Enhanced Radar Backscatter from the Ionosphere

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Abstract

Incoherent scatter radars are powerful ground based instruments for ionospheric measurements. By analysis of the Doppler shifted backscatter spectrum, containing the signature of electrostatic plasma waves, plasma bulk properties are estimated. Occasionally, the backscattered radar power is enhanced several orders of magnitude above the thermal backscatter level. These enhancements occur during naturally disturbed ionospheric conditions and in ionospheric modification experiments, where a powerful radio wave is incident on the ionospheric plasma. In both of the cases the non-linearity is thought to be turbulence of electrostatic Langmuir waves. The Langmuir turbulence theory and models account for many features of enhanced ionospheric radar backscatter reported on in the literature. During disturbed conditions, with precipitation of auroral electrons, Langmuir turbulence is thought to be driven by a low energy electron beam. Optical and radar observations of naturally enhanced radar backscatter indicate Alfvénic type of aurora during events reported on in the literature. However, contrasting conclusions have been drawn from optical observations. While some reports suggest that enhanced radar backscatter is observed at the edge of auroral structures others suggest that the enhanced backscatter region and auroral precipitation are co-located. Optical imagers with a narrow field of view resolve auroral structures with tens of meters scale size. The cross beam resolution of radars, however, is limited by the width of the radar beam, typically several kilometers wide at auroral altitudes. By using several radar receivers for observations - radar interferometry - the cross beam resolution is increased. Simultaneous observations of enhanced radar backscatter with radar interferometry and narrow field of view optical observations will increase the understanding of the physical processes involved and will make it possible to associate auroral structures with the enhanced radar backscatter. An interferometric radar receiver system has been built and a calibration technique for the system developed. In ionospheric modification experiments, the Langmuir turbulence is driven by a powerful electromagnetic wave incident on the ionosphere and electrons are significantly accelerated. The acceleration of electrons is not yet fully understood. Ionospheric modification experiments and ground based measurements, as reported on herein, contribute to the understanding of ionospheric instabilities induced by a power electromagnetic wave.
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## Acronyms

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<th>Definition</th>
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<tbody>
<tr>
<td>AST</td>
<td>Aperture Synthesis Toolbox</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>DV</td>
<td>Digital Video</td>
</tr>
<tr>
<td>EASI</td>
<td>EISCAT Aperture Synthesis Imaging</td>
</tr>
<tr>
<td>EISCAT</td>
<td>European Incoherent SCATter</td>
</tr>
<tr>
<td>EMCCD</td>
<td>Electron Multiplying Charge Coupled Device</td>
</tr>
<tr>
<td>ESR</td>
<td>EISCAT Svalbard Radar</td>
</tr>
<tr>
<td>FOV</td>
<td>Field Of View</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>GUISDAP</td>
<td>Grand Unified Incoherent Scatter Data Analysis Program</td>
</tr>
<tr>
<td>IAE</td>
<td>Ion Acoustic Enhancements</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>IME</td>
<td>Ionospheric Modification Experiment</td>
</tr>
<tr>
<td>IPP</td>
<td>Inter Pulse Period</td>
</tr>
<tr>
<td>ISR</td>
<td>Incoherent Scatter Radar</td>
</tr>
<tr>
<td>LP</td>
<td>Lag Profile</td>
</tr>
<tr>
<td>LPM</td>
<td>Lag Profile Matrix</td>
</tr>
<tr>
<td>LT</td>
<td>Langmuir Turbulence</td>
</tr>
<tr>
<td>NEIAL</td>
<td>Naturally Enhanced Ion Acoustic Line</td>
</tr>
<tr>
<td>PAL</td>
<td>Phase Alternation Line</td>
</tr>
<tr>
<td>PDI</td>
<td>Parametric Decay Instability</td>
</tr>
<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
</tr>
<tr>
<td>VHF</td>
<td>Very High Frequency</td>
</tr>
<tr>
<td>XLPM</td>
<td>Cross Lag Profile Matrix</td>
</tr>
</tbody>
</table>
List of Papers

This thesis is based on the work presented in the following manuscripts.

I ‘Radar interferometer calibration of the EISCAT Svalbard Radar and a additional receiver station’
N. M. Schlatter, T. Grydeland, N. Ivchenko, V. Belyey, J. Sullivan, C. La Hoz and M. Blixt

II ‘Enhanced radar spectra from distinct altitude regions observed during high energy electron precipitation’
N. M. Schlatter, N. Ivchenko, T. Sergienko, B. Gustavsson and B. U. E. Brändström

III ‘HF modification of the auroral E region’
N. M. Schlatter, N. Ivchenko, B. Gustavsson and M. T. Rietveld

Manuscripts with contribution of the author not included in this thesis:

I ‘Results from the intercalibration of optical low light calibration sources 2011’
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Chapter 1

Introduction

To us humans the most familiar states of matter are the solid, liquid and gas state all of which we can observe in our daily life on the earth’s crust. However, more than 99% of matter in the universe are plasma, often referred to as the fourth state of matter. In a plasma neutral atoms and molecules are partially ionized or even fully dissolved into their constituents. Although plasma hardly occurs naturally on the earth’s crust it is found in sporadic events such as lightning strikes and fire. As we zoom out from earth plasma accounts for increasing amounts of matter. At 100 km altitude the atmosphere is ionized by sun light and cosmic radiation to such extent that plasma dynamics have a significant role. As the density of the neutral atmosphere decreases exponentially the degree of ionization increases. Outside the earth’s magnetosphere, i.e. outside the part of space where earth’s magnetic field dominates, the solar wind, a stream of charged particles originating from the sun, fills the almost empty space. Further away matter in stars and planetary nebula are almost completely ionized. Despite our opposite experience, the universe is over large parts affected by the dynamics of a plasma.

Although on a large scale plasma is quasi neutral each charged particle is affected by electric and magnetic fields. And the particles interact with each other over long ranges. Plasma is thus a medium with a variety of dynamical effects not present in the other states of matter. The aurora australis and aurora borealis the southern and northern lights are one prominent signature of plasma dynamics and are a popular object for research and study. The optical emissions of aurora arise from relaxation processes of excited atoms and molecules at roughly 90 to 300 km altitude where earth’s ionosphere is situated. The energy source for the excitation are predominantly electrons precipitating down to the ionosphere along the magnetic field. Ground based instrumentation developed over the last centuries and their further development have contributed to a basic understanding of the aurora and ionospheric processes. One of the most powerful ground based instruments for ionospheric measurements are Incoherent Scatter Radar (ISR), which are able to measure plasma bulk properties remotely. In situ measurements by satellites and
rockets have increased our understanding further and extended the region covered with measurements out to the magnetosphere. Satellites orbiting the sun and placed outside earth’s magnetosphere made it even possible to study the solar wind and its interaction with the magnetosphere.
The advance of ground based instrumentation made measurements with higher spatial and temporal resolution of aurora possible and has revealed scale sizes down to tens of meters in active aurora. While the spatial resolution of optical imagers is almost without limit the temporal resolution of low light measurements has been improved with the development of Electron Multiplying Charge Coupled Device (EMCCD) imagers. Physical processes responsible for the acceleration of the precipitating electrons and the origin of the fine scale auroral features are a active field of research. Complementary measurements with ISR are limited to temporal resolution of seconds and the spatial resolution is limited by the beam width of the radar antenna. A technique called aperture synthesis imaging, developed in the field of astrophysics, can be used to increase the spatial resolution of ISR. Such improvement is necessary to study fine scale auroral structures in detail and to understand the physical processes involved. Future instrumentation, such as proposed in the EISCAT_3D project, will implement aperture synthesis imaging in large scale ISR. A test facility at the EISCAT Svalbard Radar (ESR), EISCAT Aperture Synthesis Imaging (EASI), for implementing aperture synthesis imaging in ISR measurements has been built. Despite the technical limitations, a number of science cases exist. The possible observations with EASI include naturally and artificially produced plasma instabilities in the ionosphere.

This licentiate thesis is focused on naturally occurring and artificially created plasma instabilities in the ionosphere observed with ground based instrumentation. In chapter 2 introduction to the near earth environment is given and in chapter 3 concepts of wave propagation in a plasma are presented. Chapter 3 also gives an introduction to plasma instabilities. An introduction to the technique of incoherent scatter radars, which are used for observations, is given in chapter 4 followed by instrumental details in chapter 5. The papers included in this thesis are summarized in chapter 6 and an outlook on future plans of study for the doctoral thesis are presented in chapter 7.
Chapter 2

Space Plasma Physics

The study of the ionized outermost part of the atmosphere, the stream of charged particles from the sun, the interaction of the particle stream with planets and comets and the study of the sun are vaguely combined in the field of space plasma physics. Basic concepts of plasma physics and the near earth environment are outlined in this chapter. In the section 2.1 the force on charged particles under the influence of electric and magnetic fields and some of the basic properties of a plasma are described. In section 2.2 the earth’s magnetosphere is described followed by characteristics of the inner part of the magnetosphere, the ionosphere, in section 2.3. Auroral current systems and acceleration mechanisms are described in section 2.4 and 2.5 respectively. In section 2.6 optical aurora and the most prominent emissions are described. Ionospheric modification experiments are covered in section 2.7.

