Statistical Study on Langmuir Turbulence Radar Signatures Observed by the ESR

ALEXANDER KARLSSON
Abstract

In this thesis data taken by the EISCAT Svalbard Radar during the International Polar Year have been analyzed. The radar data have been searched for anomalous radar echoes. These radar echoes appear in an altitude range between 200 and 300 km, show a strong enhancement of the backscattered power and are limited in altitude to tens of kilometers. These anomalous radar echoes also show a distinct zero Doppler shifted peak in the ion line spectrum. The power profile of the data have been visually inspected to identify the anomalies. The data have then been analyzed using a Matlab program called GUISDAP in order to get basic plasma parameters. It has been found that there is a high occurrence of these anomalies during particle precipitation and at a certain E-region electron density peak more than 40 % of the data contains these anomalies.
Acknowledgements

I would like to thank everyone in my life who made this thesis possible. I would like to express my gratitude to my supervisors Nicola Schlatter and Nickolay Ivchenko for their unwavering enthusiasm, staying engaged and guiding me through this thesis. I would also like to thank all my friends and colleges at the Alfvén laboratory who helped me and a special thanks to Rebecca Ilethag for her constant nagging and support.
# Contents

Acknowledgements iii  
Contents iv  
List of Figures vi  
List of Tables vii  
Abbreviations viii

1 Introduction 1  
1.1 Introduction 1  
1.2 International Polar Year 1  
1.3 Incoherent Scatter Radar 2  
1.3.1 EISCAT and ESR 2  
1.4 Ionosphere 3  
1.5 Aurora 4

2 Physics of the Events 5  
2.1 Plasma 5  
2.2 Waves in the Ionosphere 6  
2.2.1 Ion Acoustic Waves 6  
2.2.2 Langmuir Waves 7  
2.3 NEIALs 7  
2.4 Landau Damping and Inverse Landau Damping 8  
2.5 Bragg Condition 9  
2.6 Parametric Instability and Langmuir Turbulence 9

3 Data Selection 11  
3.1 Data Selection 11  
3.2 Identifying Events 12

4 Data Analysis 15  
4.1 Characterization of Events 15  
4.2 Analyzing Plasma Parameters of the Events 18  
4.3 Electron Density in the E-region 18
4.4 Electron Density in the F-region ............................................. 20
4.5 Electron Temperature in the F-region ..................................... 20
4.6 Ion Temperature in the F-region ........................................... 23
4.7 Ratio Between Electron and Ion Temperature in the F-region ...... 24
4.8 Electron Temperature in the E-region ..................................... 24
4.9 Ion line Analysis of the Events ............................................. 24
4.10 Electron Energy Profiles ...................................................... 30

5 Summary and Conclusions ....................................................... 31

Bibliography ............................................................................. 33
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Electron density profile of the ionosphere and how it is divided into different layers. Adapted from Hanson [1965]</td>
<td>3</td>
</tr>
<tr>
<td>2.1</td>
<td>Dispersion relation for Langmuir waves. The vertical line is the wave number of an arbitrary radar. The scales on the x- and y-axis are arbitrary</td>
<td>7</td>
</tr>
<tr>
<td>2.2</td>
<td>Dispersion relation for Langmuir oscillations after collapse has occurred. The horizontal lines corresponds to cavities created after collapsing wave packets. Adapted from Robinson [1997]</td>
<td>10</td>
</tr>
<tr>
<td>3.1</td>
<td>Power Backscatter data from the first of October 2007.</td>
<td>13</td>
</tr>
<tr>
<td>3.2</td>
<td>Power spectrum and Ion Line spectrum</td>
<td>14</td>
</tr>
<tr>
<td>3.3</td>
<td>Ion line for all the events normalized to maximum power spectral intensity</td>
<td>14</td>
</tr>
<tr>
<td>4.1</td>
<td>Range distribution of events</td>
<td>16</td>
</tr>
<tr>
<td>4.2</td>
<td>Power backscattered from events relative to the background</td>
<td>16</td>
</tr>
<tr>
<td>4.3</td>
<td>Life time of events</td>
<td>17</td>
</tr>
<tr>
<td>4.4</td>
<td>Range distribution of events</td>
<td>17</td>
</tr>
<tr>
<td>4.5</td>
<td>Peak electron density in the E-region for all data (a), events (b) and the ratio (c)</td>
<td>19</td>
</tr>
<tr>
<td>4.6</td>
<td>Peak electron density in the F-region for all data (a), events (b) and the ratio (c)</td>
<td>21</td>
</tr>
<tr>
<td>4.7</td>
<td>Average electron temperature in the F-region for events (a), all data (b) and the ratio (c)</td>
<td>22</td>
</tr>
<tr>
<td>4.8</td>
<td>Ion temperature in the F-region for events (a), all data (b) and the ratio (c)</td>
<td>23</td>
</tr>
<tr>
<td>4.9</td>
<td>Ion and electron temperature in the F-region for all data (a), events (b) and the ratio (c)</td>
<td>25</td>
</tr>
<tr>
<td>4.10</td>
<td>Ion and electron temperature in the F-region for events (a), all data (b) and the ratio (c)</td>
<td>26</td>
</tr>
<tr>
<td>4.11</td>
<td>Electron Temperature in the E-region for events (a), all data (b) and the ratio (c)</td>
<td>27</td>
</tr>
<tr>
<td>4.12</td>
<td>Strength of the center peak relative to the mean of the two side peaks</td>
<td>28</td>
</tr>
<tr>
<td>4.13</td>
<td>Characteristics of Ion line spectrum of the events. The left column shows the Center Ion Lin (CIL), the middle column shows the Upshifted Ion Line (UIL) and the right column shows the Downshifted Ion Line (DIL)</td>
<td>29</td>
</tr>
<tr>
<td>4.14</td>
<td>Modeled electron density profiles</td>
<td>30</td>
</tr>
</tbody>
</table>
List of Tables

