent models that incorporate more complex coronal structures, including streamers, holes, and active regions. Despite its simplicity and the assumption of spherical symmetry, the model remains a cornerstone for studies of the solar corona, particularly in the field of solar astronomy.

In this study, the Newkirk model was chosen for its simplicity and its agreement with recent models, such as those by Saito and Leblanc, to determine shock characteristics such as speed and source height. Additionally, this study focused on calculating the aforementioned characteristics using a one-fold Newkirk model, i.e., $\beta = 1$. [25, 31, 15].

3.1.2 Plasma Frequency

Plasma frequency is a fundamental property of plasma, which are ionized gases consisting of electrons, ions, and neutral atoms or molecules. The plasma frequency represents the natural oscillation rate of the electron density in a plasma in response to a small perturbation without the presence of an external electric field.

Consider a simple model of a plasma with a uniform background of positive ions and a density n_e of electrons that can move freely. When the electrons are displaced from their equilibrium position by a small distance under the influence of a perturbing electric field, they experience a restoring force due to the separation of charge. This situation sets up oscillations of the electron density at the natural frequency of the plasma, the plasma frequency [26].

The restoring force per unit volume on the electrons is given by:

$$F = -en_e E \quad (3.2)$$

Where E is the electric field caused by the displacement of electrons, e is the elementary charge, m_e is the electron mass, and n_e is the electron density. Applying Newton's second law for the

electrons, we get:

$$m_e \frac{d^2x}{dt^2} = \frac{F}{n_e} = -eE \quad (3.3)$$

The electric field E is related to the displacement x by:

$$E = \frac{n_e e x}{\epsilon_0} \quad (3.4)$$

where ϵ_0 is the permittivity of the vacuum. Substituting this into the equation 3.3, we obtain the differential equation for the harmonic oscillator:

$$\frac{d^2x}{dt^2} + \frac{n_e e^2 x}{\epsilon_0 m_e} = 0 \quad (3.5)$$

Thus the angular frequency denoted by ω_{pe} is given by:

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \quad (3.6)$$

Since $f_{pe} = \frac{\omega_{pe}}{2\pi}$ we have the plasma frequency f_{pe} :

$$f_{pe} = \frac{1}{2\pi} \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \quad (3.7)$$

Substituting constants for the above equation and then we can approximate the plasma frequency f_{pe} as follows:

$$f_{pe} = 8.978 \times 10^{-3} \sqrt{n_e} \text{ cm}^{-3} \quad (3.8)$$

3.2 Shock Speed and Source Height from Newkirk Density Model

The one-fold Newkirk density model is employed in this study to obtain the shock characteristics. Recall the equation 3.1 in one-fold form.

$$n_e(R) = n_0 \times 10^{\alpha \frac{R_0}{R}} \quad (3.9)$$

Where $\alpha = 4.32$ and $n_0 \approx 4.2 \times 10^4 \text{ cm}^{-3}$ are constants and $R_0 \approx 696340 \text{ km}$ is the solar radius and R is the radial distance measured from the center of the sun.

The plasma frequency f_{pe} and the electron density n_e are related by,

$$f_{pe} = \kappa \sqrt{n_e} \quad (3.10)$$

Where $\kappa = \frac{1}{2\pi} \sqrt{\frac{e^2}{\epsilon_0 m_e}} \approx 8.978 \times 10^{-3} \text{ MHz/cm}^{\frac{3}{2}}$. All symbols have usual meanings.

Taking the square of both sides of 3.10 we get,

$$f_{pe}^2 = \kappa^2 n_e \quad (3.11)$$

Combining 3.9 and 3.11 we get,

$$f_{pe}^2 = \kappa^2 n_0 10^{\alpha \frac{R_0}{R}} \quad (3.12)$$

Taking the natural logarithm of both sides we get,

$$\ln \left(\frac{f_{pe}^2}{n_0 \kappa^2} \right) = \alpha \ln(10) \frac{R_0}{R}$$

$$\frac{R_0}{R} = \frac{1}{\alpha \ln(10)} \ln \left(\frac{f_{pe}^2}{n_0 \kappa^2} \right)$$

taking the reciprocal of 3.13, we have,

$$\frac{R}{R_0} = \frac{\alpha \ln(10)}{\ln \left(\frac{f_{pe}^2}{n_0 \kappa^2} \right)} \quad (3.13)$$

$$R = \frac{R_0 \alpha \ln(10)}{\ln \left(\frac{f_{pe}^2}{n_0 \kappa^2} \right)} \quad (3.14)$$

Hence, the source height of the CME or the Solar Flare can be estimated using the equation 3.14.

Taking the time derivative of R leads to the radial speed of the Shock Wave generated by a CME or a Solar Flare. This speed is known as the Shock Speed and is denoted by V_s . Thus,

$$V_s = \frac{dR}{dt}$$

Therefore the time derivative of R is given by,

$$\frac{dR}{dt} = \frac{-2R_0\alpha \ln(10)}{f_{pe} \ln^2(\frac{f_{pe}^2}{n_0\kappa^2})} \cdot \left(\frac{df_{pe}}{dt} \right)$$

$$V_s = \frac{2R_0\alpha \ln(10)}{f_{pe} \ln^2(\frac{f_{pe}^2}{n_0\kappa^2})} \cdot \left| \frac{df_{pe}}{dt} \right| \quad (3.15)$$

Substituting the above values for the constants we get the expression for V_s in km/s as follows.

$$V_s = \frac{1.385 \times 10^7}{f_{pe} \ln^2(0.295f_{pe}^2)} \cdot \left| \frac{df_{pe}}{dt} \right| \quad (3.16)$$

Chapter 4

METHODOLOGY

4.1 Data Collection

The data was collected by the e-Callisto network, and all data were publically available at [e-Callisto Database](#). 25 well-defined Type II solar radio bursts were selected. The observation dates for bursts were between January 2022 and October 2023.

Table 4.1: Data sets obtained from different stations around the world.

Date	Time (UT)	Station
2022-01-12	04:22-04:58	AUSTRALIA ASSA
2022-02-20	04:11-04:21	AUSTRALIA ASSA
2022-03-13	23:27-23:46	ALASKA-COHE
2022-04-02	13:21-13:40	ARECIBO
2022-04-11	05:08-05:24	AUSTRIA
2022-05-10	13:56-14:24	ARECIBO
2022-06-13	03:22-03:34	ALASKA-COHE
2022-08-14	12:02-12:11	GLASGOW
2022-10-11	10:59-11:13	GLASGOW
2022-11-09	19:58-20:17	MEXICO LANCE A
2022-12-03	17:42-18:02	ARECIBO
2023-01-10	00:20-00:23	AUSTRALIA
2023-02-21	20:17-20:32	MEXICO LANCE B
2023-02-25	19:23-19:39	ALASKA-HAARP
2023-03-02	17:37-17:58	GREENLAND
2023-03-04	15:31-15:35	GLASGOW
2023-05-09	00:14-00:27	AUSTRALIA

Table 4.1 continued from previous page

Date	Time (UT)	Station
2023-06-13	17:41-17:53	ARECIBO
2023-07-10	11:44-12:01	GLASGOW
2023-07-14	16:44-16:58	ARECIBO
2023-07-15	10:14-10:28	SRI LANKA
2023-08-17	12:36-12:52	GLASGOW
2023-08-18	19:23-19:49	ALASKA-HAARP
2023-08-26	12:56-12:59	GREENLAND
2023-10-26	23:17-23:34	AUSTRALIA

4.2 Data Preprocessing

4.2.1 FITS Reading

The downloaded data files from the e-Callisto database are in the 'fit.gz' format, in other words, the compressed FITS (Flexible Image Transport System) file format. The file name consists of the station where the burst was detected, the date, the time in Universal Time (UT), and the frequency range number of the instrument. For instance, consider the following data file name downloaded from the e-Callisto network:

GREENLAND_20220302_1737_1758.fit.gz

The following information can be gathered from the file name:

1. Station - GREENLAND
2. Burst date - 2022-03-02
3. Burst start time - 17:37 UT
4. Burst end time - 17:58 UT
5. File Type - fit.gz

Python 3.10 was utilized to analyze the FITS files by using the Astropy library. Also numpy, pandas, scipy, and matplotlib libraries were employed to process data.

Using the Astropy library, the 'fit.gz' file was opened and read. A FITS file contains two headers: the first header stores the numerical values of intensity data for a radio signal detected by the e-Callisto network as an $n \times m$ matrix, while the second header contains the 'frequency' and 'time' data for a radio signal. Utilizing this information, the complete picture of radio signals was plotted using the 'matplotlib' library. As mentioned, the data consists of an $n \times m$ matrix, where n represents the frequency channel and m represents the time channel. Consequently, the matrix values indicate the intensities of the radio signal for corresponding frequency and time channels. Figure 4.1 shows the plotted image of a radio burst.

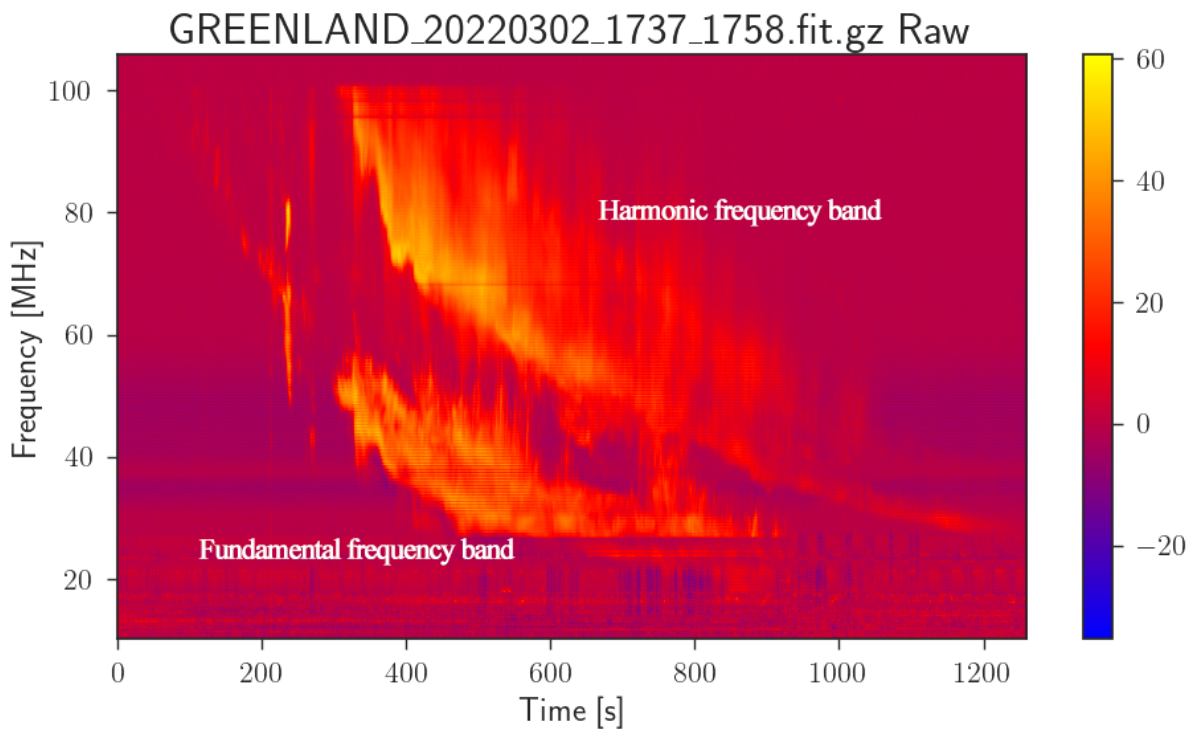


Figure 4.1: A raw plot of the Type II solar radio burst, recorded on March 02, 2022, from 17:37 to 17:58 UT at the Greenland station, clearly shows the fundamental and harmonic bands.