2.1 Basic Plasma Properties

The force $F$ on a particle with charge $q$ due to an electric field $E$ and a magnetic field $B$ is called Lorentz force and given by:

$$F = q(E + v \times B). \quad (2.1)$$

For zero electric field particles gyrate around in the plane perpendicular to the magnetic field with the Larmor radius of gyration:

$$r_L = \frac{m v_\perp}{|q| B}, \quad (2.2)$$

where $B = |B|$ is the strength of the magnetic field. The frequency of the gyration is:

$$\omega_c = \frac{qB}{m} \quad (2.3)$$
and referred to as cyclotron frequency. The gyration of a charged particle is associated with a magnetic moment $\mu$ due to the current produced by the particle:

$$\mu = \frac{E_{\perp}}{B} = \frac{mv_{\perp}^2}{2B}. \quad (2.4)$$

In a sufficiently slow varying environment, i.e. sufficiently slow varying magnetic field, the magnetic moment of a particle is constant. Therefore, if the magnetic field is increased also the perpendicular velocity of a particle will increase. Since the energy of the particle is conserved the velocity component parallel to the magnetic field has to decrease. At a certain strength of the magnetic field the parallel component of the particle will reach zero and the particle will be reflected. This concept of so called mirroring is useful to think of in case of the earth’s magnetic field. At the magnetic equator the strength of the magnetic field is at its minimum and increasing towards the magnetic poles. Charged particles moving under the influence of the earth’s magnetic field will therefore eventually be reflected at high latitudes before reaching the dense ionosphere.

In the presence of a force perpendicular to the magnetic field a drift motion is superimposed on the gyration of a particle. The drift velocity is given by:

$$v_D = \frac{1}{q} \frac{F \times B}{B^2}. \quad (2.5)$$

The force can be e.g. an electric field ($E \times B$ drift), due to a curvature in the magnetic field (curvature drift) or a gradient in the magnetic field (gradient drift). In case of the $E \times B$ drift the resulting drift direction is independent of the charge of the particle.

In a plasma where the number of charged particles is large each of the particles is affected by the other particles due to long range forces. A characteristic length scale for a plasma is the Debye length which describes how well a charge is shielded within the plasma. For example electrons will be attracted to a positive charged ion and shield the ion potential. The length scale of the shielding potential, the Debye length ($\lambda_D$) can be expressed as:

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T}{nq^2}}, \quad (2.6)$$

with $n$ the charge carrier density, $T$ the temperature, $\epsilon_0$ the permittivity of free space and $k_B$ the Boltzmann constant. On spatial scales close to and below the Debye length the quasineutrality of the plasma is not necessary valid.

An important temporal scale of a plasma is the plasma frequency:

$$\omega_p = \sqrt{\frac{ne^2}{\epsilon_0 m_e}}, \quad (2.7)$$
2.2. EARTH’S MAGNETOSPHERE

Here $e$ and $m_e$ are the electron charge and mass. The plasma frequency is independent on the magnetic field and describes how the plasma reacts to charge density fluctuations. It is the frequency of oscillation of charged particles where the force on the particles is due to an electrostatic potential caused by charge separation.

On a large scale, plasma can be described as a conductive fluid. The magnetic Reynolds number $R_m$ relates convection to diffusion and can be expressed as:

$$R_m = \frac{\mu_0 \sigma v L}{\mu_0}$$

(2.8)

where $\mu_0$ is the permeability, $v$ is the characteristic velocity, $L$ the characteristic length and $\sigma$ the electric conductivity. When $R_m \gg 1$, i.e. the plasma has a high conductivity, diffusion is negligible and the magnetic field is tied to the motion of the particles and vice versa. $R_m \gg 1$ is often referred to as the frozen-in condition.

2.2 Earth’s Magnetosphere

The earth is protected from the solar wind by the magnetic field created in the earth’s core. Due to the frozen-in condition the solar wind can not penetrate into the part of space where the earth’s magnetic field dominates. This region is called magnetosphere, see Figure 2.2. In the sunward direction the magnetosphere is compressed by the magnetic and dynamic pressure of the solar wind and extends $\sim 10 R_E$ (one earth radius $R_E \approx 6378$ km). On the dayside magnetosphere earth’s magnetic field is roughly dipole shaped. On the nightside earth’s magnetic field is stretched and the magnetosphere extends for $\sim 200 R_E$. The extended nightside magnetosphere is referred to as the tail of the magnetosphere. Current sheets separate the magnetosphere from the solar wind plasma. A current sheet called the tail current is also found in the tail or nightside of the magnetosphere separating the northern and southern lobes of with opposite direction of the magnetic field.

The main mechanism for solar wind plasma to enter the magnetosphere is thought to be magnetic reconnection on the earth’s dayside. When the frozen-in condition breaks down the magnetic field carried in the solar wind can connect to the earth magnetic field and create open field lines which extend far into space where the field lines are closed. The open field lines created on the dayside are pulled along in the solar wind and add up to the lobes of the magnetotail on the nightside.

Opposing the decrease in magnetic flux due to dayside reconnection is nightside reconnection. In the magnetotail oppositely directed field lines of the northern and southern hemisphere can reconnect. The tension in the magnetic field causes the created closed field line to drift back to earth into a more dipole shaped form. This process is called dipolarisation.
2.3 Earth’s Ionosphere

The ionosphere of the earth extends from about 85 km out to 600 km altitude and is the transition layer between the neutral atmosphere and the fully ionized magnetosphere. In the ionosphere a large part of atmospheric gas is ionized by solar photons. Other sources of ionization are energetic particles originating from acceleration processes within the magnetosphere or from outside the magnetosphere, *bremsstrahlung* emitted from deceleration processes and photons emitted from within ionosphere. On the dayside of the earth’s ionosphere, photoionization by solar photons (10 nm to 100 nm) is the dominating source of ionization.

The dominating neutral species in the ionosphere are $N_2$, $O_2$, O, He and H. Because of their different mass each species has its specific altitude profile and scale height with which the density is decreasing with altitude as shown in Figure 2.2. Since the flux of photo electrons on the other hand is increasing with altitude, the ionization will have a maximum at a certain altitude. For each ionospheric species the ionization rate can be calculated by the so called *Chapman theory*. The total ionization, which is the sum of the single species ionization, will result in a layered
2.4 CURRENT SYSTEMS

...
field is dominated by the $\mathbf{E} \times \mathbf{B}$ drift at these altitudes. Since the direction of the $\mathbf{E} \times \mathbf{B}$ drift is independent of charge the current perpendicular to the magnetic field is negligible. At lower altitudes where the collision frequency of electrons and protons with neutrals is of the order of the gyration frequency, the particles are deflected from the $\mathbf{E} \times \mathbf{B}$ direction and a net current perpendicular to the magnetic field exists. The conductivity of the ionosphere is often described with the conductivity along the electric field component perpendicular to the magnetic field, the Pedersen conductivity and the Hall conductivity which is the conductivity in the $\mathbf{E} \times \mathbf{B}$ direction.

Ionospheric conductivities are affected by the plasma density and the conductivity is enhanced in regions of electron precipitation. As a result, polarization charges and polarization electric fields build up at the edges of auroral arcs. These effects complicate the E region current systems. A discussion of auroral current systems and electric fields in and around auroral arcs is given by e.g. Brekke [1997], Paschmann et al. [2003].

### 2.5 Acceleration Mechanisms

The energy of electrons precipitating down to the dense ionosphere and causing optical aurora reach from hundreds of eV to tens of keV. Acceleration mechanisms are necessary to account for the high flux of energetic particles in the ionosphere.

Large scale auroral arc systems are well described by electrostatic accelera-
tion due to field aligned potential drops. In-situ measurements made by satellites show that auroral electrons undergo electrostatic acceleration up to tens of keV at altitudes of 5000 – 8000 km [Reiff et al., 1988, Block and Fälthammar, 1990]. Marklund et al. [2001] showed that the acceleration region for the return current region is located at 1500 – 3000 km and electrons reach a few keV. After undergoing acceleration by a electrostatic potential the energies of the precipitating electrons are nearly mono energetic.

In observations of small scale auroral features bursts of field aligned electrons with a wide range of predominantly low energy electrons have been reported. These electron bursts are thought to be driven by inertial Alfvén waves [Stasiewicz et al., 2000]. Signatures of Alfvén waves have been identified in in-situ magnetic and electric field measurements in the topside ionosphere [Chaston et al., 1999, Knudsen and Wahlund, 1998] and in rocket measurements (altitude ~ 500 km) [Ivchenko et al., 1999, Mella et al., 2011].

2.6 Optical Aurora

Optical aurora is a result of excitation of atoms and molecules in the ionosphere by precipitating particles. As the composition of the ionosphere is changing with altitude also the observed colors of aurora change with the altitude region where the energy of precipitating particles is deposited. Electron precipitation with low energy, hundreds of electron volt, deposits its energy due to collisions at altitudes...
of about 150 to 300 km where the main constituent is atomic oxygen. Precipitation of a few keV deposits most of its energy at altitudes between 100 and 150 km where molecular species dominate. Energy deposition profiles for different electron populations and different electron energies are published in the work of Rees [1989]. With the increase in electron energy the observed emissions change from red to green. Also other emissions are observed in aurora, however, less intense. Table 2.1 summarizes important auroral emissions and the state from which the photon is emitted. The optical observation of aurora not only gives the temporal and spatial development of aurora, but also the energy of precipitation, the flux and even neutral flows can be measured.

Table 2.1. Prominent optical auroral emissions where $\lambda$ is the emission wavelength.

<table>
<thead>
<tr>
<th>$\lambda$ [nm]</th>
<th>Species (emitting state or band)</th>
</tr>
</thead>
<tbody>
<tr>
<td>557.7</td>
<td>$O(^1S_0)$</td>
</tr>
<tr>
<td>630.0</td>
<td>$O(^1D_2)$</td>
</tr>
<tr>
<td>673.0</td>
<td>$N_2(B^3\Pi_g)$</td>
</tr>
<tr>
<td>732.0</td>
<td>$O(^2P)$</td>
</tr>
<tr>
<td>777.4</td>
<td>$O(3p^3P)$</td>
</tr>
<tr>
<td>427.8</td>
<td>$N_2^+(B^2\Sigma^+_u)$</td>
</tr>
<tr>
<td>844.6</td>
<td>$O(3p^3P)$</td>
</tr>
</tbody>
</table>

2.7 Ionospheric Modification Experiments

Ionospheric heating refers to electron heating in the ionosphere by powerful HF waves. Although the effect of a radio wave is not limited to electron heating active ionospheric experiments with powerful radio waves are usually referred to as heating experiments, alternatively Ionospheric Modification Experiment (IME) is a more appropriate term. At altitudes where the heater or so called pump wave matches eigen-frequencies of the ionospheric plasma the energy of the pump wave can be transferred to the plasma very effectively. In a well designed modification experiment plasma instabilities can be excited and for further studies their signature can be observed by ground based instruments such as Incoherent Scatter Radar (ISR).