3.1 Date, time and radar program used for the data. . . . . . . . . . . . . . . 12
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPY</td>
<td><strong>International Polar Year</strong></td>
</tr>
<tr>
<td>ESR</td>
<td><strong>EISCAT Svalbard Radar</strong></td>
</tr>
<tr>
<td>NEIAL</td>
<td><strong>Naturally Enhanced Ion Acoustic Line</strong></td>
</tr>
<tr>
<td>PDI</td>
<td><strong>Parametric Decay Instability</strong></td>
</tr>
<tr>
<td>EISCAT</td>
<td><strong>European Incoherent Scatter Scientific Association</strong></td>
</tr>
<tr>
<td>ASK</td>
<td><strong>Auroral Structure and Kinetics</strong></td>
</tr>
<tr>
<td>CIL</td>
<td><strong>Central Ion Line</strong></td>
</tr>
<tr>
<td>UIL</td>
<td><strong>Upshifted Ion and Line</strong></td>
</tr>
<tr>
<td>DIL</td>
<td><strong>Downshifted Ion and Line</strong></td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Introduction

This thesis is a continuation on the previous work done by Schlatter et al. [2014] where a statistical study was performed on data obtained using the EISCAT Svalbard Radar (ESR) during the International Polar Year (IPY). In that paper they used an automatic search algorithm to look through the entire database gathered by the ESR during the IPY to look for anomalous radar signatures, a special form of Naturally Enhanced Ion Acoustic Line (NEIAL), that show a power enhancement at zero Doppler shift. These special form of NEIALs will be referred to as events from here on. The automatic search algorithm allowed for a fast way to look through the large set of data gathered by the ESR during the IPY. However, the automatic search algorithm may have missed events. This thesis focuses on a smaller set of data where the events have been registered from the previous study to see if more events could be discovered and to characterize these events. This study also analyses several key plasma parameters, such as electron density and temperatures, obtained from analysis of the radar data in order to find which parameters and conditions are important for the occurrence of these events.

Data has also been gathered from outside of the IPY. This data have been selected in order so that the radar data can be analyzed in conjunction with optical data taken by the ASK instrument.

1.2 International Polar Year

IPY took place from March 2007 to March 2008 and was a large scientific program which focused on Arctic research. It was organized by the International Council of Science and
the WORLD Meteorological Organization and involved over 200 projects and scientists from over 60 nations. During the IPY the ESR ran two versions of the same radar program to collect radar data continuously for one year. It is from this database that the original list used in Schlatter et al. [2014] was created. At a six second integration time and 365 days of continuous running the data from the ESR corresponds to roughly half a million data packages.

1.3 Incoherent Scatter Radar

Incoherent scatter radars are an important tool to measure ionospheric plasma parameters. It uses incoherent scatter also know as Thomson scattering which describes how electromagnetic radiation scatters off charged particles. The incident electromagnetic waves, from the radar, cause the charged particles in the ionosphere to oscillate. Particles which oscillate give off electromagnetic radiation which can then be observed by the radar. Most of the signal from the radar will pass through the ionosphere but a small fraction will be scattered back due to the scattering process. Both ion acoustic and Langmuir waves can be observed using incoherent scatter radars. These natural waves in the ionosphere will cause different Doppler shifts in the received signal and results in the so called double humped spectrum from which plasma parameters can be determined by analyzing the spectrum. Different programs can be run on the radars each one giving emphasis on different aspects of the ionospheric environment. This gives the user the possibility to chose between different time and range resolutions and what fits their purpose best. However a incoherent scatter radar can only observe waves which have a wavenumber corresponding to two times the radar’s wavenumber and can only measure waves in the line of sight of the radar. There are therefore waves in the ionosphere which can not be observed directly by the radar.

1.3.1 EISCAT and ESR

European Incoherent Scatter Scientific Association (EISCAT) is a collaboration between Norway, Finland, Sweden, Germany, France, United Kingdom, China and Japan. The organisation operates three incoherent scatter radars, two located close to Tromsø and one on Svalbard. The Svalbard site, ESR, consists of two dishes, 42 and 32 meters in diameter respectively and transmits at 500 MHz. The 42 meter dish is fixed and is pointing along the direction of the geomagnetic field and the 32 meter antenna is steerable. In this thesis data taken from the ESR 42 meter dish taken during the International Polar Year is used.
Chapter 1. Introduction

1.4 Ionosphere

This section uses information on the ionosphere given in Fälthammar [2001]. The ionosphere is a part of Earth upper atmosphere and starts from around 85 km and partially consists of ionized molecules. There are a number of different ion species in the ionosphere including $NO^+$, $O_2^+$, $O^+$, $He^+$ and $H^+$. Interaction between these species causes different scale heights resulting in altitude regions in the ionosphere, the D-region, the E-region and the F-region. The E-region altitude is between 85 and 140 km and the F-region extends from 140 km and up to ca 600 km and they both have two distinct maximum electron density peaks. Using the Chapman approximation of the ionosphere one can estimate the electron density in the E-region. Other important parameters in the ionosphere are ion and electron temperatures, electric field and magnetic field components and plasma bulk velocity. Figure 1.1 shows the electron distribution in the ionosphere and its corresponding electron density peaks.