4.2.2 Background Noise Reduction

The numerical observation data extracted from the FITS file comprises an $m \times n$ matrix. The mean (μ_i) of each row is subtracted from every data point in the matrix, resulting in the following filtered data:

$$data_{ij} = data_{ij} - \mu_i \quad (4.1)$$

Subsequently, the filtered data was further processed using a filter that sets threshold values.

$$data_{ij} = \begin{cases} L, & \text{if } data_{ij} < L \\ data_{ij}, & \text{if } L < data_{ij} < U \\ U, & \text{if } U < data_{ij} \end{cases} \quad (4.2)$$

For each numerical value in the data, the lower threshold L and the upper threshold U are defined uniquely for each dataset. If a data value falls below the lower threshold, it is replaced with L ; if it exceeds the upper threshold, it is replaced with U . Otherwise, the data value remains unchanged. The final data values are normalized and plotted.

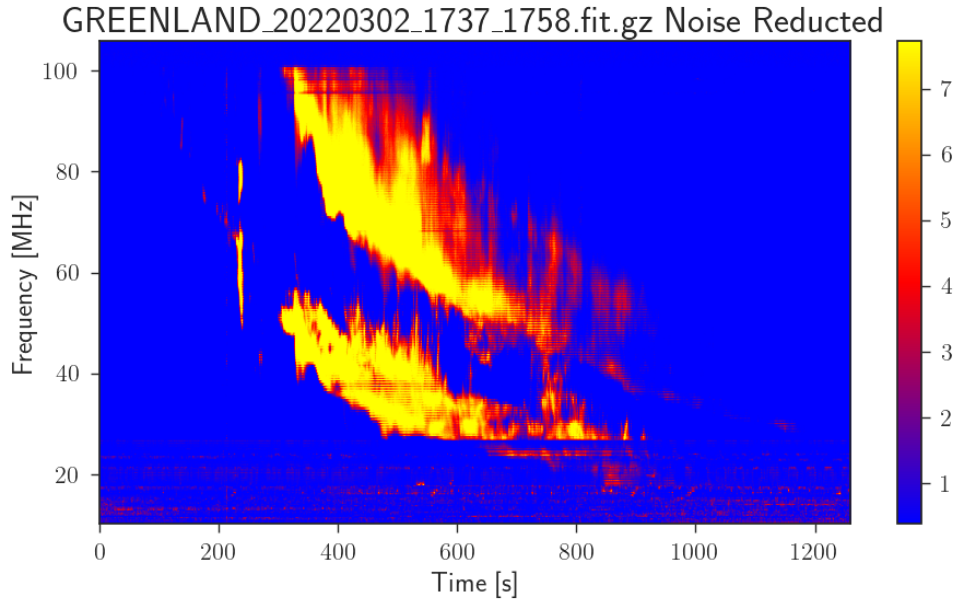


Figure 4.2: Noise-reduced plot of the Type II solar radio burst, recorded on March 02, 2022, from 17:37 to 17:58 UT at the Greenland station, which clearly shows the fundamental and harmonic bands. The burst is highlighted effectively after the noise reduction process, with background noise significantly reduced.

4.2.3 Burst Isolation

Isolating the fundamental frequency band is essential to calculate the shock speed. This was accomplished by loading the filtered data into Python and then manually setting the margins of the data matrix to select the fundamental band. Subsequently, all other data values were set to zero, effectively isolating the burst's fundamental band as shown in Figure 4.3.

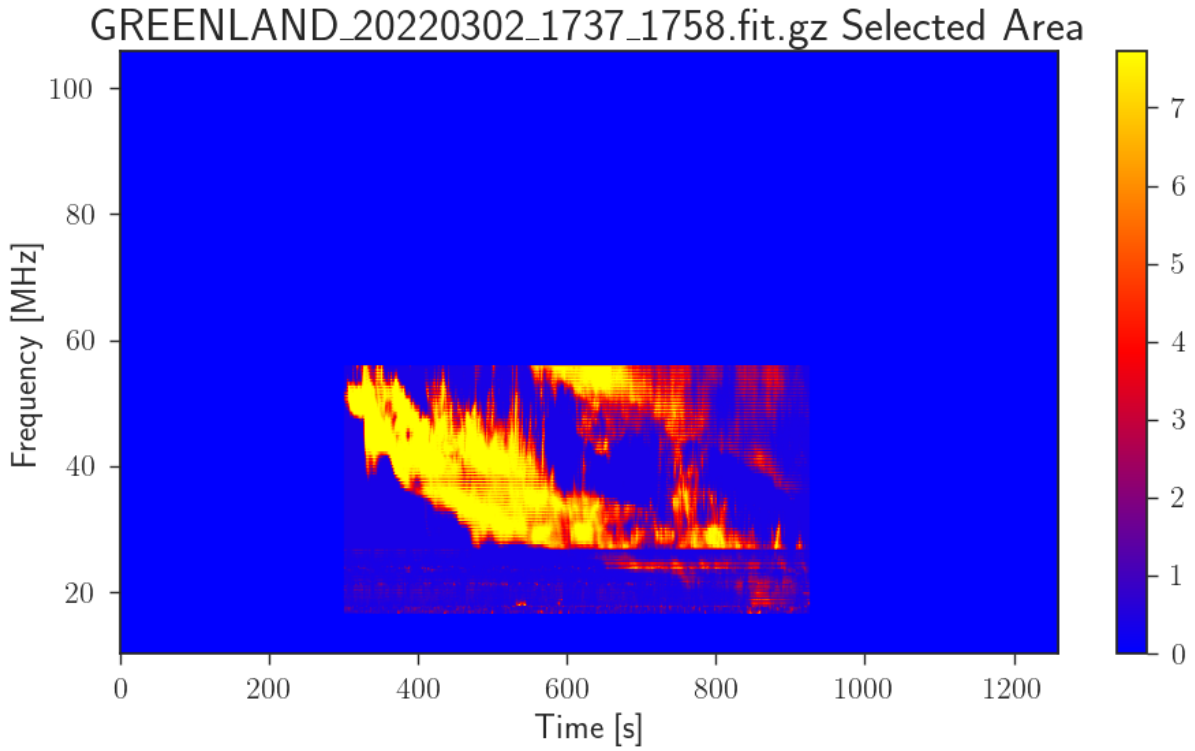


Figure 4.3: Selection of the fundamental frequency band of the Type II solar radio burst observed on March 2, 2022, from 17:37 to 17:58 UT at the Greenland station.

Then, the maximum intensity for each frequency channel was obtained and plotted against the burst time (Figure 4.4).

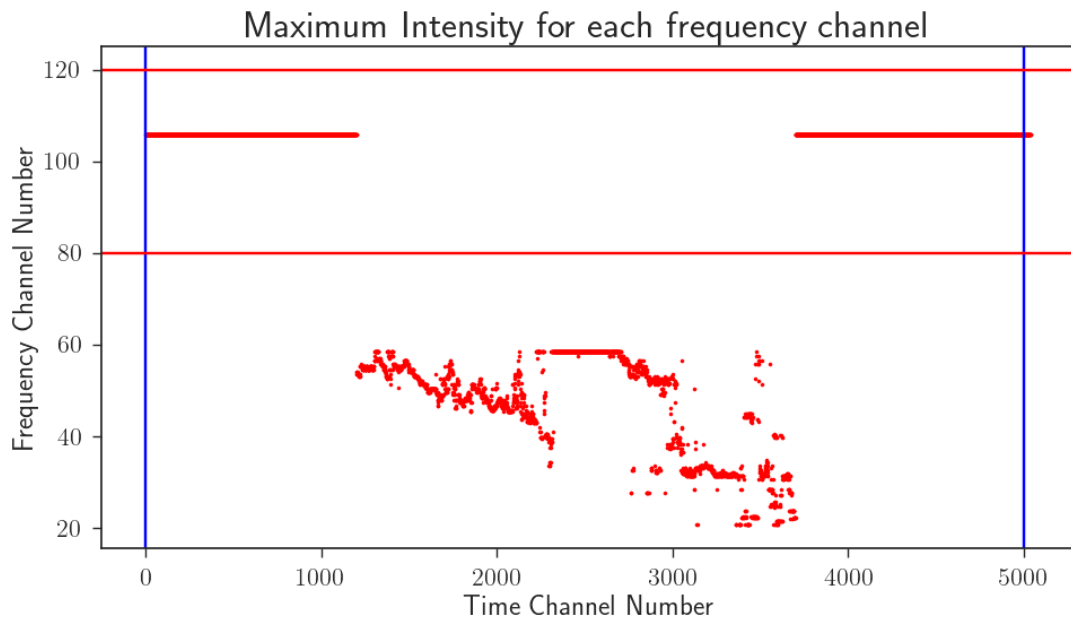


Figure 4.4: The maximum intensity for each channel plotted against the time channel number requires the reduction of noise outliers to isolate the real burst. The two blue vertical and red horizontal lines set the margins to remove noise outliers.

Even though the burst is isolated from the FITS image, it still contains some noise from the harmonic band. To remove these outliers, an area containing the outliers was selected using two horizontal lines and two vertical lines, and the outliers were removed. Several manual filters were applied to obtain the isolated fundamental band of the Type II radio burst.