In IME with overdense conditions, i.e. the ionospheric peak plasma frequency is higher than the frequency of the pump wave, Parametric Decay Instability (PDI) (see section ??) can be triggered near the reflection height. PDI describes the decay of the heater pump wave in a Langmuir and ion acoustic wave. ISR observations during induced PDI exhibit enhanced backscattered power observed from a narrow altitude below the reflection altitude.

Another manifestation of ionospheric modifications induced by heating is observed artificial airglow in well designed experiments. The heater induced artificial airglow can reach up to thousands of Rayleigh in the red line emitted by atomic oxygen at 630.0 nm. Artificial airglow has also been observed at other wavelengths
such as 557.7, 844.6, 777.4 and 427.8 nm [e.g. Djuth et al., 2005, Gustavsson et al., 2005, Kosch et al., 2007]. Electron energies of several eV are necessary for excitation of atoms leading to the observed enhanced emissions. Acceleration of thermal electrons is thought to be due to Langmuir Turbulence (LT). However, increases in airglow when the double resonance condition is fulfilled, i.e. when the pump frequency is a multiple of the cyclotron frequency at the interaction height argue for an interplay between different acceleration mechanisms [Djuth et al., 2005].
Chapter 3

Plasma Wave Interaction

A large number of wave modes exist in a plasma and the definition of these wave modes is beyond the scope of this thesis. A detailed description of the wave modes can be found e.g. in the book by Baumjohann and Treumann [1996]. In section 3.1 the equations describing the propagation of electromagnetic waves in a cold magnetized plasma are derived following the book by Gurnett and Bhattacharjee [2005]. Section 3.2 covers electrostatic waves in a thermal plasma. Naturally occurring plasma instabilities in the ionosphere and artificial induced plasma instabilities are discussed in section 3.3. Langmuir turbulence occurring both in naturally and artificially excited instabilities is covered in section 3.4.

3.1 Electromagnetic Waves

The basic equations describing the coupling between the electric and magnetic field are Maxwell’s equations. Maxwell’s equations are:

\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \epsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} \]  
(3.1)

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  
(3.2)

\[ \nabla \cdot \mathbf{E} = \frac{\rho_e}{\epsilon_0} \]  
(3.3)

\[ \nabla \cdot \mathbf{B} = 0. \]  
(3.4)

In order to analyze waves in plasma one has to couple the equation of motion of charged particles to the equations describing the electric and magnetic fields. A plasma with an external magnetic field, similar to the ionosphere, is assumed. For simplification the plasma is assumed to be cold, i.e. thermal motion is neglected. A procedure commonly used to derive the dispersion relation of waves is to linearize the set of equations and transform them to Fourier space. Following this approach is the book by Gurnett and Bhattacharjee [2005].
The force acting on particles due to electric and magnetic fields is the Lorentz force, Eqn.(2.1). The magnetic field is the sum of the background magnetic field $B_0$ and the wave magnetic field $B_1$. The background electric field is assumed to be zero and the wave electric field $E$. After linearization the particle equation of motion is:

$$m_s \frac{\partial v_s}{\partial t} = e_s [E + v_s \times B_0], \quad (3.5)$$

where $m_s$ is the particle mass, $e_s$ the particle charge and the index $s$ stands for the species. The index 0 stands for zero-order property and the term $v_{s1} \times B_1$ has been dropped due to linearization. Without loss of generality, the direction of the magnetic field is in z-direction. It is useful to transform Eqn.(3.5) to Fourier space, in vector notation it becomes:

$$-i\omega m_s \tilde{v}_{sx} = e_s [\tilde{E}_x + \tilde{v}_{sy} B_0],$$
$$-i\omega m_s \tilde{v}_{sy} = e_s [\tilde{E}_y + \tilde{v}_{sx} B_0],$$
$$-i\omega m_s \tilde{v}_{sy} = e_s \tilde{E}_y. \quad (3.6)$$

The tilde above variables signifies that these are in Fourier space. With the above equations the current density which is defined by $\tilde{J} = \sum_s n_s e_s \tilde{v}$ can be computed and further the conductivity tensor $\sigma$ defined by $\tilde{J} = \sigma \cdot \tilde{E}$. The conductivity tensor is then given by:

$$\sigma = \sum_s \frac{n_s e_s^2}{m_s} \begin{bmatrix} -i\omega & \frac{\omega}{\omega - \omega_{cs}} & \frac{\omega_{ps}}{\omega - \omega_{cs}} & 0 \\ \frac{\omega}{\omega - \omega_{cs}} & 0 & \frac{\omega}{\omega - \omega_{cs}} & 0 \\ \frac{\omega_{ps}}{\omega - \omega_{cs}} & \frac{\omega}{\omega - \omega_{cs}} & 0 & 0 \\ 0 & 0 & 0 & \frac{i}{\epsilon_0} \end{bmatrix}. \quad (3.7)$$

The dielectric tensor is given by $K = 1 - \frac{\sigma}{i\omega\epsilon_0}$ and has the form:

$$K = \begin{bmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{bmatrix}, \quad (3.8)$$

where

$$S = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2 - \omega_{cs}^2}, \quad D = \sum_s \frac{\omega_{ps}^2\omega_{cs}}{\omega(\omega^2 - \omega_{cs}^2)} \quad (3.9)$$

and

$$P = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2} \quad (3.10)$$

In order to derive the dispersion relation Maxwell’s equations are needed. Faraday’s, Eqn.(3.2), and Ampere’s law, Eqn.(3.1), can be used to eliminate either $E$ or $B$. In Fourier space the equations are:

$$ik \times \tilde{k} \tilde{E} = -(-i\omega) \tilde{B}$$
$$ik \times \tilde{B} = -i\omega c^2 K \cdot \tilde{E}. \quad (3.11)$$
Choosing to eliminate the magnetic field a homogeneous equation for the electric field is obtained:
\[ \mathbf{k} \times (\mathbf{k} \times \tilde{\mathbf{E}}) + \frac{\omega^2}{c^2} \mathbf{K} \cdot \tilde{\mathbf{E}} = 0. \] (3.12)

The definition of the refractive index is \( n = \frac{c k}{\omega} \) which can be used to simplify the equation above to:
\[ n \times (n \times \tilde{\mathbf{E}}) + \mathbf{K} \cdot \tilde{\mathbf{E}} = 0. \] (3.13)

For simplicity the coordinate system is chosen such that \( \mathbf{k} \) and therefore also \( \mathbf{n} \) lie in the x-z plane, \( \mathbf{B}_0 \) is along the z axis. The angle between \( \mathbf{B}_0 \) and \( \mathbf{n} \) is \( \theta \). The refractive index \( n \) is:
\[ n = (n \sin \theta, 0, n \cos \theta). \] (3.14)

Combination of Eqn.(3.13) and (3.14) with the results for \( S, D \) and \( P \) leads to the matrix equation:
\[
\begin{bmatrix}
S - n^2 \cos^2 \theta & -iD & n^2 \sin \theta \cos \theta \\
iD & S - n^2 & 0 \\
n^2 \sin \theta \cos \theta & 0 & P - n^2 \sin^2 \theta
\end{bmatrix}
\begin{bmatrix}
\tilde{E}_x \\
\tilde{E}_y \\
\tilde{E}_z
\end{bmatrix} = 0.
\] (3.15)

Non-trivial solutions to this equation can be found by computing the determinant of the matrix and setting it to zero which can be written as:
\[ \tan^2 \theta = -\frac{P \left( n^2 - R \right) \left( n^2 - L \right)}{(Sn^2 - RL)(n^2 - P)}. \] (3.16)

In the following the case of waves traveling parallel to the magnetic field (\( \theta = 0 \)) and the case of transverse traveling waves (\( \theta = \pi/2 \)) are discussed.

### 3.1.1 Propagation Parallel to the Magnetic Field

For waves parallel to the magnetic field (\( \theta = 0 \)) the matrix Eqn.(3.15) simplifies to:
\[
\begin{bmatrix}
S - n^2 & -iD & 0 \\
iD & S - n^2 & 0 \\
0 & 0 & P
\end{bmatrix}
\begin{bmatrix}
\tilde{E}_x \\
\tilde{E}_y \\
\tilde{E}_z
\end{bmatrix} = 0,
\] (3.17)

for which three non-trivial solutions exist:
\[ P = 0, \quad \tilde{\mathbf{E}} = (0, 0, E_0) \] (3.18)
\[ n^2 = R, \quad \tilde{\mathbf{E}} = (E_0, iE_0, 0) \] (3.19)
\[ n^2 = L, \quad \tilde{\mathbf{E}} = (E_0, -iE_0, 0), \] (3.20)

where
\[ R = 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega + \omega_{cs})} \quad \text{and} \quad L = 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega - \omega_{cs})}. \] (3.21)
The first solution \((P = 0)\) is associated with electrostatic oscillation with the frequency \(\omega_p\).

The second and the third solution with \(n^2 = R\) and \(n^2 = L\) are transverse waves for which the electric field is perpendicular to the wave vector \(k\). With the use of Gauss’s law (Eqn.(3.3)) it can be shown that there are no charge fluctuations associated with these waves and with Faraday’s law it is easily shown that these waves are electromagnetic waves since the wave magnetic field is non-zero. The only difference between these two modes is that one is a right hand polarized wave and the other a left hand polarized which is important in terms of wave plasma interactions. Electrons gyrate in the right-hand sense around the magnetic field while ions have a left-handed rotation. Therefore L-mode waves close to the ion cyclotron frequency \(\omega_{ci}\) interact strongly with the ions whereas R-mode waves with a frequency close to the electron cyclotron frequency interact strongly with the electrons.