Figure 1.1: Electron density profile of the ionosphere and how it is divided into different layers. Adapted from Hanson [1965]
1.5 Aurora

The aurora is caused by highly energetic electrons of up to a few keV (see Fälthammar [2001]) traveling along the geomagnetic field and colliding with molecules in the atmosphere. They will interact which molecules causing them to excite. When the excited molecules relax they emit light causing the aurora. In Schlatter et al. [2014] optical data indicates that the events occur during auroral breakup. Akbari et al. [2015] used a one dimensional Zakharov simulation to determine which physical mechanisms cause the events. This paper suggests that similar radar echoes to the events investigated in this thesis can be caused by electron beams of 1 keV, which is in the same regime as the energy of auroral electrons during precipitation and may explain why aurora is present when the events are.
Chapter 2

Physics of the Events

2.1 Plasma

Plasma is often referred to as the fourth state of matter. It consists of a conductive gas of partially ionized molecules. Plasma is created by introducing enough energy into a gas so that the electrons are knocked from the molecules. In the plasma state the gas becomes an electrically conductive gas where the positive ions and negative electrons are not bound to each other. This creates some interesting, and sometimes quite unintuitive, physical phenomena. Some fundamental equations that are used later in this chapter are the plasma frequency and the Debye length

\[ \omega_p = \sqrt{\frac{n q^2}{m \epsilon_0}}, \]  

(2.1)

\[ \lambda_d = \sqrt{\frac{\epsilon_0 k_B T_e}{n q^2}}, \]  

(2.2)

\( \omega_p \) is the plasma angular frequency, \( n \) is the electron density, \( q \) is the elementary charge, \( m \) is the mass of the species and \( \epsilon_0 \) is the permittivity of free space. The plasma frequency describes the natural oscillation frequency of a given plasma. The Debye length is the distance at which an electric charge is screened out in a plasma and is given by

where \( \lambda_d \) is the Debye length, \( k_B \) is Boltzmann’s constant, \( T_e \) is the electron temperature.
Chapter 2. Physics of the events

2.2 Waves in the Ionosphere

There are naturally occurring waves in the ionosphere. The most basic waves in the ionosphere being ion acoustic and Langmuir waves. This derivation of the two basic electrostatic waves in plasmas uses section 5 from Gurnett and Bhattacharjee [2005] to derive the dispersion relations for ion acoustic waves and Langmuir waves. The ion acoustic wave is the most important wave observed by incoherent scatter radars.

2.2.1 Ion Acoustic Waves

Ion acoustic waves behave similarly to regular acoustic waves. Normal acoustic waves in air are formed because of adiabatic compression and decompression where the air pressure is the restoring force. In ion acoustic waves the restoring force that causes the adiabatic compression and decompression is caused by electric field interaction between the ions in the plasma. The ion acoustic waves are important to incoherent scatter radar and by analyzing the ion acoustic spectrum one can determine ion and electron temperatures. The longitudinal part of the dispersion relation is given by

\[ D_l(k, \omega) = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2 - \omega_{ps}^2 - \gamma_s C_s^2 k^2} = 0, \]  

(2.3)

where \( C_s \) is the acoustic speed, \( \gamma_s \) is the adiabatic constant, \( s \) is the species and \( k \) is the wave number and \( \omega \) is the angular frequency. By assuming that the ion temperature is small and putting the ion acoustic speed \( C_i = 0 \) in (2.3) gives

\[ 1 - \frac{\omega_{pi}^2}{\omega^2} - \frac{\omega_{pe}^2}{\omega^2 - \gamma_e C_e^2 k^2} = 0, \]  

(2.4)

by assuming that the phase velocity of the ion acoustic wave is much smaller than the electron thermal velocity i.e.

\[ \frac{\omega}{k} \ll \sqrt{\gamma_e C_e^2}, \]  

(2.5)

resulting in

\[ \omega^2 = \frac{1}{1 + \gamma_e \lambda_d^2 k^2} \left( \frac{\gamma_e k_b T_e}{m_i} \right) k^2. \]  

(2.6)
2.2.2 Langmuir Waves

Langmuir waves or plasma oscillations are oscillations of electron densities in a plasma. The dispersion relation for Langmuir waves can be derived from

\[ 1 - \frac{\omega_{pe}^2}{\omega^2 - \gamma_e C_e^2 k^2} = 0, \tag{2.7} \]

where \( \omega_{pe} \) is the plasma angular frequency. (2.7) can be rewritten into (2.8) by putting \( \omega_{pe} \Lambda_{De} = C_e \)

\[ \omega^2 = \omega_{pe}^2 \left[ 1 + \gamma_e \lambda_d^2 k^2 \right]. \tag{2.8} \]

Figure 2.1 shows the dispersion relation \( \omega(k) \) for Langmuir waves. Langmuir waves are important for the formation of strong Langmuir turbulence through parametric decay instabilities. Constructive interference from strong Langmuir turbulence is believed to cause the events.