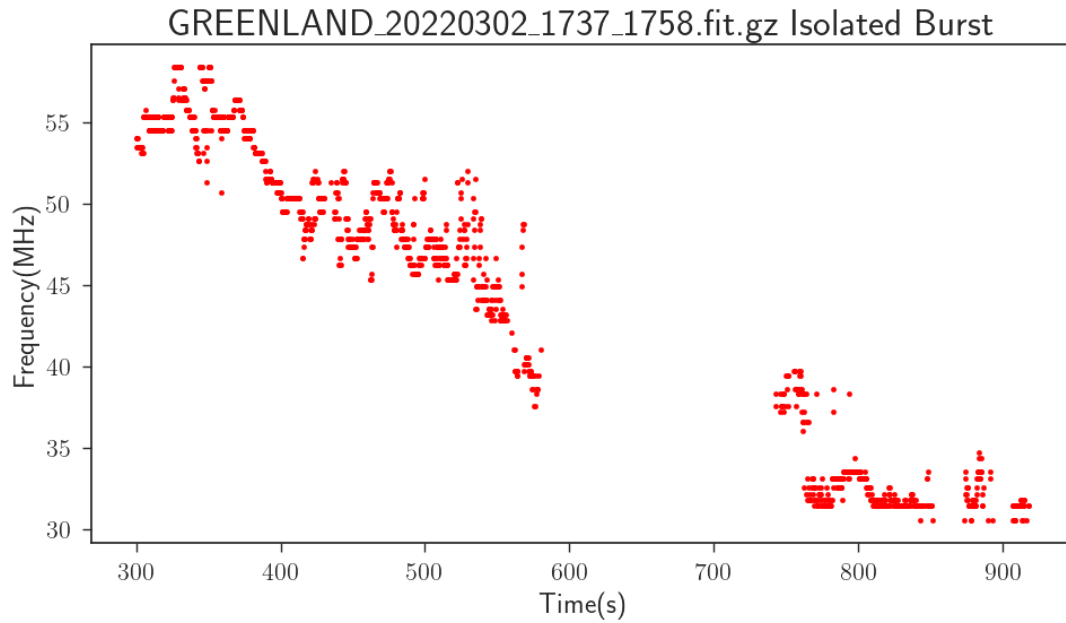


Figure 4.5: Final view of the isolated fundamental frequency band of the Type II solar radio burst.

The same procedure was carried out to isolate the fundamental frequency band for another 24 FITS files.

4.2.4 Calculation of Shock Speed and Source Height

To calculate the shock speed and source height, the obtained filtered dataset must be fitted to a function. It was assumed that the behavior of the isolated burst follows the form $f = A \times t^b$, which obeys the power law.

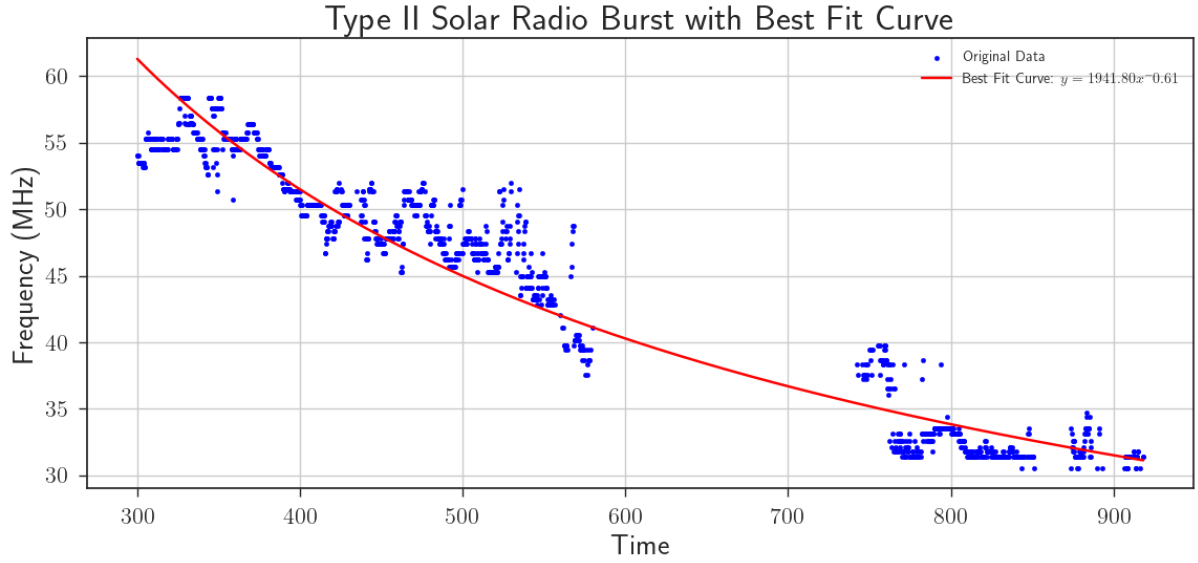


Figure 4.6: The best-fit curve for the Type II solar radio burst observed on March 2, 2022, from 17:37 to 17:58 UT at the Greenland station is given by $f(t) = 194.80t^{-0.61}$. For this particular burst, the R^2 value is 0.922, indicating that the fit agrees with the scattered data points.

In this research, we are interested in finding the initial shock speed it is necessary to find an estimation for the start frequency of the burst. However, the data points are scattered, and the percentile threshold method was used to estimate the start frequency f_{pe} .

Using the fitted curve, the frequency drift rate $\frac{df_{pe}}{dt}$ was calculated and stored in an array. Then, utilizing Equation 3.16, the shock speed for each time point was calculated and stored in an array. Additionally, using Equation 3.13, the source height for each time point was calculated and stored in an array.

The highest 90th percentile of all frequencies was selected to determine the start frequency. Subsequently, the average of these highest 90th percentile frequencies was calculated. The closest index to the calculated average frequency was then identified, and the corresponding frequency in the frequency array was chosen as the starting frequency of the burst. Thus, the corresponding shock speed and source height were obtained using the index of the starting frequency.

4.3 Isolation of the burst using the second maximum intensity of the burst

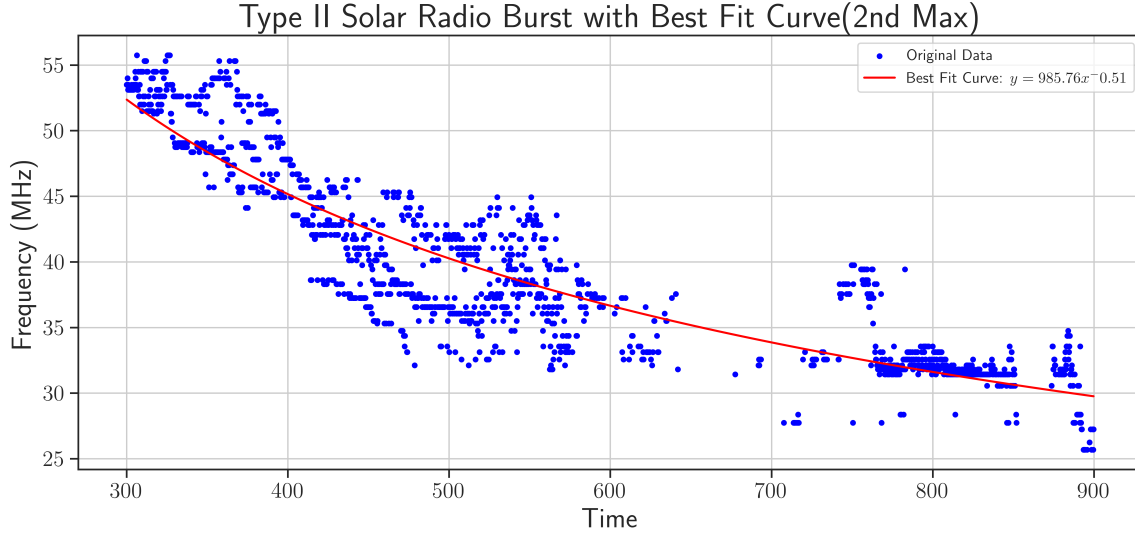


Figure 4.7: The isolated burst using the second maximum frequency value for the Type II solar radio burst observed on March 2, 2022, from 17:37 to 17:58 UT at the Greenland station. (Same burst in the previous step). The best-fit curve is given by $f(t) = 985.76t^{-0.51}$ and the R^2 value is 0.836.

A similar procedure was then carried out for the second maximum intensity value of the type II solar radio burst. In this case, to isolate the burst from the FIT file, the frequency of the second maximum intensity value was chosen instead of the maximum intensity frequency value. The second maximum intensity frequency calculations were carried out to verify whether the trend of the frequency drift rate in the raw burst is the same as the trend given by the maximum intensity frequency.

In this burst isolation, extra data points have been added, and the data points are scattered. Therefore, the R-squared value is less than the previous isolation. The same procedure was carried out to identify the starting frequency.

Chapter 5

RESULTS AND DISCUSSION

5.1 Initial Results

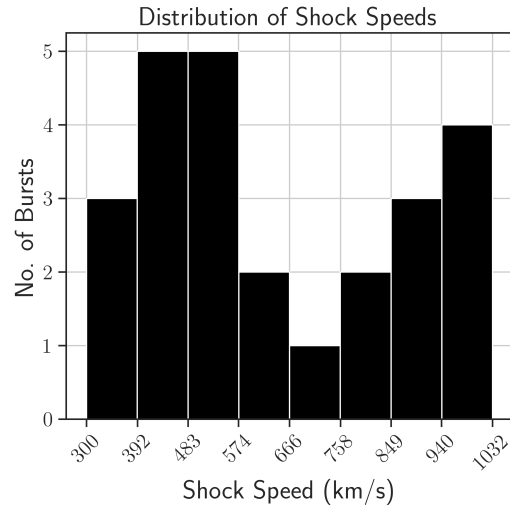
The determination of shock speed and source height of a shock wave generated by a solar flare or a CME was carried out by approximating the solar coronal density by using the Newkirk density model. Then MHD is applied to the corona and assumed that the Type II radio burst frequency detected by the e-Callisto network is equal to the plasma oscillations frequency in the solar corona. Combining the Newkirk model for the solar coronal density and the plasma frequency, the initial radial speed of the shock and its source height were calculated (Table 5.1).

Table 5.1: Initial results for the Shock speed and Source height for 25 type II solar radio bursts.