Those frequencies where the index of refraction is zero are called cut-off frequencies. At frequencies below the cut-off frequency the index of refraction is imaginary. In such regimes the wave is evanescent.

### 3.1.2 Propagation Perpendicular to the Magnetic Field

Propagation perpendicular to the magnetic field corresponds to the case that \(\theta = \pi/2\) and from the dispersion relation and Eqn.(3.15) two roots are found with their corresponding eigenvectors:

\[
\begin{align*}
\dot{n}^2 &= P, \quad \dot{E} = (0, 0, E_0) \\
\dot{n}^2 &= RL, \quad \dot{E} = \left( \frac{iD}{S} E_0, E_0, 0 \right).
\end{align*}
\]

The magnetic field has no effect in the first solution since the particle motion is parallel to the magnetic field. This mode is called ordinary (O) mode. The second case is a bit more complicated since the wave interacts with the external magnetic field. This wave mode is called extraordinary (X) mode. The dispersion of the X mode has a resonance, so called hybrid resonance, associated with each species of the plasma.

### 3.2 Electrostatic Waves

In a plasma there are always waves present, e.g., thermally excited waves. In incoherent scatter radar experiments ion acoustic waves, section 3.2.1, play a significant role. By measuring the spectra of these waves important plasma properties can be deduced such as the electron temperature. Another important type of thermal excited waves are Langmuir waves (section 3.2.2).

In order to describe a plasma with a non zero temperature a statistical approach is needed which is called kinetic theory. The Boltzmann equation describes the
3.2. ELECTROSTATIC WAVES

Evolution of the distribution function $f$ in phase space:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \frac{\mathbf{F}_m}{m} \cdot \nabla_v f = \frac{\delta_c f}{\delta t},$$

(3.24)

where $\nabla_v$ is the gradient operator in velocity space and $\delta_c f/\delta t$ accounts for collisions. In order to obtain macroscopic averages of properties such as the density a set of equations called the moment equations is useful. The moment equations are obtained by multiplying the Boltzmann equation by powers of the velocity and integrating over velocity space. The zeroth moment of the Boltzmann equation yields the equation of continuity:

$$\frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \mathbf{U}_s) = 0,$$

(3.25)

where $\mathbf{U}_s$ is the average velocity and $n_s$ the average number density. The first moment equation is called momentum equation and can be written in the form:

$$m_s n_s \frac{d\mathbf{U}_s}{dt} = n_s q_s \left[ \mathbf{E} + \mathbf{U}_s \times \mathbf{B} \right] - \nabla \cdot \mathbf{P}_s + \frac{\delta \mathbf{P}_s}{\delta t},$$

(3.26)

where the second term on the right hand side describes the momentum change per unit volume due to pressure ($\mathbf{P}_s$) gradients and the third term the collisional drag force per unit volume.

Using the continuity equation, Eqn.(3.25), the momentum equation, Eqn.(3.26), and the adiabatic equation of state:

$$PV^\gamma = \text{constant},$$

(3.27)

where $\gamma$ is the adiabatic constant, the dispersion relation for longitudinal electrostatic waves can be obtained [Gurnett and Bhattacharjee, 2005]:

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

(3.28)

Here $C_s$ is the acoustic speed, $C_s = \sqrt{\kappa T_s/m_s}$, and $\gamma_s$ the adiabatic constant of the species $s$.

### 3.2.1 Ion Acoustic Wave

A significant simplification of Eqn.(3.28) is the assumption that the ion temperature is small, i.e., $C_i = 0$:

$$1 - \frac{\omega^2_{pi}}{\omega^2} - \frac{\omega^2_{pe}}{\omega^2 - \gamma_e C_e^2 k^2} = 0.$$  

(3.29)

Furthermore limiting the phase velocity to less than the electron thermal velocity $\omega^2 \ll \gamma_e C_e^2 k^2$:

$$\omega^2 = \frac{1}{1 + \gamma_e \lambda_{De}^2 k^2} \left( \frac{\gamma_e k_B T_e}{m_i} \right) k^2,$$  

(3.30)
which is plotted in Figure 3.1(a). For long wavelengths i.e. \( k \lambda_D \ll 1 \) Eqn.(3.30) simplifies to:

\[
\omega_S = \pm k v_S \quad (3.31)
\]
\[
v_S = \sqrt{\frac{\gamma_e k_B T_e}{m_i}}. \quad (3.32)
\]

In ion acoustic waves the oscillation of electrons and ions is almost in phase and density perturbations are associated with the wave.

Wave dispersion can include complex solutions, i.e. \( \omega = \omega_r - i \gamma_D \) where \( \gamma_D \) is the damping rate of the wave, resulting in either a growth or decay of the wave amplitude depending on the sign of \( \gamma_D \):

\[
E = E_0 e^{-i \omega_r t} e^{-\gamma_D t}. \quad (3.33)
\]

With kinetic theory the damping coefficient \( \gamma_S (k) \) for ion acoustic waves can be derived [Stix, 1992]:

\[
\gamma_S (k) = \omega_S (k) \left( \frac{\pi \gamma}{8} \right)^{1/2} \left[ \left( \frac{m_e}{m_i} \right)^{1/2} + \gamma \left( \frac{T_e}{2 T_i} \right)^{3/2} \exp \left( -\gamma T_e/T_i \right) \right]. \quad (3.34)
\]

### 3.2.2 Langmuir Waves

In the following, the high frequency branch of the Dispersion relation is examined. The high frequency oscillations are called Langmuir waves. For high frequencies Eqn.(3.28) simplifies to:

\[
1 - \frac{\omega^2_{pe}}{\omega^2 - \gamma_e C_e^2 k^2} = 0, \quad (3.35)
\]

here the ion motion was neglected, due to their slow response to electric fields. Rewriting the equation in terms of \( \omega \) and using the relation \( C_e = \omega_{pe} \lambda_D \) for the thermal electron velocity leads to the dispersion relationship for the Langmuir mode:

\[
\omega_L^2 = \omega_{pe}^2 \left( 1 + \gamma_e \lambda_D^2 k^2 \right), \quad (3.36)
\]

which is plotted in Figure 3.1(b). In the long wavelength limit the Langmuir mode is equivalent to oscillations of the electrons with the cold plasma frequency \( \omega_{pe} \). With decreasing wavelength the electron pressure adds to the restoring force in the oscillations. In the short wavelength limit the phase velocity of the Langmuir wave is equivalent to the electron sound speed \( \sqrt{\gamma_e C_e} \).

Langmuir waves dissipate energy through Landau damping to electrons which move at a velocity close to the phase velocity of the wave. From kinetic theory the damping rate \( \gamma_L (k) \) can be derived for a Maxwellian plasma [Stix, 1992]:

\[
\gamma_L (k) = \omega_p \left( \frac{\pi}{8} \right)^{1/2} (k \lambda_D)^{-3} \exp \left( -\frac{1}{2 k^2 \lambda_D^2} \right). \quad (3.37)
\]
3.2. ELECTROSTATIC WAVES

Figure 3.1. Dispersion for (a) the ion acoustic mode and (b) the Langmuir mode. Also shown in (b) is the short wavelength approximation \( \omega \sim k \sqrt{\frac{e\nu_{Te}}{m_i}} \). Both dispersion relations are plotted for values of the Tromsø E-region.
for \( (k^2 \lambda_D)^2 \ll 1 \).

Although the Langmuir wave spectrum, i.e. the plasma line, is not routinely measured in Incoherent Scatter Radar (ISR) (section 4) experiments it can be used for density calibration of ISR and the observation of Langmuir wave activity is crucial in modification experiments and observations of Ion Acoustic Enhancements (IAE)(section 2.7).

### 3.3 Instability

Processes due to which a small perturbation or disturbance grows with time are called instabilities. During auroral particle precipitation the so called bump-in-tail instability is thought to excite Langmuir waves. The velocity distribution of a plasma with two plasma populations streaming relative to each other is depicted in Figure 3.2. For a wave with phase velocity \( v_{ph} \), indicated in Fig. 3.2, the velocity distribution function of the plasma has a positive slope. More particles have a slightly higher velocity \( v_{ph} + dv \) than particles have a slightly lower velocity \( v_{ph} - dv \) and energy is transferred from particles to the wave. The transfer of energy from particles to a wave is called inverse Landau damping. Langmuir waves are thought to be excited in the ionosphere by the bump-in-tail instability on magnetic field lines where the precipitating electrons cause a bump-in-tail of the electron velocity distribution.

![Figure 3.2. Velocity distribution of a plasma with a so called bump-in-tail. Waves with phase velocity \( v_{ph} \) gain energy from the particles.](image)

### 3.4 Nonlinear Wave-Wave Interaction

Density fluctuations associated with ion acoustic waves affect the propagation of high frequency Langmuir waves. The Langmuir waves refract into regions of low electron density. This wave-wave interaction provides a mechanism to couple Langmuir waves to ion acoustic waves. In the following a heuristic description of the so called Langmuir turbulence is given, following the review on Langmuir turbulence
3.4. NONLINEAR WAVE-WAVE INTERACTION

by Robinson [1997] and a review of nonlinear effects in the ionosphere by Gurevich [2007].