2.3 NEIALs

A NEIAL is an enhancement in the ion acoustic spectrum. There has been extended studies done on NEIALs in the past e.g [Foster et al. [1988]; Sedgemore-Schulthess and
St. Maurice [2001]; Ogawa et al. [2011]] where NEIALs have been interpreted as plasma instabilities.

The regular NEIAL show enhancement in the frequency shifted humps of the ion acoustic spectrum and over large altitude ranges. There is a specific form of NEIALs, that differ from NEIALs previously studied, that is examined in this thesis. These specific NEIALs show a strong enhancement at zero Doppler shift effectively creating a triple humped spectrum in the ion line data. These events are rare and there have been a few studies on these events, Schlatter et al. [2013],[2014]; Isham et al. [2012]; Akbari et al. [2012] and Ekeberg et al. [2010]. According to Schlatter et al. [2014] these NEIALs are confined to a couple of kilometers in altitude and show a peak occurrence rate at around 220 km. According to Ogawa et al. [2011], where a study on NEIALs was conducted using data from the ESR taken during the IPY, the normal NEIALs have a low occurrence between an altitude of 190 to 240 km which is the same altitude range where most of the events have been observed.

The zero Doppler shift feature is suggested to be created due to non propagating electron density cavities created by strong Langmuir turbulence. Strong enhanced backscatter will occur when these electron cavities fulfill the Bragg condition of the radar.

### 2.4 Landau Damping and Inverse Landau Damping

Landau damping explains energy interaction between charged particles and electrostatic waves. The basic theory is that if the phase velocity of a wave is comparable to the speed of charged particles, e.g electrons, traveling along the same direction as the wave. Energy will then either be given or taken away from the wave. This depends on which of the two speeds is the higher. The phase velocity of a wave is given by

$$v_{ph} = \frac{\omega}{k},$$

and $v_{ph}$ is the velocity at which the phase of a wave travels.

The analogy of a surfer on a wave is often used to describe the phenomena of Landau damping. One can consider the scenario when a surfer travels slower than the wavefront of a wave which he is surfing on, the wave will then push the surfer and give him a more energy, i.e speed. If the surfer travels faster than the wave front of the wave then the surfer will give energy to the wave. Energy can in this way be transferred from a electron beam to electrostatic waves in a plasma. This is known as inverse Landau damping and
is an important part of what causes parametric decay instabilities. Parametric decay instabilities are explained in section 2.6.

2.5 Bragg Condition

The anomalous backscatter of the events is believed to be caused by electron density cavitations causing constructive interference when the Bragg condition of the radars is met. Given the wave number of the radar $k$ and the distance between the electron density cavitations $d$ constructive interference occurs when

$$ d = \frac{\pi}{k}. \quad (2.10) $$

Since the electron density cavitations are a non propagating wave this constructive interference will show up, in the power spectrum, as an enhancement at zero Doppler shift.

2.6 Parametric Instability and Langmuir Turbulence

Parametric instabilities can cause strong Langmuir turbulence and have been suggested to be what causes the anomalies. Here is a short introduction to parametric instability it follows the review given by Robinson [1997]. In a plasma electron density fluctuations are caused by ion acoustic waves. These density fluctuations cause changes in the refracted index of the medium and thereby reflect waves. This wave to wave interaction causes coupling between Ion acoustic and Langmuir waves in the plasma.

A Langmuir wave packet can, if enough energy is supplied, collapse, causing it to self focus into shorter scales and higher intensities. It is possible for several coexisting collapsing wave packets to be formed if energy from an external source is supplied. This causes strong Langmuir turbulence where phase-coherent wave packets are formed. A system which is steadily driven by an external source will have several wave packets to be simultaneously present. These wave packets are not stable and will go through a life cycle where they form, collapse, dissipate and then reform meanwhile drawing energy from the external source.

Parametric Decay Instability (PDI) describes how a wave can decay into two new waves. If a Langmuir wave grows strong enough it will decay into a new Langmuir wave with lower frequency and a corresponding ion acoustic wave with a lower frequency. The decay
of naturally occurring Langmuir waves can be created by enhancement of the wave due to inverse Landau damping caused by electron precipitation along the geomagnetic field. This results in two new frequencies and wave numbers

$$\omega_0 = \omega_1 + \omega_2, \quad (2.11)$$

$$k_0 = k_1 + k_2, \quad (2.12)$$

where $\omega_0$ and $k_0$ are the wave number and angular frequency of the original wave. $\omega_{1,2}$ and $k_{1,2}$ are the angular frequency and wave number of the resulting ion acoustic and Langmuir waves. If the resulting Langmuir wave is strong enough then it may decay into two new waves and if enough energy is put into the system then this process will continue. Density cavities are created with each decay. When the distance between the wave packets correspond to the Bragg condition of the radar an echo, with a zero Doppler shift feature, can be observed. Figure 2.2 shows the dispersion relation of a Langmuir wave considering parametric decay. The non propagating wave packets can be observed by the radar when the wavenumber of the horizontal lines in Figure 2.2 match that of the radar.
All Gauss fits in this chapter are created using the fit function in Matlab.