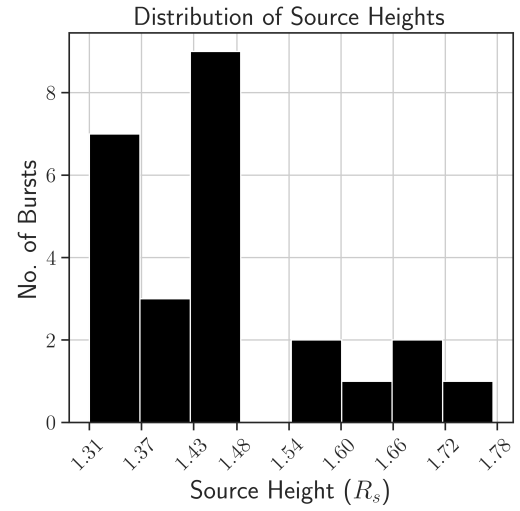
Date	Station	f_s	$\frac{df_{pe}}{dt}$	V_s	R
2022-01-12	AUSTRALIA	56.1	-0.0558	653	1.463
2022-02-20	AUSTRALIA	36.3	-0.0321	638	1.668
2022-03-13	ALASKA-COHE	81.2	-0.1175	456	1.313
2022-04-02	ARECIBO	59.5	-0.0756	900	1.431
2022-04-11	AUSTRIA	75.7	-0.0502	343	1.338
2022-05-10	ARECIBO	72.9	-0.0937	985	1.352
2022-06-13	ALASKA-COHE	34.7	-0.0205	510	1.694
2022-08-14	GLASGOW	60.5	-0.0775	510	1.429
2022-10-11	GLASGOW	72.9	-0.0675	378	1.352
2022-11-09	MEXICO LANCE	58.3	-0.1084	694	1.439
2022-12-03	ARECIBO	82.1	-0.1962	888	1.31
2023-01-10	AUSTRALIA	58.8	-0.1578	1032	1.436
2023-02-21	MEXICO LANCE	74.1	-0.0692	446	1.346
2023-02-25	ALASKA-HAARP	38.2	-0.0279	457	1.640

Table 5.1 continued from previous page

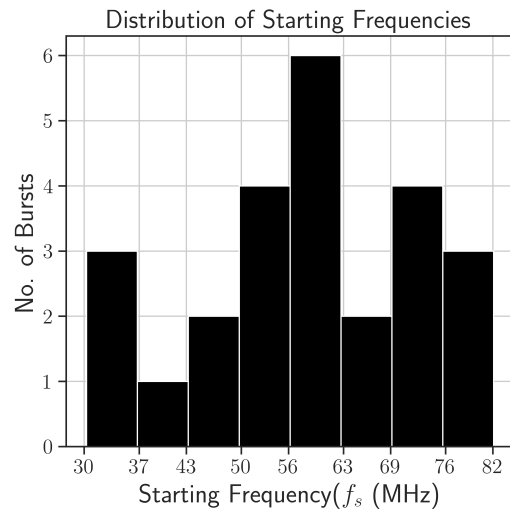
Date	Station	f_s	$\frac{df_{pe}}{dt}$	V_s	R
2023-03-02	GREENLAND	55.8	-0.0629	562	1.458
2023-03-04	GLASGOW	71.0	-0.092	988	1.361
2023-05-09	AUSTRALIA	43.4	-0.0304	567	1.573
2023-06-13	ARECIBO	60.6	-0.0959	783	1.423
2023-07-10	GLASGOW	62.8	-0.0792	760	1.409
2023-07-14	ARECIBO	67.8	-0.0647	466	1.391
2023-07-15	SRI LANKA	56.6	-0.0721	482	1.452
2023-08-17	GLASGOW	52.8	-0.044	300	1.482
2023-08-18	ALASKA-HAARP	55.3	-0.0744	929	1.462
2023-08-26	GREENLAND	45.7	-0.0642	513	1.548
2023-10-26	AUSTRALIA	30.3	-0.0373	1010	1.775



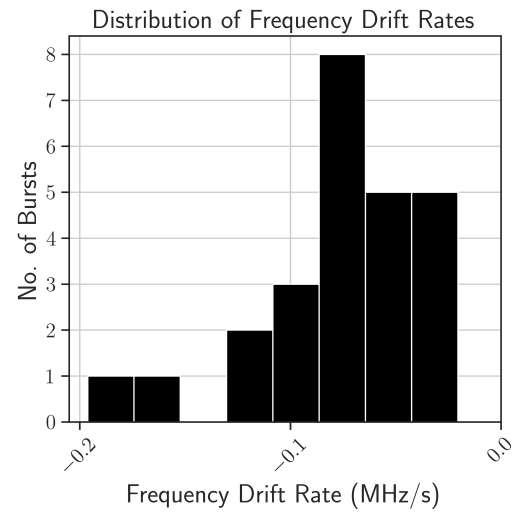
(a)



(b)



(c)



(d)

Figure 5.1: The distribution of (a) shock speed (b) source height (c) Starting frequency (d) frequency drift rate of selected 25 type II metric type solar radio bursts.

Figure 5.1 shows the distributions of the shock characteristics such as shock speed, source height(shock formation height), the starting frequency of the shock, and the frequency drift rate of the type II bursts. The mean and median values for each distribution are given in the table 5.2

Table 5.2: The mean and median values for the distributions of shock speed, source height, starting frequency, and frequency drift rate.

Distribution	Mean	Meadian
Shock Speed	650.0	567.0
Source Height	1.46	1.44
Starting Frequency	58.5	58.8
Frequency Drift Rate	-0.0747	-0.0692

The mean and median values for the distributions of source height and starting frequency closely align, suggesting that these distributions are symmetric. Similarly, the median and mean values for shock speed and frequency drift rate are approximately equivalent, further indicating that these distributions are also roughly symmetric. These findings are consistent with those reported by Aguilar et al. (2005), affirming the symmetry observed in the distributions of these variables.

5.2 Validation of the Noise Reduction and Burst Isolation Procedure

In this study, all chosen Type II radio bursts were of the metric type, which typically encompasses solar radio bursts within a wavelength range of 0 to 10 meters. The obtained frequency drift rates were plotted against the starting frequencies of the corresponding bursts, as shown in Figure 5.2 to validate the noise reduction process.

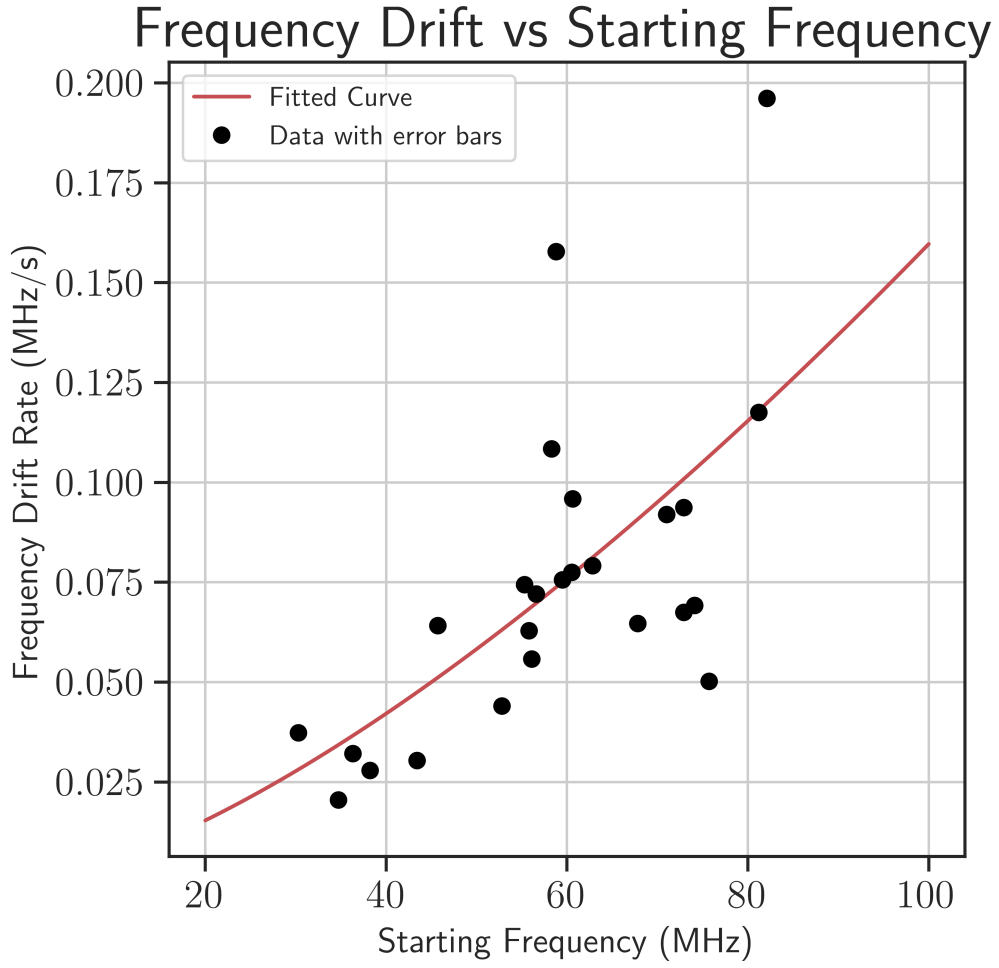


Figure 5.2: The graph of the absolute value of frequency drift versus and starting frequency of type II solar radio bursts. The best-fit curve is $\frac{df}{dt} = -0.000197 f_s^{1.454}$. The correlation coefficient is found to be 0.65.

It was observed that the frequency drift rate ($\frac{df}{dt}$) and starting frequency (f_s) conform to a power law function, expressed as $\frac{df}{dt} = a \times f_s^\psi$. As per Aguilar et al. (2005), for metric-type, Type II solar radio bursts, the power law index (ψ) stands at 1.44. In this study, the power law index ψ was determined to be 1.45 ± 0.42 , suggesting that the noise reduction procedure employed is suitable for further analysis. Additionally, the correlation coefficient indicated a reasonable association between the frequency drift rate and the starting frequency. Although the accuracy of the power law index is deemed satisfactory, the precision of the measurements raises concerns. Thus, it underscores the need for enhancing the noise reduction process. During the burst isolation process, it was noted that some significant intensity points of the burst were

lost, which resulted in less precise measurements, as evidenced by the larger variance.

5.3 Analysis of the Shock Speed

This study aims to estimate the shock speed by integrating the electron density model with plasma frequency. Through the application of the Newkirk density model for the solar corona alongside the local plasma frequency relations, Equation 3.16 for the radial shock speed was derived.

The average shock speed for the selected Type II bursts was determined to be 650 ± 226 km/s, with the calculated shock speeds spanning from 343 km/s to 1032 km/s. These findings agree with previous research on shock speed estimations using Type II solar radio bursts [23].

Current knowledge on Type II solar radio bursts remains limited, with recent studies indicating that the shock speeds of Type II solar radio bursts range from a few hundred to a thousand kilometers per second [23, 17, 32, 10]. Nevertheless, the shock speeds calculated in this study are consistent with these documented results.