In the presence of electron density fluctuations the dispersion relation of Langmuir waves is:

\[ \omega_L = \omega_p + \frac{3k^2C_e^2}{2\omega_p} + \frac{\delta n_e\omega_p}{2n_e} - i\gamma_L(k), \]  

(3.38)

where \( \delta n_e \ll n_e \) is a small density perturbation, \( (k\lambda_D)^2 \ll 1 \) has been assumed, and the damping of the Langmuir waves has been included. For waves with a frequency close to the plasma frequency the electric field \( E \) can be approximated by:

\[ E = \frac{1}{2} \left[ E \exp(-i\omega_pl) + E^* \exp(i\omega_pl) \right], \]  

(3.39)

where \( E \), the complex field envelope varies slowly compared with the plasma frequency. Fourier transformation of Eqn.(3.38) to coordinate space and applying an additional divergence operator, acting on the left, yields:

\[ \nabla \cdot \left( i\frac{\partial}{\partial t} + \frac{3C_e^2}{2\omega_p} \nabla^2 + i\hat{\gamma}_L \right) E = \nabla \cdot \left( \frac{\omega_p\delta n_e}{2n_e} E \right), \]  

(3.40)

with \( \hat{\gamma}_L \) an appropriate Langmuir damping operator. The divergence operator acting on both sides of the above equation ensures that the Langmuir field remains electrostatic, even if the coupling to density perturbations \( \delta n_e E \) is not necessarily curl free. Equation (3.40) shows how density fluctuations affect Langmuir waves and is the first (electrostatic) Zakharov equation [Zakharov, 1972]. The derivation of the first electromagnetic Zakharov equation:

\[ \frac{1}{c^2} \left( \frac{\partial^2 E}{\partial t^2} + \omega_p^2 E \right) + \nabla \times (\nabla \times E) - 3\frac{C_e^2}{c^2} \nabla \nabla \cdot E = -\omega_p^2 \frac{\delta n_e}{n_e} E \]  

(3.41)

is omitted here. A closed system of equations must include the effect of Langmuir waves on density perturbations. The Langmuir waves affect the density perturbations via the ponderomotive force. In the presence of a Langmuir electric field, a particle oscillates about a fixed mean position to zeroth order. However, when the Langmuir field is nonuniform the mean position slowly drifts as if subject to the force [e.g. Melrose, 1986]:

\[ \mathbf{F}_P = -\frac{q^2}{4m\omega_p^2} \nabla |\mathbf{E}|^2. \]  

(3.42)

Due to the inverse dependency on the particles mass \( m \), this force is much stronger for electrons than for ions. Thus, electrons are expelled from the region of intense Langmuir electric field subsequently pulling along the ions to maintain quasineutrality.

The divergence of the ponderomotive force enters the ion acoustic wave equation as a forcing term:

\[ \left( \frac{\partial^2}{\partial t^2} + 2\hat{\gamma}_S \frac{\partial}{\partial t} - v_S^2 \nabla^2 \right) \delta n_e = \frac{\epsilon_0}{4m_i} \nabla^2 |\mathbf{E}|^2. \]  

(3.43)
The linear damped ion acoustic wave equation is obtained from the above equation by setting the right hand side to zero. Equation (3.43) is the second Zakharov equation [Zakharov, 1972].

The Zakharov equations contain terms to describe three- and four-wave interactions between plane waves [e.g. Robinson, 1997]. In the presence of the Zakharov equations nonlinear terms a monochromatic plane Langmuir wave of field strength $|\mathbf{E}|$ is not necessarily stable. Zakharov et al. [1985] showed that five instability regimes exist including the electrostatic decay instability and the modulational instability. In the regime of the electrostatic decay instability or the parametric decay instability Langmuir waves decay into a daughter Langmuir wave and an ion acoustic wave. In the regime of the modulational instability two Langmuir waves interact via an ion acoustic wave and excite two daughter Langmuir waves. Langmuir turbulence is discussed in great detail with respect to ionospheric modification experiments by DuBois et al. [1993] and Gurevich [2007].

The Parametric Decay Instability (PDI) describes the decay of a mother wave into daughter waves. In ionospheric modification experiments PDI is occurring close to the reflection height of a pump electromagnetic O-mode wave [e.g. Kohl et al., 1993]. At the reflection height the pump wave is slowed down and linearly polarized, in the direction of earth’s magnetic field, in the case of an O-mode wave. The pump wave and the reflected wave make up a standing wave. The linear polarization leads to swelling of the pump wave and the wave electric field at the so called Airy maxima close to reflection can exceed the pump wave field by several orders of magnitude depending on the density gradient [e.g. Lundborg and Thide, 1986, Shoucri et al., 1984]. Energy and momentum of the pump wave are conserved in PDI description:

\[
\omega_0 = \omega_1 + \omega_2, \quad (3.44) \\
k_0 = k_1 + k_2, \quad (3.45)
\]

where $k_i$ and $\omega_i$ are wave vector and frequency of the mother and the two daughter waves respectively. In ionospheric modification experiments the daughter waves are a Langmuir and ion-acoustic wave, see Figure 3.4.
Figure 3.3. Schematic graphical solution to the PDI, adapted from Kohl et al. [1993]. The red line shows the ion-acoustic dispersion function and the two blue lines the dispersion for the Langmuir mode for two different plasma frequencies. The black vectors show a graphical solution of the PDI. Dotted vectors correspond to a second decay with $\omega_1$, $k_1$ as the mother wave.
Incoherent Scatter Radars (ISR) date back to the 70’s when backscatter from the ionosphere was measured with a radar. Since the beginning of ISR the technique has been refined and ISR become a powerful instrument for measurements of ionospheric plasma bulk properties such as electron density, electron and ion temperature and ion drift velocity.

Section 4.1 describes how plasma properties can be derived from the backscatter spectrum. The technique of ISR has been developed over the years in order to increase time and altitude resolution of the measurements. Section 4.2 gives a short introduction in the ISR techniques used in current experiments. The radar beam cross section ($>1^\circ$) limits the cross beam spatial resolution. Recent attempts to advance ISR measurements include radar interferometry techniques, a brief introduction to which is given in section 4.3.

4.1 The ISR Backscatter Spectrum

Bulk properties of plasma can be derived from Doppler broadened and Doppler shifted radar backscatter spectrum, see Fig. 4.1. Often the part of the ISR spectrum containing the ion acoustic signature is referred to as the ion line. Besides the ion line spectrum the backscattered signal also contains the plasma line originating from Langmuir waves in the ionosphere. The plasma line is however orders of magnitude weaker compared to the ion line.

The backscatter arises due to Thomson scattering of the radar signal by electrons. Although the motion of the thermal electrons is not completely random, but strongly influenced by the ion motion and therefore by ion acoustic waves, the scattering is referred to as incoherent. Due to the strong influence of the ion motion on the electrons the Thomson backscatter of the electrons includes the signature of ion acoustic waves. To find electron temperature, electron to ion temperature ratio, electron density and line of sight ion velocity the measured backscatter spectrum is
fitted by model spectra. In principle it is furthermore possible to fit for different ion compositions. Figure 4.2 shows a number of ion line spectra computed for different plasma bulk properties.

A number of possible non-thermal backscatter sources are known. Non-thermal backscatter can arise for example when a non Maxwellian plasma population exists and result in asymmetric backscatter spectra. Furthermore the coherent superposition of backscatter can lead to enhancements in backscattered power orders of magnitude above the thermal level. The coherent superposition is thought to be caused by enhanced levels of wave activity in the plasma. Ion Acoustic En-
enhancements (IAE) can be triggered in artificial modification experiments [e.g. Rietveld et al., 2000, Kohl et al., 1993, DuBois et al., 1993] and during disturbed conditions, during which IAE are referred to as Naturally Enhanced Ion Acoustic Line (NEIAL) [e.g. Rietveld et al., 1991, Sedgemore-Schulthess and St. Maurice, 2001, Isham et al., 2012]. The Power Spectral Density (PSD) of a typical NEIAL backscatter spectrum is compared to thermal backscatter PSD in Figure 4.3.

![Figure 4.3. PSD for (a) thermal plasma (2012-03-27, 10:22:42 UT) and (b) with NEIALs (2012-03-27, 10:24:34 UT).](image)

**4.2 Radar Codes**

This short introduction to radar codes is inspired by Farley [1996] and the interested reader is referred to it.

In radar jargon one can distinguish between over- and underspread targets. For overspread targets, such as the ionosphere, the wish for high range resolution and spectral resolution conflict as the former requires short pulses while the later requires long pulses. For measurements of the ionosphere the Doppler shifted backscatter spectrum of the radar signal consists of the ion line spectrum and contributions at higher Doppler shift with less power. The ion line spectrum typically has a spread of $\pm 25$ kHz around the transmitted frequency. Therefore, samples are needed every 20 $\mu$sec to provide non-aliased spectra. It is obvious that the ionosphere can not be probed with pulses at this short time interval while avoiding range ambiguity, caused by backscatter of different pulses reaching the receiver simultaneously. In order to still get high temporal and spatial resolution one can take advantage of the fact that measurements from disjoint regions are uncorrelated. Furthermore one is bound by technical limitations of the transmitter system such as maximum transmitted power and duty cycle. To cope with these problems techniques such as multi-pulse, multi-frequency, Barker codes and alternating codes have been developed. The following introduction to radar codes is only targeted at
aspects relevant to radar programs implemented and used at the EISCAT facilities as well as in use during interferometric observations at ESR.

4.2.1 Uncoded Pulses

The basic transmission scheme for a radar is to transmit a single pulse of suitable length at a given frequency. In order to increase the SNR one would like to transmit at maximum power for the longest time possible. Here one is already facing the problem of a large smear in the range regime and one needs to limit the duration of transmission. In order to prevent range aliasing the time between transmitted pulses needs to be sufficiently large.

![Figure 4.4](image)

**Figure 4.4.** Range time diagram for radar experiments, reproduced from Farley and Hagfors. a) Long pulse and b) coded long pulse.

In Figure 4.4 the range time diagram for a long pulse is schematically shown. A pulse of length $T_p$ is transmitted at $t = 0$. At a later time $T_s$ backscatter from the altitude region around $h$ is detected at the receiver. With a matched filter, where the impulse response function $h(t)$ has the same shape as the envelope of the transmitted pulse $env(t)$, one can sample the whole altitude region from which the backscatter is arising. It is also possible to oversample with receiver filter having a shorter impulse response function than the duration of the transmitted pulse. To get the auto correlation function (ACF) of the backscatter target one can use oversampling to get lagged samples from a given altitude.