3.1 Data Selection

During the IPY an entire year of data from ESR were recorded. This chapter describes how the entire database from the IPY was reduced in order to get a set of data during favorable conditions for events that was small enough so that it could be manually analyzed.

The database used in this thesis was created from three different datasets. The first dataset was taken from two separate days during the IPY, i.e. 48 hours, where a high number of events relative to the number of total events that have been recorded. The list of recorded events was provided by Nicola Schlatter and is the same list of events used in the paper published by Schlatter et al. [2014]. These two days are shown in the first two rows of Table 3.1. In the same paper it was indicated that the events have a high occurrence when there is high geomagnetic activity. Therefore, the second dataset was chosen by analyzing the local geomagnetic activity during the entire IPY and selecting data when the K-index was high. Data from the Longyearbyen magnetometer was used to calculate the local K-index, it is located approximately 8 km from the radar. A K-index of higher than 5 was chosen which resulted in a total 36 hours of data. The dates, universal time and radar program used for this data are shown in Table 3.1. Each data point from when the experiments ”IPY.42m_ipy_fixed42p.1.0l_IPY” and ”IPY.42m_ipy_fixed42p.2.0l_IPY” are 6 seconds long resulting in a total of around 50 minutes of event data from the IPY. These two datasets have resulted in 519 data points where the events were present. In the list recorded by Schlatter et al. [2014] 53 events
Table 3.1: Date, time and radar program used for the data.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UT)</th>
<th>Radar Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007-10-01</td>
<td>00:00-24:00</td>
<td>ipy_fixed42p_2.0I_IPY@42m</td>
</tr>
<tr>
<td>2008-01-21</td>
<td>00:00-24:00</td>
<td>ipy_fixed42p_2.0I_IPY@42m</td>
</tr>
<tr>
<td>2007-03-07</td>
<td>15:00-18:00</td>
<td>ipy_fixed42p_1.0I_IPY@42m</td>
</tr>
<tr>
<td>2007-03-16</td>
<td>21:00-24:00</td>
<td>ipy_fixed42p_1.0I_IPY@42m</td>
</tr>
<tr>
<td>2007-04-02</td>
<td>21:00-24:00</td>
<td>ipy_fixed42p_1.0I_IPY@42m</td>
</tr>
<tr>
<td>2007-04-10</td>
<td>15:00-18:00</td>
<td>ipy_fixed42p_1.0I_IPY@42m</td>
</tr>
<tr>
<td>2007-04-29</td>
<td>18:00-21:00</td>
<td>ipy_fixed42p_1.0I_IPY@42m</td>
</tr>
<tr>
<td>2007-05-27</td>
<td>15:00-18:00</td>
<td>ipy_fixed42p_2.0I_IPY@42m</td>
</tr>
<tr>
<td>2007-07-04</td>
<td>19:00-22:00</td>
<td>ipy_fixed42p_2.0I_IPY@42m</td>
</tr>
<tr>
<td>2007-09-22</td>
<td>18:00-21:00</td>
<td>ipy_fixed42p_2.0I_IPY@42m</td>
</tr>
<tr>
<td>2007-09-29</td>
<td>19:00-22:00</td>
<td>ipy_fixed42p_2.0I_IPY@42m</td>
</tr>
<tr>
<td>2007-09-30</td>
<td>18:00-21:00</td>
<td>ipy_fixed42p_2.0I_IPY@42m</td>
</tr>
<tr>
<td>2007-10-04</td>
<td>17:00-20:00</td>
<td>ipy_fixed42p_2.0I_IPY@42m</td>
</tr>
<tr>
<td>2008-01-05</td>
<td>19:00-22:00</td>
<td>ipy_fixed42p_2.0I_IPY@42m</td>
</tr>
<tr>
<td>2011-12-14</td>
<td>20:00-21:00</td>
<td>taro_any_1.00_FI@42m</td>
</tr>
<tr>
<td>2013-12-04</td>
<td>18:00-22:00</td>
<td>beata_fixed42p_1.0L_SP@42m</td>
</tr>
<tr>
<td>2014-01-08</td>
<td>21:00-22:00</td>
<td>ipy_fixed42p_4.1L_CP@42m</td>
</tr>
<tr>
<td>2014-01-21</td>
<td>15:00-20:00</td>
<td>ipy_ip2_4.1L_CP@42m</td>
</tr>
</tbody>
</table>

were recorded during the same time interval. This means that the events are more than 9.7 times more common in the data analyzed compared to the list. This shows that the events are more common than previously shown.

The third dataset was not selected from the IPY but was selected so that it would be possible to compare the radar data to optical data obtained from ASK. These dates are shown in the bottom four rows of Table 3.1. The work on this dataset is a collaboration between Alexander Karlsson, Nicola Schlatter, Nickolay Ivchenko, Hanna Dahlgren and Lorenz Roth at the department of space and plasma physics, KTH. In this thesis the radar data of this dataset has been analyzed and 12 events have been identified. The second part the analysis is the optical analysis of the events which has not yet been finished.