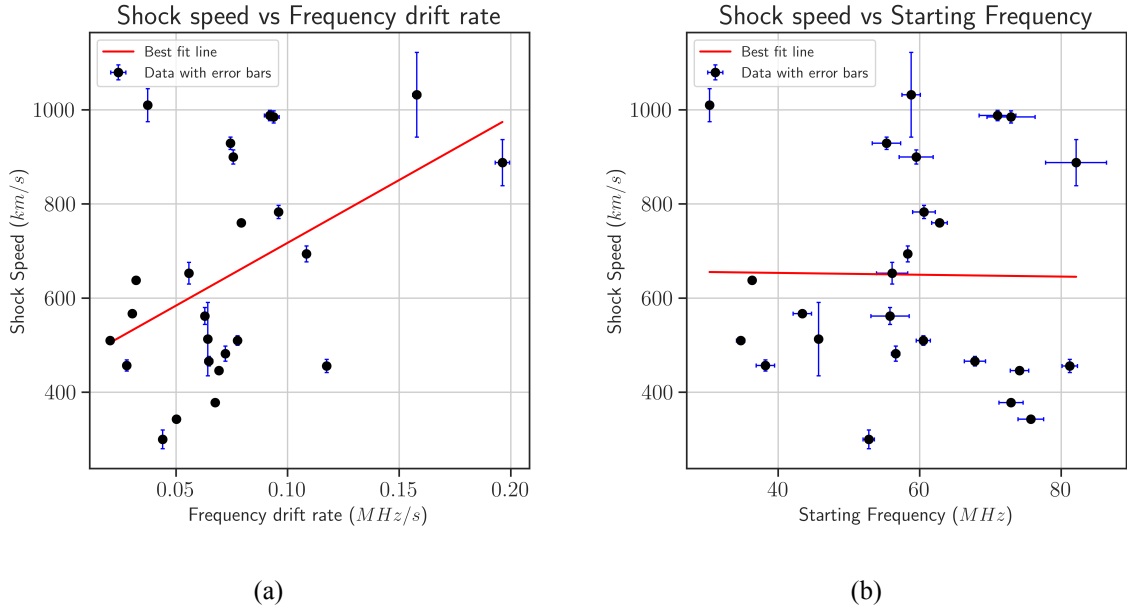


Figure 5.3: (a). The graph of shock speed vs Frequency drift rate. The best-fit line is given by $V_s = 2668.28 \left| \frac{df}{dt} \right| + 450.7$ and The correlation coefficient is 0.463. (b). The graph of shock speed vs Starting frequency. The best-fit line is given by $V_s = -0.194f_s + 661.4$, and The correlation coefficient is -0.012 .

Figure 5.3(a) illustrates the relationship between shock speed and frequency drift rate. The

correlation coefficient of 0.463 suggests a weakly positive correlation between shock speed and drift rate, which agrees with the expectations set forth by Equation 3.16; the equation posits that shock speed is directly proportional to the absolute value of the drift rate. Conversely, Figure 5.3(b) depicts the variation of shock speed with the starting frequency, where a correlation coefficient of -0.012 indicates an absence of correlation between the two variables. This outcome is consistent with predictions from Equation 3.16, which states that shock speed does not have a direct or inverse proportional relationship with the starting frequency. Furthermore, it is evident that the error in calculating the shock speed increases with higher shock speeds. The starting frequency was determined using the percentile method, which also exhibits increasing errors as the starting frequency increases.

Type II solar radio bursts are typically associated with coronal mass ejections (CMEs) and solar flares [33, 24]. However, instances of Type II radio bursts occurring independently of a CME or solar flare have been documented [21]. In the dataset of 25 Type II solar radio bursts analyzed in this study, 24 bursts were associated with a CME. Notably, one burst was observed from the Australian ASSA station on May 9, 2023, from 00:14 to 00:27 Universal Time was not associated with a CME.

The associated CME speeds were obtained from the [SOHO LASCO CME Catalog](#). Both the Type II solar radio bursts and the CMEs were observed concurrently. The corresponding CME speeds were then plotted against the Type II shock speeds, as shown in Figure 5.4.

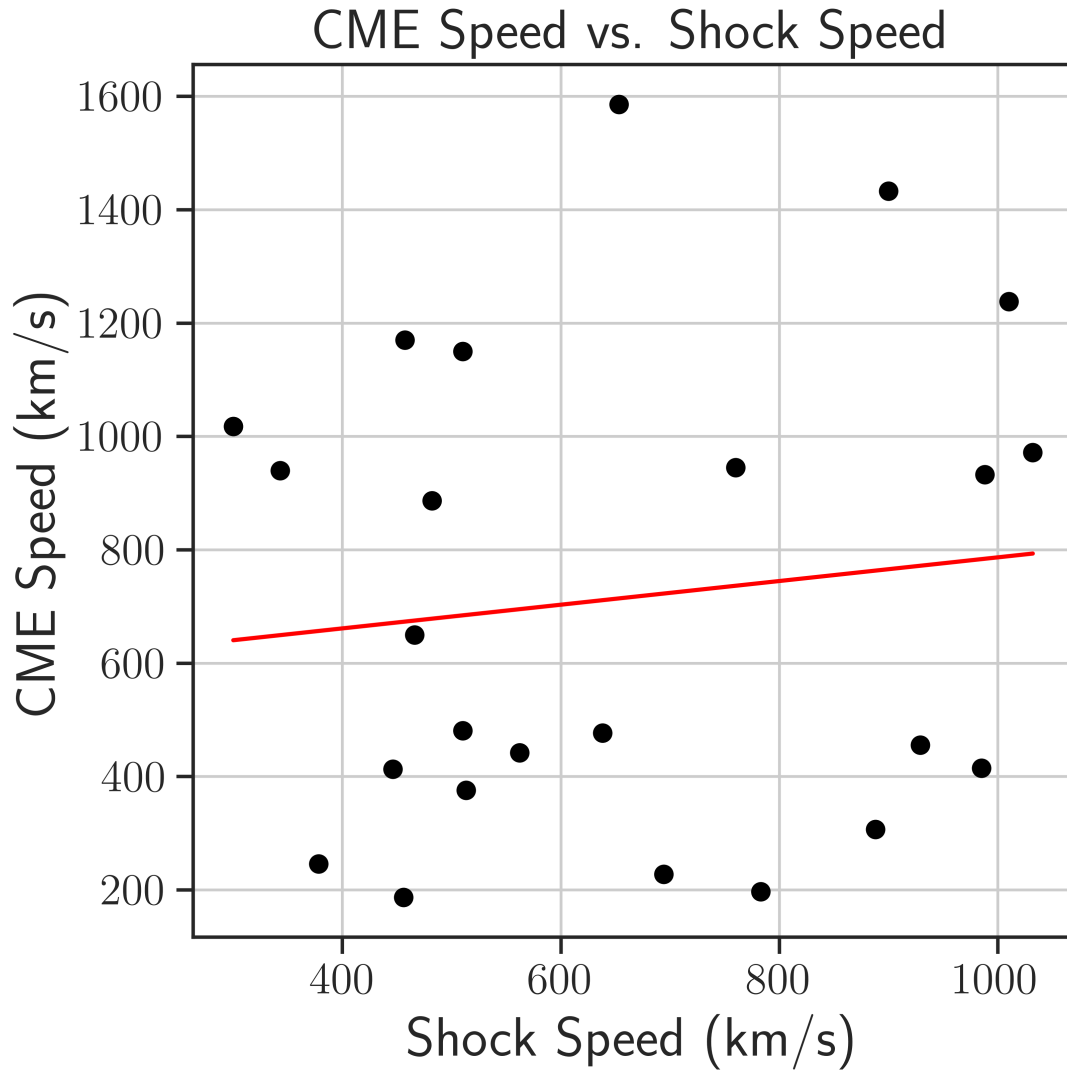


Figure 5.4: The graph of the associated CME speed vs shock speed. The correlation coefficient was found to be 0.117.

Reiner (2001) reported that shock speed parameters derived from metric Type II radio bursts, which are generated in the middle corona ($1.4\text{--}2.0 R_s$), show no significant correlation with the corresponding CME speeds [30]. In agreement with these findings, the correlation coefficient in this study was determined to be 0.117, indicating that there is no significant correlation between CME speed and shock speed, given that all analyzed data pertain to metric Type II solar radio bursts.

5.4 Analysis of the Source Height

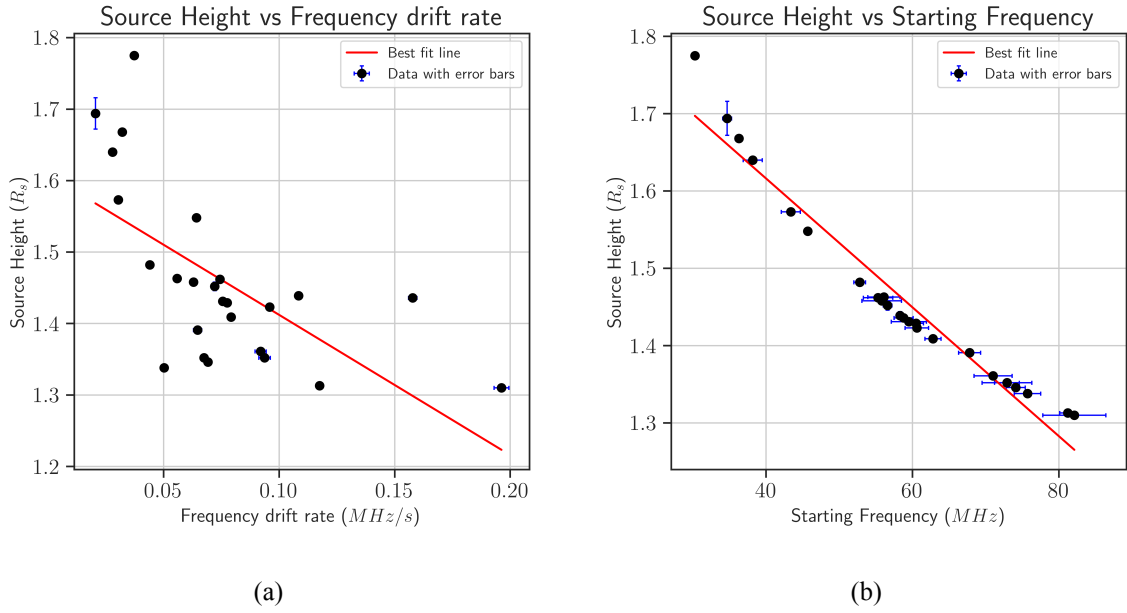


Figure 5.5: (a). The graph of shock formation height vs frequency drift rate. The correlation coefficient is $0 - 0.634$. (b). The graph of shock formation height vs starting frequency. The correlation coefficient is -0.974 .

The source height of the coronal shock, also known as the shock formation height, represents the initial radial distance from the center of the Sun, measured in units of solar radii (R_s). Figure 5.5a illustrates the relationship between source height and frequency drift rate, with a correlation coefficient of -0.634 . This indicates a weak negative correlation, suggesting an inversely proportional relationship between the source height and frequency drift rate. Additionally, Figure 5.5b displays the relationship between source height and the starting frequency. The correlation coefficient of -0.974 indicates a strong negative correlation between these variables. However, the best-fit curve depicted in the graph is not a straight line but rather a curve, as shown in Figure 5.6.