The altitude resolution of the uncoded long pulse experiments is limited by the length of the transmitted pulse. With the use of inverse theory it is however possible to decrease the altitude resolution by including assumptions for the backscattered signal Hysell et al. [2008]. This technique is amongst others used at the Jicamarca radio observatory and the AMISR radars.
4.2.2 Coded Pulses

Coded pulses are a technique to increase the altitude resolution of the measurements and are used at many ISR facilities. This technique takes advantage of the possibility to modulate the radar signal at transmission. The most common modulation is to alter the phase of the transmitter signal between 0 and 180° corresponding to a code. During each transmission cycle a specific code set is transmitted. Consider the case where the signal has the bit sequence $a_0$ to $a_3$ as shown in Figure 4.4. The code can be described as a series of bits with value $\pm 1$. At reception the data is decoded with the bit scheme used at transmission. The lagged product of first two samples $V_0 = V(t_0)$ and $V_1 = V(t_1)$ is formed by their complex multiplication:

$$a_0 V_0 a_1 V_1^* = a_0 (a_0 s_h + a_1 s_{h-1} + a_2 s_{h-2} + a_3 s_{h-3})$$
$$\times a_1 (a_0 s^*_h + a_1 s^*_{h-1} + a_2 s^*_{h-2} + a_3 s^*_{h-3})$$

(4.1)

where the $s_h$ are the signal contributions from height $h$. We can now take advantage of $a_n^2 = 1$ and $\langle s_h + s^*_h \rangle = 0$ if $|\alpha - \beta| \geq 2$ since the backscatter from different volumes are uncorrelated. The notation $\langle ... \rangle$ is used for the expectation value. For the lagged product of samples $V_0$ and $V_1$ the expectation value after a large number of pulses is:

$$\langle a_0 V_0 a_1 V_1^* \rangle = \langle s_h s^*_h \rangle$$
$$+ \langle a_0 a_2 \rangle \langle s_{h-1} s^*_{h-1} \rangle + \langle a_0 a_1 a_2 a_3 \rangle \langle s_{h-2} s^*_{h-2} \rangle$$
$$+ \langle a_0 a_1 a_2 a_3 \rangle \langle s_{h-1} s^*_{h-1} \rangle + \langle s_{h-2} s^*_{h-2} \rangle$$

(4.2)

Here the term we are interested in is the first term on the right hand side representing backscatter from height $h$. All the other terms represent unwanted signal termed clutter. By choosing a suitable sequence of transmitted codes $a_n$ one can minimize $\langle a_x a_y \rangle$ and therefore reduce the clutter. With the transmitted code being random these expectation values will even vanish for a large number of transmitted pulses [Sulzer, 1986]. This is called ‘coded long pulse’. Another approach is to chose the transmitted codes in such way that the expectation values of the clutter terms vanish, this technique is called ‘alternating codes’ [Lehtinen, 1986]. For the clutter terms to vanish in alternating code experiments it is necessary that a complete set of code is transmitted, and the lag products are estimated from Eqn.(4.2).

4.3 Radar Interferometry

Modern ISR radars have a beam width at half power of about 1° corresponding to 2 km at 120 km range. In optical observations of fine scale aurora scale sizes of a few hundreds of meters across the magnetic field direction are present [e.g. Sandahl et al., 2008], i.e. not resolved within the radar beam. Radar interferometry is a
technique to estimate the cross beam structure of the scattering target at sub beam scales. The technique of radar interferometry has first been utilized for ionospheric studies by Farley et al. [1981], Kudeki et al. [1981] and since then further developed [e.g. Hysell and Chau, 2006]. By measurement of the backscatter signal at receivers at position $\mathbf{R}_i$, the moments of the arrival-angle distribution of the backscatter medium can be found and the cross beam structure of the backscatter medium investigated. The considerations here are limited to the case of a single coherent backscatter target.

For the signal propagation of a UHF radar the atmosphere and ionosphere can be regarded as vacuum, i.e. a medium with refractive index $n = 1$. Two receivers displaced by the baseline $\mathbf{b}$, where $\mathbf{b} = \mathbf{R}_2 - \mathbf{R}_1$ will observe the same signal $S$ with a time lag $\tau$, i.e. $S_1(t) = S_2(t + \tau)$. The phase difference between the two observed signals, in the following named cross phase, is a measure of the time lag. With the assumption that the length of the baseline is negligible compared to the range of the backscatter target the cross phase can be expressed as:

$$\phi = \frac{2\pi}{\lambda} \mathbf{s} \cdot \mathbf{b},$$

where $\lambda$ is the wavelength of the signal and $\mathbf{s}$ is a unit vector pointing in the direction from which the scatter is arriving, see Figure 4.5. In practice a phase offset will be introduced in either receiver system due to filtering, mixing and signal path. Therefore, the phase offset $\delta_0$ between the two receiver systems needs to be taken into account and the cross phase of the two receiver systems becomes:

$$\phi = \delta_0 + \frac{2\pi}{\lambda} \mathbf{s} \cdot \mathbf{b}. \quad (4.3)$$

![Figure 4.5. Interferometer with baseline $\mathbf{b}$ and scatter arising from direction $\mathbf{s}$. $P$ is the difference in path length for the signals observed at the two receivers.](image)

Computing the direction $\mathbf{s}$ from which the scatter is arising by measuring the cross phase and knowledge of the baseline is an inverse problem. The measure of the cross phase is limited to $\pm \pi$ therefore introducing ambiguities in the inverse
4.3. RADAR INTERFEROMETRY

problem. Furthermore in the projection of $s$ on $b$ all directional information in the plane perpendicular to the baseline is lost. In order to reconstruct $s$ from Eqn.(4.3) multiple observation baselines with different orientation and length are needed. In the case of a backscatter medium the observed signal at a receiver station is a superposition of signal contributions of scatter sources within the scattering volume. The distribution of backscatter power in the plane perpendicular to the beam is called the brightness distribution and the from the measurements reconstructed distribution is called apparent brightness. A example of an apparent brightness distribution calculated for a satellite transit observed with all three EASI receivers and the ESR dishes is shown in Figure 4.6.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.6.png}
\caption{ASK FOV ($3^\circ \times 3^\circ$) and overlayed radar brightness distribution for a satellite transit. The radar brightness distribution was computed around the center of the radar main lobe. A white circle is drawn around the position where the satellite is seen with ASK.}
\end{figure}
Chapter 5

Instrumentation

The base of the observations reported on in this thesis have been conducted with the EISCAT radars. In section 5.1 the EISCAT radars and radar programs used for observations are described. The phased array receiver system for radar interferometry is described in section 5.2. Section 5.3 briefly describes the radar data handling and radar data analysis tools. For modification experiments of the ionosphere the EISCAT heater on the mainland was operated and the relevant array of the heater is described in section 5.4. For the observations on Svalbard the Odin camera installed at the EISCAT Svalbard Radar (ESR) facility was used, which is described in section 5.5.

5.1 EISCAT Radars

The principle of Incoherent Scatter Radar (ISR) measurements is to transmit a powerful radar wave and measure the Doppler shifted backscatter as described in chapter 4. Thus, any ISR consists of a transmitter chain in which the radar signal is generated and amplified and a receiver chain. The simplified diagram of a ISR for which the transmitting and receiving antenna is the same is depicted in Figure 5.1(a). In the receiver chain the signal is pre-amplified at the antenna and the pre-amplifier is protected from saturation during transmission. After amplification the signal is mixed down to the Intermediate Frequency (IF) followed by digitization. At this point of the receiver chain raw data is stored depending on the radar program. In the next step the Lag Profile (LP) are formed from lagged data products, as described in section 4.2.2, and stored in a Lag Profile Matrix (LPM). In case of phase coded experiments, the LPMs are calculated from data measured during a complete code cycle. To minimize the amount of data LMPs are integrated over a few code cycles and the integrated LPMs are stored in time steps of a few seconds. In some experiments raw data are stored for post processing, so called software radar [e.g. Grydeland et al., 2005b]. Raw data are necessary for interferometry analysis.

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5.1.1 EISCAT Mainland Radar

The EISCAT mainland facilities are located close to Tromsø in northern Norway. Two independent radar systems are operated at Very High Frequency (VHF) and Ultra High Frequency (UHF) frequencies. During campaigns with the ASK [see Dahlgren et al., 2008] optical instrument, situated at the EISCAT site in the 2005/2006 optical season, the UHF system has been operated. The UHF antenna is a parabolic dish with the diameter of 32 m and an antenna gain of 48.1 dBi. The dish antenna is fully steerable in azimuth and elevation. Transmitted frequency is 930 MHz at a peak power of 2 MW.

A large number of radar programs exist for the EISCAT mainland radars and are commonly used. The arc1 experiment is of interest for high time and range resolution. High range and time resolution of estimated plasma parameters, while keeping the variances of the estimated parameters low, is only possible during ionospheric conditions with high electron density. arc1 on the mainland radar has
a counterpart on the ESR which is described in detail in section 5.1.2.

5.1.2 ESR

The ESR is situated on the Norwegian archipelago of Svalbard at 78.15° N latitude and 16.02° E longitude. The radar facility consists of two parabolic radar dishes with 32 m and 42 m diameter and antenna gains of 42.5 dBi and 44.8 dBi respectively. Peak power of the transmitter system is 1 MW. Whereas the larger dish is pointed towards magnetic zenith 184.5° azimuth (measured from north towards east) and 81.6° elevation, the 32m dish is fully steerable. In combination the two antennas can be used as a radar interferometer [e.g., Grydeland et al., 2003] with a baseline of approximately 128 m. The transmitter frequency is 500 MHz.