3.2 Identifying Events

Possible events were identified by analyzing the power parameter of the raw data files which were obtained from the EISCAT web page. In order to identify events from the raw power parameter a surface plot is used. The y-axis represents the raw (power range) in km and the x-axis in local time. The possible events are recognized by their narrow range in altitude of strong backscatter and have been observed at ranges of 200-300 km. Figure 3.1 shows an example of the surface plot used to identify possible events. Possible
events can be seen at an altitude of around 230 km. All possible events in the datasets were then identified by visually inspecting the surface plots of the received power and the time of possible events were recorded. The recorded time was used when looking at the ion line spectrum of the possible events to make sure that that the possible events are actually the events we are looking for. There are certain backscatter signatures that show a similar power profile in the surface plots as the events but do not have the characteristic peak at zero Doppler shift and show the regular ion line spectrum.

The possible events that were identified through the surface plots were checked for the zero Doppler shift peak by looking at the ion line spectrum for each point in time where possible events were present in order to determine that there in fact was a peak in the ion line spectrum at zero Doppler shift. The possible events that did not show the peak at zero Doppler shift were removed from the list of events. A list was created of all of the identified events. This list contained, for each event, the time, the range, the width, the peak power and the background power.

The event in Figure 3.2 (A) is located between ranges 200 and 250 km, the frequency shift is shown on the X-axis and its corresponding ion line spectrum at the event altitude is seen in 3.2 (B) where the peak at zero Doppler shift can be observed.

Figure 3.3 shows the ion line spectrum at the event altitude for all of the events. In most of the events the center peak enhancement is strong relative to the side peak. However some of the center peaks appear to be considerably weaker than the side peaks and are hard to spot in Figure 3.3.
Figure 3.2: Power spectrum and Ion Line spectrum

Figure 3.3: Ion line for all the events normalized to maximum power spectral intensity
Chapter 4

Data Analysis

4.1 Characterization of Events

The identified events were characterized in order to get an understanding of how the events differ from each other. The characterization stored the maximum scattered power the width of the peak and the range where the peak occurred, the background power outside of the event and the time the event occurred. This was done by fitting a Gauss curve to the event power profile. The mean of the Gauss fit is the event peak altitude, the standard deviation is the width of the peak and the amplitude is the maximum reflected power from the events. Figure 4.1 show how the events are distributed in altitude. The occurrence of events maximizes at an altitude of 230 km. In this thesis no events have been observed where E-region ionization has not been present at the same time as the event or in close temporal relation to the event.

Figure 4.2 shows the backscattered power from the events relative to the background power. The background power has been defined as the mean value of the power between 15 to 30 kilometers above and below the peak of the event. More than 60% of the events are about 2.5 times stronger than the background. However events have been observed when the backscattered power from the peak is about 20 times stronger than the background.

Figure 4.3 shows for how long the same event has been visible in the radar data. The temporal resolution on the x-axis in Figure 4.3 is 6 seconds since that is the resolution of the radar data. Most events only last for a short amount of time, 6 seconds or less. Events have however been recorded that appear for over one minute. 72 seconds is the longest recorded event in this thesis. Even though some of the events are visible for a long time the power enhancement from the events is not consistent for the entire duration.
Events have been observed with more than one layer of enhanced backscatter. These extra layers occur at a lower altitude than the main peak, the main peak being the stronger of the two. Out of the total event data 34 events contains more than one layer making 6 % of the event data containing more than one layer of enhanced backscatter.

Figure 4.4 shows the time of day occurrence of the events recorded. It shows that the events have a high occurrence during the evening with a peak at around 19:00. More than 60% of the events from the datasets occur between 18:00 and 24:00 UT. It is worth noting that the data is not distributed evenly over the time of day. The second dataset
was chosen in such a way that it did not take into account time of day but rather the local k-index. By looking at table 3.1 one can see that most of the data selected based on the local k-index is during the time of peak occurrence.
4.2 Analyzing Plasma Parameters of the Events

In this section different plasma parameters are analyzed in order to determine which parameters and conditions are important for events to occur. In order to analyze the plasma parameters during the events, mainly electron density, electron and ion temperatures a Matlab program called GUISDAP is used. GUISDAP is available on the EISCAT webpage and is commonly used to analyze EISCAT radar data. In GUISDAP it is possible to select the integration time, a higher integration time means smaller errors in the fitted data but at the same time a lower temporal resolution. In the analysis of the IPY data an integration time of 18 seconds is used. This means that there will be three times as many data point of raw data compared to the analyzed data. The most important effect of this is that some of the events from the raw data will end up in the same data points in the analyzed data. The fact that some of the analyzed data points may include between 1 to 3 of the raw data event points has not been taken into account in the analysis.

In GUISDAP there is a script called satch.m. This scripts checks for satellites and adjusts the data for when a satellite passes through the radar beam. The backscatter from a hard target, such as a satellite, is much stronger than the ambient backscatter from the ionosphere and will ruin the data received by the radar. Since events appear as a very discrete power enhancement in the data, much like that from a hard target, they may be interpreted by GUISDAP as satellites. Therefore the parameter asatch.do in satch.m has been set to 0 in order to disable satellite checking in GUISDAP.