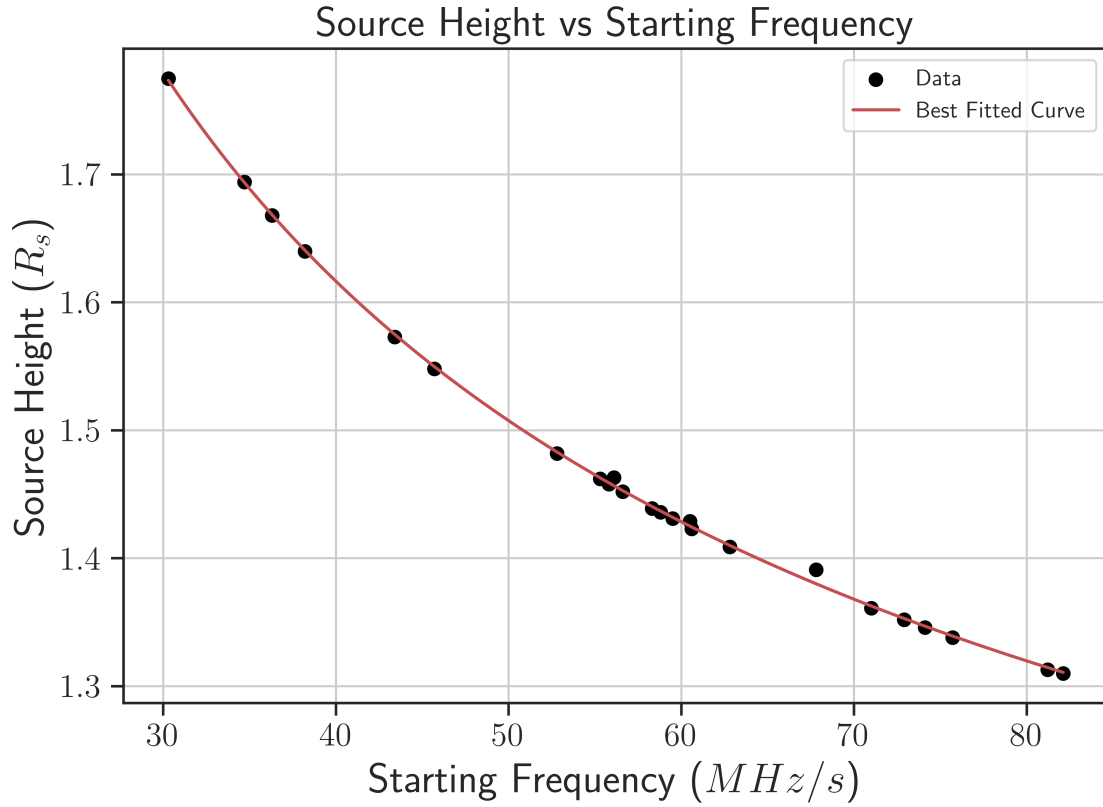


Figure 5.6: The relationship between the source height and starting frequency is characterized by the best-fit curve, represented by the equation $R_s = 7.7f_s^{0.59} + 0.73$. This formula indicates how the source height, measured in solar radii (R_s), varies as a function of the starting frequency (f_s).

The best-fit curve for predicting the source height (R_s) based on the starting frequency (f_s) is represented by the equation $R_s = 7.7f_s^{0.59} + 0.73$. The robustness of this model is supported by an R -squared value of 0.999 and a Root Mean Square Error (RMSE) of 0.003, indicating an excellent fit to the data points. Thus, within the metric wavelength range of Type II solar radio bursts, the source height (R_s) can be accurately predicted using this equation, provided that the starting frequency (f_s) is known.

5.5 Analysis of the bursts isolated with second maximum intensities.

The identification of bursts from the raw data represents the most crucial aspect of this study. Typically, bursts are isolated using apparent methods and the maximum intensity method, the latter of which was discussed in a previous section. However, there is some uncertainty in the literature regarding which intensity level should be used to isolate the burst for processing radio

burst data. In this section, for all 25 datasets, the shock parameters were calculated using the second maximum intensity observed in the dynamic radio spectrum.

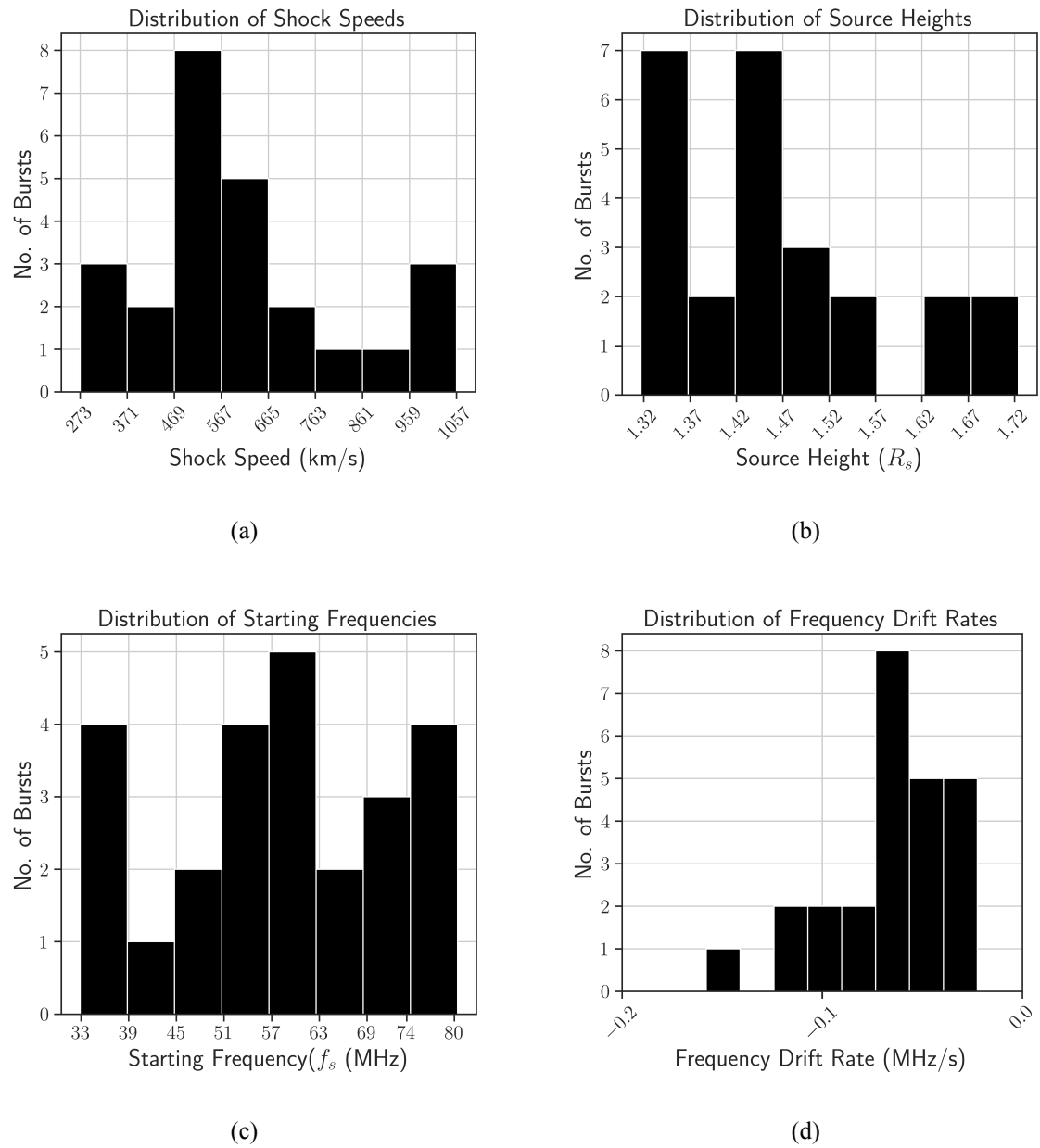


Figure 5.7: The distribution of (a) shock speed (b) source height (c) Starting frequency (d) frequency drift rate of selected 25 type II metric type solar radio bursts calculated using the second maximum intensity in the dynamic radio spectrum.

Figure 5.7 illustrates the distributions of shock speed, frequency drift, source height, and starting frequency, calculated using the second maximum intensity values of each burst. The distribution parameters, including the mean and median values, are presented in Table 5.3.

Table 5.3: The mean and median values for the distributions of shock speed, source height, starting frequency, and frequency drift rate.

Distribution	Mean	Meadian
Shock Speed	605	549
Source Height	1.46	1.44
Starting Frequency	58.1	58.9
Frequency Drift Rate	-0.0673	-0.0669

In this case, all distributions, except for the shock speed, approximate a roughly symmetric distribution. These findings are consistent with those reported by Aguilar et al. (2005), who also observed symmetry in the distributions of similar variables [1].