In the following radar programs used at the ESR for interferometry and suitable for future interferometry campaigns are described.

LT4

LT4 is a very basic radar program used in early interferometry campaigns at the ESR. Different versions of the program exist of which LT4DL was used during campaigns in 2006 and LT4FL in 2010, 2011 and 2012. A pair of two pulses is transmitted during each Inter Pulse Period (IPP) consecutive to each other at frequencies $\nu_1$ and $\nu_2$. Every second IPP the frequency of the pulse pair will be the same. While pulses are transmitted at frequencies $\nu_3$ and $\nu_4$ in the second IPP background samples can be taken on receiver channels for $\nu_1$ and $\nu_2$ for the reduction of background noise. It is possible to connect one additional receiver antenna to the ESR plasma line channel to record ion line data.

$$\text{env}(t)$$

Figure 5.2. Pulse scheme for $LT_4$.

The $LT_4$FL experiment has four pulses with the frequencies of 499.35, 499.45, 499.55 and 499.65 MHz with a length of 360 µsec. The pulses are transmitted in pairs of two on the 32m antenna, and received on both antennas: 32m and 42m. Raw voltage data are recorded for each IPP of 10 ms. Sampling range is 190.5 – 1423.5 km for the first transmitted pulse and 135 – 1368 km for the second pulse. The $LT_4$ long pulse experiment is sampled at 50 kHz giving 18 laged samples and a Doppler spectrum between ±25 kHz. The real altitude resolution of $LT_4$ is 54 km. An overview of $LT_4$FL is given in Table 5.1. In difference to the $LT_4$FL experiment the pulse length in the $LT_4$DL experiment is 350 µsec.
**Beata**

The ESR alternating code experiment *beata* is transmitting at 500.3 MHz. Transmission starts on the 42m antenna at 50 µsec with a pulse length of 1500 µsec. Bit length of the transmitted code is 50 µsec and the code consists of 30 bits. Figure 5.3(a) shows the *beata* code. Samples are taken between 1827 and 5995 µsec and plasma line data is recorded. Two samples are taken per bit corresponding to a sampling frequency of 40 kHz. After 6250 µsec the next subcycle is started. A total number of 64 subcycles are transmitted. Thus, for complete decoding a minimum integration period of 0.4 sec is needed. LPMs are dumped in blocks of 6 sec in the data vector and raw data samples are saved in the raw vector. A summary of the *beata* program is given in Table 5.1.

![Figure 5.3. Alternating code of the beata and arc_sliceiASK experiment.](image)

**Arc_slice**

*Arc_slice* is an alternating code experiment commonly used at the ESR. The code consists of 128 subcycles with 64 bits each. Figure 5.3(b) shows the *arc_slice* code. The experiment is characterized by a high range resolution of 0.9 km as well as high time resolution of 0.5 sec. Based on this program is *arc_sliceiASK* which includes storing of raw data samples for reception on the 32m and 42m antenna.

*Arc_sliceiASK* is using 500.95 MHz as transmitting frequency which corresponds to IF of 10.3 MHz. Transmission starts on the 32m antenna at $t = 100$ µsec. Data sampling on the 32m and 42m antenna starts at $t = 670$ µsec to 3700 µsec corresponding to range 85.5 - 540 km on channels 1 and 4 respectively. The sampling period is 6 µsec corresponding to the bit length of the transmitted pulse code and a sampling frequency of 166.66 kHz. The IPP between the subcycles is 3906 µsec.
5.2. EASI

After 10 cycles, corresponding to an integration period of 5 sec, the LPM is dumped in the data vector and raw data samples are saved in the raw data vector. A summary of the arc_sliceASK program is given in Table 5.1.

The radar experiment arc1 on the EISCAT mainland radars differs from arc_slice in the following way. Altitude ranges between 96 and 422 km are covered and the duration of a code cycle is 0.44 sec.

5.2 EASI

EISCAT Aperture Synthesis Imaging (EASI) [Grydeland et al., 2005a] is an interferometric system with three additional antennas to the ESR radar facility. Each of the three antennas is a phased array with 4 x 4 antennas. The signal of the 16 UHF TV antennas with a gain of ~12.5 dBi is combined and pre-amplified directly at the antenna panel. The look direction is fixed to the field aligned direction. Each pre-amplifier has a gain of 29 dB and is protected by an inter pulse signal to prevent the pre-amplifier from saturation during pulse transmission. The signal from the pre-amplifier is first mixed down to the IF at 70 MHz and then passed to an Echotek receiver card (manufactured by Mercury Computer Systems). The Echotek is a receiver card usually used in Global System for Mobile Communications (GSM) applications. Inside the receiver the signal is sampled at 30 MHz. The trigger for data acquisition and the clock signal are both fed in externally from the ESR system. The time-stamp for the data is provided by an IRIG-B card connected to the timing signal of the ESR radar system. Figure 5.1(b) schematically summarizes the EASI receiver system.

During the season in 2006 only one EASI antenna panel, named EASI-A in Figure 5.4, was operational with a somewhat different set up then described above. The antennas used were 18-element Yagi UHF antennas (manufactured by Triax Denmark) with a gain of ~14.5 dBi. Due to problems with wind and snow drift the Yagi antennas were replaced with the TV panel antennas. EASI antenna panels B and C were completed in 2010.

5.3 Radar Data Handling

At the EISCAT radars data is stored in .mat data files. This data format is a file format which can be read with the proprietary MATLAB software. Each .mat file contains an integrated LPM for a data dump of several seconds and additional parameters (e.g. time, transmitted power, antenna elevation and azimuth).

Figure 5.5 depicts a flow diagram of handling of radar data. Ionospheric parameters are obtained by fitting a model LP to each of the LPs stored in the LPM. The software package Grand Unified Incoherent Scatter Data Analysis Program (GUISDAP) [Lehtinen and Huuskonen, 1996] is used for the parameter estimation. Standard output of GUISDAP are ion temperatures, electron densities, electron to
<table>
<thead>
<tr>
<th>Transm. freq.</th>
<th>499.35 + 0.3 · 1 MHz, 300.3 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling freq.</td>
<td>500 kHz, 1 MHz, 2 MHz</td>
</tr>
<tr>
<td>Bit length</td>
<td>7.5 km, 25 km, 100 km, 360 km</td>
</tr>
<tr>
<td>No. of bits</td>
<td>30, 64, 128</td>
</tr>
<tr>
<td>Duration of cycle</td>
<td>20 msec, 0.4 sec, 0.5 sec</td>
</tr>
<tr>
<td>IPP</td>
<td>10 msec, 3.25 msec, 2.906 msec</td>
</tr>
<tr>
<td>No. of subcycles</td>
<td>2, 64, 128</td>
</tr>
<tr>
<td>Pulse length</td>
<td>384 μsec, 5.75 km, 53.75 km</td>
</tr>
<tr>
<td>Range resolution</td>
<td>54 km, 3.75 km, 0.9 km</td>
</tr>
<tr>
<td>Sampling range</td>
<td>P1 190.5 - 1123.5 km, P2 135 - 1368 km</td>
</tr>
<tr>
<td>Dump length</td>
<td>2 sec, 6 sec, 5 sec</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>7.2%, 24%, 2%</td>
</tr>
<tr>
<td>Transm. Ant.</td>
<td>32 m, 42 m, 32 m</td>
</tr>
<tr>
<td>Plasma line</td>
<td>- x -</td>
</tr>
<tr>
<td>Plasma line</td>
<td>x x -</td>
</tr>
</tbody>
</table>

Table 5.1. Summary of the radar programs at ESR suitable for interferometric radar observations with EASI.
ion temperature ratio and the ion line of sight drift velocity. Backscatter spectra are obtained by Fourier transformation of the LPs. For interferometry purposes Cross Lag Profile Matrix (XLPM) are calculated from raw data for a receiver pair. XLPM are equivalent to LPM were lagged products are formed from samples $V_0$ and $V_1$, described in section 4.2.2, measured on two different receivers. Interferometric parameters, such as coherence and cross-phase, are then calculated with software denoted Aperture Synthesis Toolbox (AST) in Figure 5.5, from the XLPMs.
5.4 EISCAT Heater

At the EISCAT Tromsø site a ionospheric heater was constructed in 1979. The heater has since undergone developments and currently three antenna arrays are available, see Figure 5.6. One of the arrays is able to operate in the frequency range $3.8 - 5.7\,\text{MHz}$ and was used in an experiment in 2006. The array has $6 \times 6$ crossed dipole antennas giving a gain of 23 dBi and a half power beam width of about 14°. The maximum effective radiated power is 152 MW. For ionospheric modification experiments the polarization of the transmitted wave is an important parameter and can be chosen to be either linearly or circular polarized.

![Figure 5.6. The EISCAT heating facility at Ramfjorden near Tromsø.](image_url)
5.5 Odin

Odin [Blixt et al., 2005] is an intensified Charge Coupled Device (CCD) imager producing PAL video signal at 25 frames per second recorded in real time in digital Phase Alternation Line (PAL) Digital Video (DV) format with 720×576 pixel resolution. The imager’s Field Of View (FOV) is 14.3° × 10.9°. The time-code is fed into the digital recorder from a Horita time reference system, which kept the image stream synchronized to the Global Positioning System time. During the observation season 2005/2006 Odin was installed outside the ESR facility, Fig. 5.7 shows the imager.

Figure 5.7. Odin imager here installed at the EISCAT Tromsø site. (Image credit: Dan Whiter)
Chapter 6

Summary of Papers

Paper I reports on a calibration technique for ISR interferometry systems and is of significance for future studies with EASI and is summarized in section 6.1. In Paper II, section 6.2, we report on observations of Naturally Enhanced Ion Acoustic Line (NEIAL) with the EISCAT UHF system. Paper III, section 6.3, presents a study of plasma instabilities induced in the auroral E region with the EISCAT heater in Tromsø.