4.3 Electron Density in the E-region

What the E-region electron density peak looks like, in altitude and density, can give a hint of what energies and energy flux the precipitating electrons have when events are present. The electron density which is acquired from GUISDAP gives the electron density as a function of the altitude. A Gauss function was fitted to the electron density profile in the E-region. This gives the altitude of where the E-region electron density peak is, the width of the peak and the maximum electron density of the peak. In Figure 4.5 the maximum electron densities of the peak for the events were compared to that of all data.

By looking at Figure 4.5 (a) and (b) that it is likely that the electron precipitation that causes the electron densities of the E-region is also related to the formation of the events. One can see in Figure 4.5 (c) that the events have a high occurrence, compared
Figure 4.5: Peak electron density in the E-region for all data (a), events (b) and the ratio (c).
to the entire database, when there is high electron density at lower altitudes in the E-region. A electron density peak in the lower E-region indicates that high energy electrons precipitation along the geomagnetic field is important for events to occur. The need for high energy electron for the detection of events is also supported by the fact that in Schlatter et al. [2014] optical data shows that events have been observed during auroral breakup. By looking at Figure 4.5 (c) one can see that with an electron density peak between 105 to 110 km and an electron density of $10^{11.5}$ to $10^{12} \text{ m}^{-3}$ more than 40 % of the total data contains events.

### 4.4 Electron Density in the F-region

Much like the E-region electron density peak, the F-region electron density peak is analyzed in order to see the background electron density in the F-region. A Gauss curve is fitted in the same way as in section 4.3 but to the F-region electron density profile. Since the backscattered power is proportional to the electron density and the increase in backscattered power from the events are actually not caused by an increase in electron density but it is the constructive interference from the events that are causing the power enhancement in backscattered power, for this reason the altitude region where the events occur were excluded from the analyzed data before the fit was produced. In Figure 4.6 the maximum electron densities of the peak for the events were compared to that of all data. One can see that the F-region electron density peak for events is concentrated in Figure 4.6 (c) at ranges between 220 and 240 km.

### 4.5 Electron Temperature in the F-region

The average electron temperature in the F-region can give a hint to if the electron temperature is important for the creation of events. The temperature has been taken as an average of the electron temperature given by GUISDAP during the events in the altitude range between 200-300 km. This region has been chosen since it corresponds to the altitudes where the events occur. The results from this analysis can be seen in Figure 4.7. From Figure 4.7 (c) one can see that the events have a higher frequency when the average electron temperature in the region is high. More than 50% of the events occur with an average electron temperature above 2000K.
Figure 4.6: Peak electron density in the F-region for all data (a), events (b) and the ratio (c).
Figure 4.7: Average electron temperature in the F-region for events (a), all data (b) and the ratio (c).
4.6 Ion Temperature in the F-region

The average ion temperature in the F-region was analyzed in the same way as the average electron temperature in the F-region. The resulting plots are shown in Figure 4.8. In Figure 4.8 (c) one can see that the frequency of events increases with higher ion temperature. However, around 70% of the events occur with an ion temperature at around 1000 K.

Figure 4.8: Ion temperature in the F-region for events (a), all data (b) and the ratio (c).
Chapter 4. Data Analysis

4.7 Ratio Between Electron and Ion Temperature in the F-region

Figure 4.9 shows the average electron temperature and average ion temperature for events, all data and ratio. The data is taken from the same altitude region as in sections 4.6 and 4.5. Figure 4.10 shows the electron-ion temperature ratio. In Figure 4.9 (c) and 4.10 one can see that the frequency of events increases when the ion and electron temperatures is high. In Figure 4.10 (a) one can see that more than 50% of the events occur at an electron-ion temperature ratio between 2 and 3.

4.8 Electron Temperature in the E-region

To see if there are any dependencies between the electron temperatures in the E-region and the events the average electron temperature in the E-region has been analyzed in the same way as sections 4.5 and 4.6. However, no dependencies to the events have been found in the E-region electron temperature. Figure 4.11 shows the average electron temperature in the E-region.

4.9 Ion line Analysis of the Events

In incoherent scatter the ion line spectrum is used to determine the plasma parameters. Figure 3.2 (B) shows an Ion line spectrum from a event. In the spectrum three peaks can be seen. The peaks are characterized by their frequency shift, the peak power and the width of the peak. The peaks are fitted to a normal distribution with three peaks. This was done manually by using the fit function in Matlab and by giving the max of each peak as the initial guess for each fit. To avoid erroneous fits the data points where the fitted data exceeded expected values were removed. The fits where any of the peaks were stronger than the strongest center peak, the width of the peaks that were wider than 10 kHz and all data points where the Doppler shift of the center peak was larger than 1 kHz, which corresponds to a bulk velocity of the plasma larger than 167 m/s, were removed.

The power of the center peak shows the strength of the backscattered power from the anomaly in the event. Figure 4.12 shows the relative backscattered power from the center peak divided by the mean backscattered power of the side peaks. The peak is centered around zero this means that most of the center peaks in the events are as strong
Figure 4.9: Ion and electron temperature in the F-region for all data (a), events (b) and the ratio (c).
Figure 4.10: Ion and electron temperature in the F-region for events (a), all data (b) and the ratio (c).
Figure 4.11: Electron Temperature in the E-region for events (a), all data (b) and the ratio (c).
Figure 4.12: Strength of the center peak relative to the mean of the two side peaks

as that backscattered from the side peaks. More than 60% of the events are between
two times stronger or weaker than the side peaks.