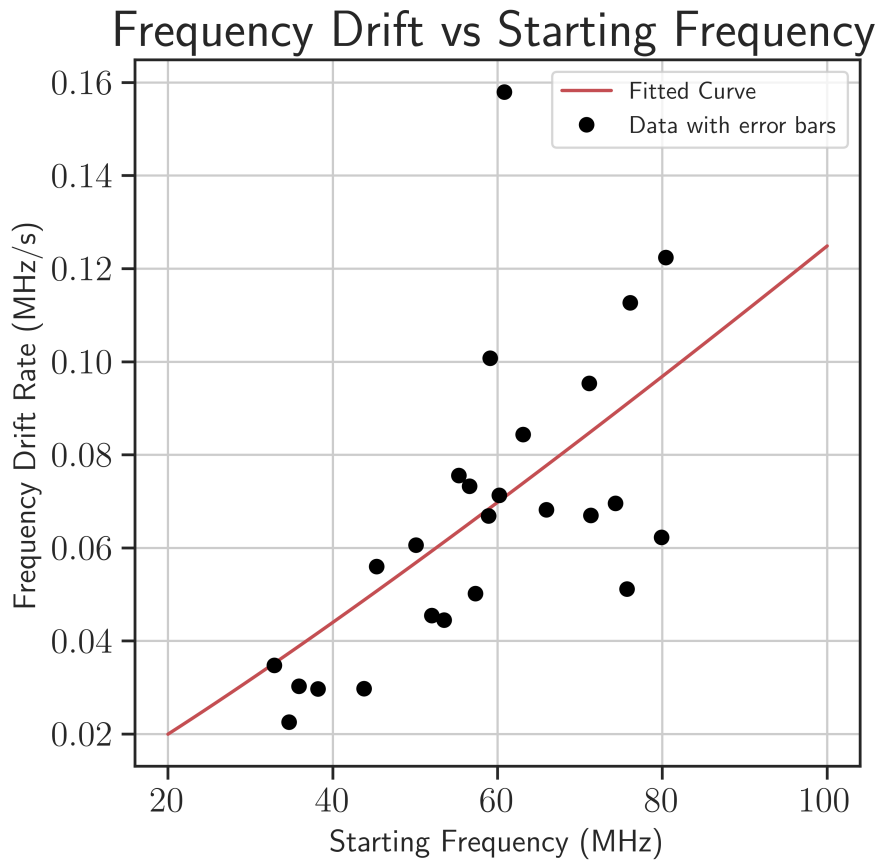
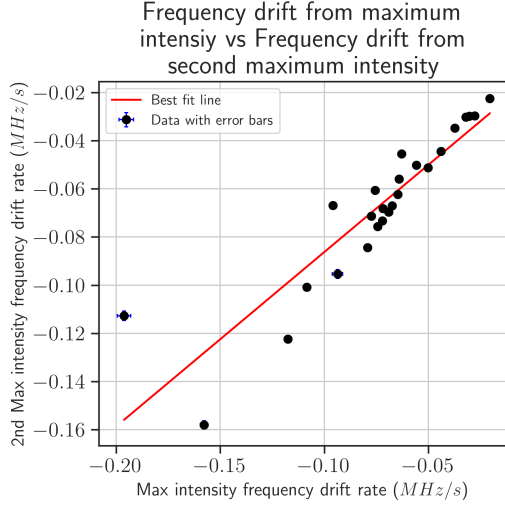
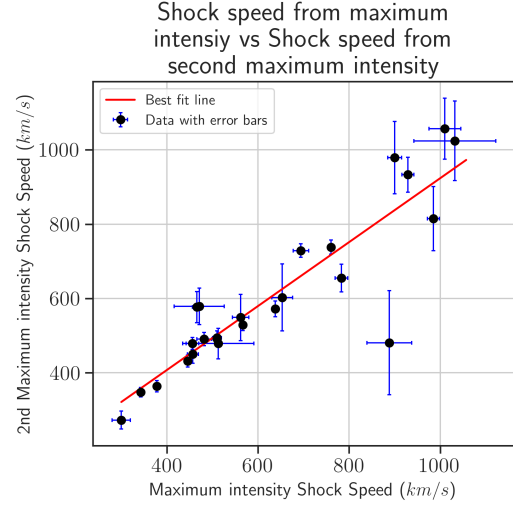


Figure 5.8: The graph of the absolute value of frequency drift versus and starting frequency of type II solar radio bursts. The best-fit curve is $\frac{df}{dt} = -0.00066f_s^{1.139}$. The correlation coefficient is found to be 0.62.

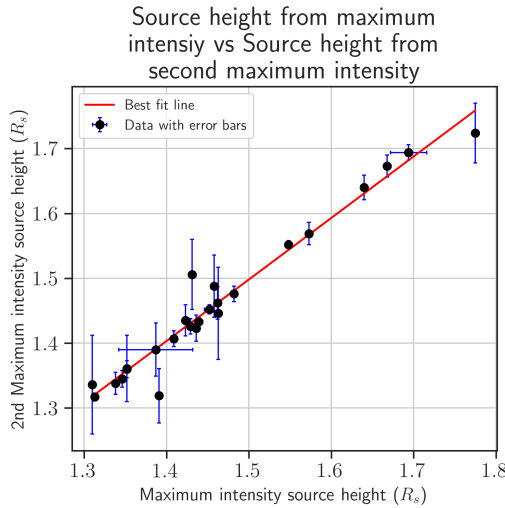
Figure 5.8 displays the graph of the frequency drift rate versus the starting frequency for the second maximum intensity burst. The power law index (ψ) for the fitted curve is 1.14 ± 0.36 , which represents a percentage error of 20.8% relative to the standard value of 1.44, as reported by Aguilar et al. (2005) [1]. For comparison, the power law index calculated from the maximum intensity burst is 1.45 ± 0.42 , with a percentage error of only 0.7%. These comparisons provide insight into which intensity from the dynamic spectrum most accurately reflects the real burst trend, indicating that the maximum intensity offers the most accurate prediction of burst behavior.



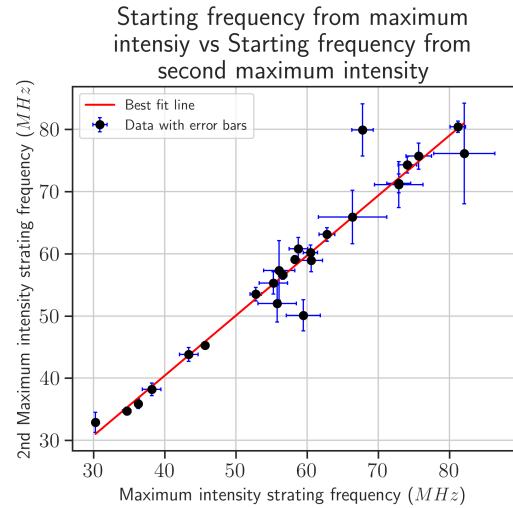
(a) The graph of frequency drift rates from maximum intensity versus second maximum intensity. The correlation coefficient is 0.900



(b) The graph of shock speed from maximum intensity versus second maximum intensity. The correlation coefficient is 0.894



(c) The graph of source height from maximum intensity versus second maximum intensity. The correlation coefficient is 0.987



(d) The graph of starting frequency from maximum intensity versus second maximum intensity. The correlation coefficient is 0.969

Figure 5.9: The variation of each shock parameter calculated from the maximum intensities and second maximum intensities.

Figure 5.9 illustrates the correlation between shock parameters frequency drift rate, source height, shock speed, and starting frequency obtained from the maximum intensity in the burst and those derived from the second maximum intensity.

Initially, it was assumed that the burst represented by the second maximum intensity is the same as the maximum intensity. Therefore it is possible to expect a perfect linear relationship with

$y = mx$ best-fit line for each parameter calculated from the maximum and second maximum intensity.

The graph in Figure 5.9a depicts the variation between the frequency drift rates for maximum and second maximum intensities. The best-fit line is represented by the equation $y = 0.72x - 0.01$, with a correlation coefficient of 0.900. This coefficient indicates a strong positive correlation between the two variables. Despite this strong correlation, the expected linear fit was not fully achieved.

Figure 5.9b illustrates the relationship between shock speeds derived from the second maximum intensity and those from maximum intensity, with a correlation coefficient of 0.894 and a fitted line described by $y = 0.86x + 63$. These results are inconsistent with the expected outcomes. It is also evident that the uncertainties associated with the shock speeds calculated from the second maximum intensity are greater than those from the maximum intensity values. Similar observations are presented in Figures 5.9c and 5.9d, which depict the source heights from second maximum intensity versus those from maximum intensity, respectively. The fitted lines for these graphs are $y = 0.95x + 0.08$ and $y = 0.97x + 1.78$, with correlation coefficients of 0.978 and 0.969, indicating very strong linear correlations. Despite these strong correlations, the uncertainties derived from the second maximum intensity remain greater than those from the maximum intensity.

Chapter 6

CONCLUSION

The study focused on determining the speed and source height of coronal shock waves through Type II solar radio bursts using 25 datasets. After implementing a noise reduction process in Python, the bursts were isolated based on their maximum intensity points in the dynamic spectrum. This revealed distributions of shock speed, source height, frequency drift rate, and starting frequency, which were symmetric and agreed with previous findings, validating the analysis methods. The power law index (ψ) relating frequency drift rate to starting frequency was calculated as 1.45 ± 0.42 , matching Aguilar's 2005 results with 99.4% accuracy. The derived formulas based on the Newkirk model provided explicit relationships for calculating shock speed and source height, yielding speeds from 343 km/s to 1032 km/s and heights from $1.317 R_s$ to $1.724 R_s$, consistent with existing literature. A relationship between source height and starting frequency was obtained as $R_s = 7.7 f_s^{0.59} + 0.73$, showing an excellent fit with an R^2 value of 0.999. The power law index using the second maximum intensity points was 1.14 ± 0.36 , but the accuracy was lower at 78.2%. Therefore, the first maximum intensity points are better for accurately characterizing Type II bursts. This study's noise reduction and burst isolation methods enhanced the accuracy of Type II burst analysis, offering valuable insights into coronal mass ejections. The explicit formulas enable precise shock speed and source height modeling, improving space weather forecasting and aiding theoretical understanding in solar physics.

6.1 Limitations

The primary limitation of this study is its exclusive focus on metric Type II solar radio bursts, omitting DH and KM types from the analysis. Shock parameters may exhibit distinct characteristics across different wavelength ranges of the burst, which means the findings of this study are specifically applicable only to metric Type II solar radio bursts. Furthermore, Type

II bursts are less frequent compared to other types of solar radio bursts, necessitating a larger dataset for more comprehensive analysis across all three wavelength ranges. Additionally, the noise reduction and burst isolation processes in this study were conducted manually, which limits the number of datasets that can be analyzed efficiently. To address this limitation, there is potential to develop and train a machine learning model using a large, manually identified dataset. Such a model could automate the noise reduction and burst isolation processes, significantly increasing the scalability of this research approach.

6.2 Future Expansions

Beyond the determination of shock parameters, this research could be expanded to derive magnetic field measurements of the solar corona using Type II solar radio bursts. The phenomenon of band-splitting in Type II bursts provides insightful information regarding density jumps in the solar corona. By correlating shock speeds with frequency band splitting and density jumps, it is feasible to calculate the Alfvén speed associated with the shock wave. Subsequently, this data could be utilized to develop a generalized model for the magnetic field in the solar corona. Such advancements would enhance our understanding of solar coronal dynamics and could significantly contribute to solar physics.

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Appendix A

Initial Results for Burst Isolation From Second Maximum Intensities.