6.1 Paper I - Radar interferometer calibration of the EISCAT Svalbard Radar and a additional receiver station

For the ESR interferometer system consisting of the two parabolic dishes and its extension the three phased array receivers (EASI) several science goals exist. The primary of those is to study so called naturally enhanced ion acoustic lines. Several studies of NEIAL events simultaneously observed with optical imagers have been reported on in the literature [e.g. Michell and Samara, 2010, Blixt et al., 2005, Collis et al., 1991]. The occurrence of NEIAL have been associated with auroral structures and boundaries of those passing the radar beam. Grydeland et al. [2004] found with the ESR interferometry system that the horizontal extent of the region with enhanced scatter is of the order of hundreds meters. Narrow field of view imagers provide the possibility to study the aurora at this scale size. The observation of NEIAL with radars is however limited by the width of the radar beam typically about 1° corresponding to 2 km at 120 km range. Multi-baseline interferometry is a technique to synthesize a larger aperture of the radar and to make it possible to study radar echoes at scales smaller than the beam width of the transmitting antenna.

In order to compare radar aperture synthesis imaging results with measurements from optical imagers, calibration of the radar interferometer system is necessary. In this work we present the phase calibration of the EISCAT Svalbard interferometer.
including one EASI array antenna. The calibration was done using the coherent scatter from satellites passing through the radar beam. Optical signatures of the satellite transits provide accurate position for the satellites. By using transits of a number of satellites sufficient for mapping the radar beam, the interferometric cross-phase was fitted within the radar beam. As a result the baseline for each antenna pair is found with accuracy higher than 1 m. This accuracy is difficult to achieve with e.g. Global Positioning System (GPS) since the phase center of the dish antennas is not well known. Furthermore the technique can be used for phase calibration in future campaigns.

6.2 Paper II - Enhanced radar spectra from distinct altitude regions during auroral high energy electron precipitation

The backscatter power in ISR experiments can sometimes be enhanced by orders of magnitude over the thermal backscatter. The enhancement of the ion line part of the spectrum is often referred to as NEIAL or Ion Acoustic Enhancements (IAE). Several observations of NEIAL have been reported on in the literature [Collis et al. [1991], Rietveld et al. [1991], Blixt et al. [2005], see Sedgemore-Schulthess and St. Maurice [2001] for a review]. NEIALs usually occur at altitudes from about 140 to 1900 km but observations of NEIAL have also been reported at altitudes as low as 140 km and up to 1900 km [Ogawa et al., 2006, 2011]. They have an altitude extent of several hundreds of kilometers. The observation of NEIALs is tied to auroral activity.

A number of theories have been proposed to explain NEIALs which can be grouped into streaming instabilities directly exciting ion acoustic waves and cascade from Langmuir waves [e.g. Rietveld et al., 1991, Forme, 1999, Sedgemore-Schulthess and St. Maurice, 2001]. Another model proposed by Ekeberg et al. [2010] describes NEIAL observations from limited altitude regions with almost flat ion line spectra, i.e. spectral uniform enhancements, by excitation from ion-solitary waves. Bahcivan and Cosgrove [2008] proposed a model for NEIALs based on observations of ion cyclotron waves in the vicinity of arcs with strong electric fields observed with the FAST satellite. In this model ion acoustic instability is driven by the ion cyclotron waves.

More recently a new kind of NEIALs with an altitude extend limited to a few kilometers and a feature at zero Doppler shift have been reported [Rietveld et al., 2002, Isham et al., 2012, Akbari et al., 2012, Michell et al., 2008, Michell and Samara, 2010].

We report on the observation of the later type of enhancement simultaneously observed from two limited altitude regions. The observations reported on have been conducted with the EISCAT UHF system. The observation of a zero Doppler shift frequency feature with the UHF system is surprising. The zero Doppler shift feature has been associated with electron density cavitation processes. The energy
density necessary to drive this cavitation with spatial scale $L$ is proportional to $L^{-1/2}$. In order to observe the cavitation the radar wavelength needs to be of the order of $L$. It is therefore unlikely to observe a zero Doppler shift feature at UHF frequencies. With the high range resolution of the observations it has furthermore been possible to show the altitude extend is limited to $\sim 2\text{ km}$ in the F region with little gradient in the background electron density. The two layers and the small altitude extend have yet to be explained within the currently existing theories for NEIALs.

6.3 Paper III - HF modification of the auroral E region

High power HF (2.6-12 MHz) radio waves can modify the ionospheric plasma significantly. The so called pump wave can interact with the plasma in a nonlinear way and excite a wide range of wave modes [Gurevich, 2007]. Close to the reflection height of the O-mode pump wave Langmuir and ion acoustic waves can be exited. The excited Langmuir and ion acoustic waves give rise to radar backscatter of incoherent backscatter radars used for measuring plasma bulk properties in the ionosphere. Ionospheric Modification Experiment (IME) have been conducted predominantly in the F region [e.g. Kohl et al., 1993, Kosch et al., 2011] and more recently observations of heating induced instabilities were also reported from the E region including sporadic E layers [e.g. Baddeley et al., 2012, Dhillon et al., 2009, Rietveld et al., 2002].

Radar backscatter enhancements from an altitude above the reflection altitude for the pump wave have been observed [Isham et al., 1990, Kosch et al., 2011]. These enhancement observed at the topside of the F region at altitudes where the plasma frequency matches the pump frequency are thought to be induced by Z mode waves [Budden, 1961, Mjølhus, 1990, Gondarenko et al., 2003]. The Z mode waves are induced by the heater through mode conversion at the bottom side of the F region. Observations of two altitude regions in the E region with enhanced radar backscatter have been reported by Rietveld et al. [2002].

Paper III reports on observations of a IME in the auroral E region based on the master thesis by Schlatter [2010]. Enhancements in backscattered radar power during ionospheric heating from two distinct altitude regions in the auroral E region above Tromsø are observed. For the experiment the EISCAT Tromsø heater was operated with O-mode and X-mode alternated. Ion line data recorded with the EISCAT UHF radar reveal different temporal evolutions as well as different ion line characteristics for the enhancements from the two altitude regions. The upper layer is dominated by a strong central feature whereas the lower layer has three peaks corresponding to the central feature and the two ion lines. The measured enhanced spectra have been analyzed and argue for different mechanisms in creating the enhancements. The altitude region of the two closely spaced (altitude separation $\sim 5\text{ km}$) but distinct enhancements is close to the critical altitude for the heater
wave.
Chapter 7

Future Work

So far the data analyzed during the licentiate have been from campaigns previous to the start of my studies. The work on some of these data will be continued as well as extended to other rich data sets. Furthermore, EASI has become fully operational during the last years with contribution of the author. New data have been collected and are being recorded in the current season. Experiments at ESR and data with EASI are recorded on a campaign basis with participation of the author. Event studies on the new data sets as well as more statistical studies on large homogeneous data sets is intended in the future work.

I NEIAL zero Doppler shift feature, radar statistical study

On the ESR an alternating code was run on an almost continuous base for over one year during the international polar year (IPY, March 2007 to March 2008). The data obtained with the IPY program constitute the largest homogeneous ISR dataset and is ideal for statistical and seasonal studies of ionospheric processes. A search code was written to search the IPY data set for NEIAL with a zero Doppler shift feature. The analysis is ongoing. Ogawa et al. [2011] conducted a statistical study on NEIAL events on the IPY data set and analyzed the data set for seasonal and daily variation as well as correlation of the likelihood for NEIAL observations with solar and geomagnetic indices. We intend to conduct a similar study and compare the results with the results obtain by Ogawa et al. [2011] for NEIAL events.

II NEIAL optical study

During the IPY the ASK optical instrument was operated at the ESR site in Longyearbyen, Norway. With NEIAL events found in the IPY ESR data set events can be identified in the ASK data set suitable for case studies. The high temporal resolution of ASK data and the advantage of the observation of three auroral emissions allows for identifying possible features in the optical data specific for the different NEIAL types. On a longer time perspective the
events recorded with ASK could be analyzed automated to allow studying a
large number of events.

III Combined interferometric and optical studies
Currently the solar cycle is close to it’s maximum of activity. The EASI in-
derferometry system as well as ASK are operated on a campaign basis during
the ongoing optical season. It is expected that event studies of radar interferometric observations and optical data will be possible with the obtained
data.

IV HF modification and interferometry
The ability to combine HF modification experiments with interferometric ob-servations at the ESR facility gives the possibility to study plasma instabilities
in the ionosphere and gain better understanding of the physics at the pump
interaction height. Due to the low power of the SPEAR heater observations
of LT and SLT with EASI are unlikely.

V Fast scanning
The EISCAT mainland UHF antenna and the ESR antenna are both fully
steerable. The possibility of scanning with the radar antenna along the mag-
netic meridian direction has been used previously with scan time scales of
minutes. In the case of high electron densities and therefore high Signal to
Noise Ratio (SNR) it is however possible to conduct scans of a few degrees
elevation on the time scale of seconds. With such fast scans new insights
in auroral arc systems can be obtained. Measurement campaigns have been
carried out using the EISCAT UHF antenna in October and December 2012.
Analysis is ongoing.

VI Electron energy distribution during HF heating
During an internship (June 2012 to August 2012) at the research group of
D. Hysell at Cornell University, US work was begun to estimate the electron
energy distribution during HF pump based on inversion of optical airglow
measurements. The work is based on a study by Hysell et al. [2012] who
derives the electron energy distribution from measurement of four emission
lines. The inversion is based on a electron transport model and a inversion
technique developed by Backus and Gilbert [1968]. The technique has been
extended for the $777.4\,\text{nm}$ emission line and adapted to use the more robust
Maximum Entropy approach . The study is ongoing.
Bibliography


D. T. Farley and T. Hagfors. AGF304 - Radar Diagnostics of Space Plasma; University in Svalbard. Textbook manuscript.