Figure 4.13 shows the parameters of the Gaussian fit plotted against ion and electron
temperatures. The first row shows the frequency shift of the three peaks plotted against
ion temperature in the region 200-300 km. The second row shows the same as the first
row with electron temperature instead of ion temperature. The third row shows the three
peaks and their corresponding widths. The fourth row shows the relative backscattered
power from each event and the width of the peaks.

The frequency shift of the CIL is in Figure 4.13 independent on temperatures and the
width of the peak. This is to be expected since what is causing the center peak frequency
shift is the bulk velocity of the plasma which is independent on temperatures. The
two side peaks, UIL and DIL, a dependence can be seen when looking at the electron
temperature, $T_e$, and the width of the peaks. The electron temperature dependence can
be explained by looking at equation 2.6, an increase in $T_e$ will give a higher frequency
shift. There is also a dependence between the frequency shift and the width of the side
peaks as can be seen in third row of Figure 4.13. There also appears to be an occurrence
Figure 4.13: Characteristics of Ion line spectrum of the events. The left column shows the Center Ion Line (CIL), the middle column shows the Upshifted Ion Line (UIL) and the right column shows the Downshifted Ion Line (DIL).

peak in the relative power of all the peaks with a width of around 2 kHz as can be seen on the fourth row.
Chapter 4. Data Analysis

4.10 Electron Energy Profiles

The energy profile of the electrons can be approximated with the use of electron density profiles in the E-region. With the help of Hanna Dahlgren Figure 4.13 was produced. The same model to fit the electron density profiles as was used in Dahlgren et al. [2008] was used to generate the density profiles in Figure 4.14 with their corresponding energies and energy flux.

The three electron density profiles in Figure 4.14 are taken from the ESR data from the IPY. Profile 1 shows the average electron density profile for the event data which had an electron density peak between between 140-145 km. Profile 2 shows the average electron density profile for the event data which had an electron density peak between between 105-110 km. Profile 3 shows the average electron density profile for the event data which had an electron density peak between between 100-105 km. The solutions are best fit solution of the density profiles for Maxwellian and monoenergetic energy distribution.

In profile 1 the data fits to a Maxwellian distribution of 550 eV. There is however some extra precipitation occurring, accounting for the deviating electron density between 90-100 km, which is not taken into account in the model. The data in profile 2 fits the profile for an electron precipitation with a Maxwellian distribution of 1.9 keV. Profile 3 fits to a 3 keV Maxwellian distribution above 110 km and a 10 keV monoenergetic energy distribution below 110 km.
Chapter 5

Summary and Conclusions

This chapter discusses the results obtained from Chapter 4, as well as comparing the results of this thesis to that of previous studies.

In the datasets analyzed more than 9.7 times more events were discovered than had been recorded in the automatic search algorithm. From Figure 4.1 it can be seen that the peak occurrence of events occur at 230 km which is a slightly higher in altitude compared to the result from Schlatter et al. [2014] which shows that the peak occurrence of events is at an altitude of 220 km. Figure 4.2 shows that the enhancement in backscattered power from the events varies from 1.5 up to 20 times stronger than the background backscattered power. More than 60% of the events show an enhancement of 2.5 times relative to the background. The lifetime of the events, i.e. how long an event has been observed by that radar, varies between 6 to 72 seconds. Most of the events observed are short lived and 40% are visible for 6 seconds or less. Events containing more than one layer of enhanced backscatter have been recorded in 6% of the events. The time of the recorded events is shown in Figure 4.4. It shows that most of the events occur during the afternoon to premidnight with more than 60% of the events occurring between 18:00-24:00 UT. One must consider that the second dataset which contains 36 hours of data were chosen based on the local k-index and not on the time of day. This causes the total data not to be distributed evenly over the time of day.

The E-region electron density peak analysis in section 4.3 shows that the events have a high occurrence in the altitude region between 105 to 110 km and a electron density $10^{11.5}$ to $10^{12}$ m$^{-3}$ in Figure 4.5. In this region the event peaks with more than 40% of the data containing events. The decrease of events in the data bins around this region may suggest that the events occur from parametric decay instabilities of Langmuir waves caused inverse Landau damping from high energy electron precipitation. As shown by Akbari et al. [2015] a electron beam of 1 keV may cause this type of plasma instability.
By analyzing the data from a electron density profile of an event can give an indication of what energies are required to create these events.

In section 4.10 electron density profiles from the ESR has been fitted to electron precipitation energy profiles. Figures 4.14 (B) and (A) fits to a Maxwellian energy distribution of 1.9 keV and 3 keV.

Sections 4.5, 4.6 show that there is an relative increase in events with an increase in both electron an Ion temperatures in the F-region. Figure 4.10 (a) shows the temperature ratio of the events in the F-region. It shows a occurrence peak of events at a temperature ratio of 2.5 and that half of the events occur at a temperature ratio in the between 2 and 3.
Bibliography