Table A.1

Date	Station	Frequency_drift	Shock_speed	R	fs
2022-01-12	AUSTRALIA	-0.0502	603	1.446	57.3
2022-02-20	AUSTRALIA	-0.0303	572	1.673	35.9
2022-03-13	ALASKA-COHE	-0.1224	479	1.317	80.4
2022-04-02	ARECIBO	-0.0606	979	1.506	50.1
2022-04-11	AUSTRIA	-0.0512	348	1.338	75.7
2022-05-10	ARECIBO	-0.0954	815	1.361	71.1
2022-06-13	ALASKA-COHE	-0.0226	492	1.694	34.7
2022-08-14	GLASGOW	-0.0713	494	1.426	60.2
2022-10-11	GLASGOW	-0.0670	364	1.360	71.3
2022-11-09	MEXICO LANCE A	-0.1008	729	1.433	59.1
2022-12-03	ARECIBO	-0.1127	481	1.336	76.1
2023-01-10	AUSTRALIA	-0.1580	1024	1.423	60.8
2023-02-21	MEXICO LANCE B	-0.0696	432	1.345	74.3
2023-02-25	ALASKA-HAARP	-0.0297	450	1.640	38.2
2023-03-02	GREENLAND	-0.0455	549	1.488	52.0
2023-03-04	GLASGOW	-0.0682	579	1.390	65.9
2023-05-09	AUSTRALIA	-0.0298	529	1.569	43.8
2023-06-13	ARECIBO	-0.0669	655	1.435	58.9
2023-07-10	GLASGOW	-0.0844	738	1.407	63.1
2023-07-14	ARECIBO	-0.0623	577	1.319	79.9
2023-07-15	SRI LANKA	-0.0733	491	1.452	56.6

Table A.1 continued from previous page

Date	Station	Frequency_drift	Shock_speed	R	fs
2023-08-17	GLASGOW	-0.0445	273	1.476	53.5
2023-08-18	ALASKA-HAARP	-0.0756	933	1.462	55.3
2023-08-26	GREENLAND	-0.0560	479	1.552	45.3
2023-10-26	AUSTRALIA	-0.0348	1057	1.724	32.9

Appendix B

Python Scripts For Analysis

B.1 Python Implementation of the Noise Reduction Process

Listing B.1: Importation of the necessary libraries and packages. The FITS files were opened using the 'astropy' library and 'numpy' and 'matplotlib' were used to do matrix calculations and plot the data respectively. Also the 'csv' library was used to handle CSV files.

```
1 import numpy as np
2 import matplotlib.pyplot as plt
3 from astropy.io import fits
4 from matplotlib.colors import LinearSegmentedColormap
5 import matplotlib.colors as mcolors
6 import csv
```

Listing B.2: The raw data files (FITS files) were opened and the intensity data was extracted to 'data' matrix and frequency and time data were extracted to 'freqs' and 'time' arrays respectively.

```
1 filepath = '/Users/saan/Desktop/Academic/Research Trial 2/Final Data FITS/'
2 filename = 'Australia-ASSA_20231026_231500_63.fit.gz'
3 hdul = fits.open(filepath+filename)
4
5 data = hdul[0].data
6 freqs = hdul[1].data['frequency'][0]
7 time = hdul[1].data['time'][0]
```

Listing B.3: The python script to plot the raw radio burst FITS files.

```
1 extent = [0, time[-1], freqs[-1], freqs[0]]
2 vmin = data.min()
3 vmax = data.max()
4 plt.imshow(data, aspect='auto', extent=extent, cmap=custom_cmap, vmin=vmin, vmax=vmax)
5 plt.xlabel('Time [s]')
6 plt.ylabel('Frequency [MHz]')
7 plt.title(filename+' Raw', fontsize = 24, fontweight="bold")
8 plt.colorbar()
```

```
9 plt.show()
```

Listing B.4: Python script to reduce noise and plot noise reduced data.

```
1 data = data - data.mean(axis=1, keepdims=True)
2 vmin = data.min()
3 vmax = data.max()
4 data = data.clip(-2,10)
5 data = data * 2500.0 / 255.0 / 25.4
6
7 plt.imshow(data, aspect='auto', extent=extent, cmap=custom_cmap)
8 plt.xlabel('Time [s]')
9 plt.ylabel('Frequency [MHz]')
10 plt.title(filename+' Noise Reduced', fontsize = 24)
11 plt.colorbar()
12 plt.show()
```

Listing B.5: Python Script to extract and plot the maximum intensity data points from the noise reduced data file.

```
1 max_intensity_freqs = freqs[np.argmax(data, axis=0)]
2 time_channel_number = np.linspace(0,3600, 3600)
3 plt.scatter(time_channel_number,max_intensity_freqs,marker="o", s=5, color = 'red')
4 plt.axvline(x = 1300, color = 'b', label = 'axvline - full height')
5 plt.axvline(x = 2790, color = 'b', label = 'axvline - full height')
6 plt.axhline(y = 50, color = 'r', linestyle = '-')
7 plt.axhline(y = 25, color = 'r', linestyle = '-')
8 plt.xlabel('Time Channel Number')
9 plt.ylabel('Frequency Channel Number')
10 plt.title('Maximum Intensity for each frequency channel', fontsize = 24)
11 plt.show()
```

Listing B.6: In this python script after the identification of the burst and isolate the fundamental frequency band from the noise reduced data.

```
1 data_new = data
2 start_row, end_row = 135,183
3 start_col, end_col = 980, 2790
4 cropped_data = np.copy(data_new)
5
6 cropped_data[start_row, :] = 0
7 cropped_data[end_row:, :] = 0
8 cropped_data[:, :start_col] = 0
9 cropped_data[:, end_col:] = 0
```

```

10
11 plt.imshow(cropped_data, aspect='auto', extent=extent, cmap=custom_cmap)
12 plt.xlabel('Time [s]')
13 plt.ylabel('Frequency [MHz]')
14 plt.title(filename+' Selected Area',fontsize = 24)
15 plt.colorbar()
16 plt.show()

```

Listing B.7: In this python script applying manual filters the bursts was completely isolated and plotted.

```

1 #Filter 1
2 x_min_1 = -1
3 x_max_1 = 5000
4 y_min_1 = 40
5 y_max_1 = 100
6
7 #Filter 2
8 x_min_2 = 0
9 x_max_2 = 1750
10 y_min_2 = 0
11 y_max_2 = 26
12
13 #Filter 3
14 x_min_3 = 0
15 x_max_3 = 2125
16 y_min_3 = 0
17 y_max_3 = 22
18
19 #Filter 4
20 x_min_4 = 2375
21 x_max_4 = 4000
22 y_min_4 = 25
23 y_max_4 = 100
24
25
26 #Filter 5
27 x_min_5 = 2500
28 x_max_5 = 4000
29 y_min_5 = 21.5
30 y_max_5 = 100
31
32 #Filter 6
33 x_min_6 = 0

```

```

34 x_max_6 = 0
35 y_min_6 = 0
36 y_max_6 = 0
37
38 #Filter 7
39 x_min_7 = 0
40 x_max_7 = 0
41 y_min_7 = 0
42 y_max_7 = 0
43
44 #Filter 8
45 x_min_8 = 0
46 x_max_8 = 0
47 y_min_8 = 0
48 y_max_8 = 0
49
50 #Filter 9
51 x_min_9 = 0
52 x_max_9 = 0
53 y_min_9 = 0
54 y_max_9 = 0
55
56 #Filter 10
57 x_min_10 = 0
58 x_max_10 = 1380
59 y_min_10 = 0
60 y_max_10 = 29.7
61
62 x = time_channel_number
63 y = max_intensity_freqs
64
65 #Filter 1
66 filtered_indices = np.where(~((x > x_min_1) & (x < x_max_1) & (y > y_min_1) & (y < y_max_1)))
67
68 filtered_x = x[filtered_indices]
69 filtered_y = y[filtered_indices]
70
71 #Filter 2
72 filtered_indices_2 = np.where(~((filtered_x > x_min_2) & (filtered_x < x_max_2) &
73 (filtered_y > y_min_2) & (filtered_y < y_max_2)))
74
75 filtered_x2 = filtered_x[filtered_indices_2]
76 filtered_y2 = filtered_y[filtered_indices_2]
77

```

```

78 #Filter 3
79 filtered_indices_3 = np.where(~((filtered_x2 > x_min_3) & (filtered_x2 < x_max_3) &
80 (filtered_y2 > y_min_3) & (filtered_y2 < y_max_3)))
81
82 filtered_x3 = filtered_x2[filtered_indices_3]
83 filtered_y3 = filtered_y2[filtered_indices_3]
84
85 #Filter 4
86 filtered_indices_4 = np.where(~((filtered_x3 > x_min_4) & (filtered_x3 < x_max_4) &
87 (filtered_y3 > y_min_4) & (filtered_y3 < y_max_4)))
88
89 filtered_x4 = filtered_x3[filtered_indices_4]
90 filtered_y4 = filtered_y3[filtered_indices_4]
91
92 #Filter 5
93 filtered_indices_5 = np.where(~((filtered_x4 > x_min_5) & (filtered_x4 < x_max_5) &
94 (filtered_y4 > y_min_5) & (filtered_y4 < y_max_5)))
95
96 filtered_x5 = filtered_x4[filtered_indices_5]
97 filtered_y5 = filtered_y4[filtered_indices_5]
98
99 #Filter 6
100 filtered_indices_6 = np.where(~((filtered_x5 > x_min_6) & (filtered_x5 < x_max_6) &
101 (filtered_y5 > y_min_6) & (filtered_y5 < y_max_6)))
102
103 filtered_x6 = filtered_x5[filtered_indices_6]
104 filtered_y6 = filtered_y5[filtered_indices_6]
105
106 #Filter 7
107 filtered_indices_7 = np.where(~((filtered_x6 > x_min_7) & (filtered_x6 < x_max_7) &
108 (filtered_y6 > y_min_7) & (filtered_y6 < y_max_7)))
109
110 filtered_x7 = filtered_x6[filtered_indices_7]
111 filtered_y7 = filtered_y6[filtered_indices_7]
112
113 #Filter 8
114 filtered_indices_8 = np.where(~((filtered_x7 > x_min_8) & (filtered_x7 < x_max_8) &
115 (filtered_y7 > y_min_8) & (filtered_y7 < y_max_8)))
116
117 filtered_x8 = filtered_x7[filtered_indices_8]
118 filtered_y8 = filtered_y7[filtered_indices_8]
119
120 #Filter 9
121 filtered_indices_9 = np.where(~((filtered_x8 > x_min_9) & (filtered_x8 < x_max_9) &

```

```

122 (filtered_y8 > y_min_9) & (filtered_y8 < y_max_9)))
123
124 filtered_x9 = filtered_x8[filtered_indices_9]
125 filtered_y9 = filtered_y8[filtered_indices_9]
126
127 #Filter 10
128 filtered_indices_10 = np.where(~((filtered_x9 > x_min_10) & (filtered_x9 < x_max_10) &
129 (filtered_y9 > y_min_10) & (filtered_y9 < y_max_10)))
130
131 filtered_x10 = filtered_x9[filtered_indices_10]
132 filtered_y10 = filtered_y9[filtered_indices_10]
133
134 time_new = filtered_x10*0.25
135
136 # Creating scatter plot without the filtered points
137 plt.figure(figsize=(10, 6))
138 plt.scatter(filtered_x10, filtered_y10, marker="o", s=10, color = 'red')
139 #plt.scatter(time_new, filtered_y10, marker="o", s=10, color = 'red')
140 plt.axvline(x = 2125, color = 'b', label = 'axvline - full height')
141 #plt.axvline(x = 1, color = 'b', label = 'axvline - full height')
142 plt.axhline(y = 21.5, color = 'r', linestyle = '-')
143 #plt.axhline(y = 72, color = 'r', linestyle = '-')
144 plt.ylabel('Frequency(MHz)')
145 plt.xlabel('Time(s)')
146 plt.title(filename + ' Isolated Burst(2nd Max)', fontsize=24)
147 plt.show()

```