Radar Signatures of Auroral Plasma Instability

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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. At high latitudes the backscattered radar power is occasionally enhanced several orders of magnitude above the thermal backscatter level. These enhancements occur during geomagnetic disturbed conditions and are referred to as naturally enhanced ion acoustic echoes (NEIALs). NEIALs are linked to auroral activity with optical auroral emission observed in the vicinity of the radar measurement volume simultaneously to NEIALs. The backscatter enhancements are thought to be caused by wave activity above thermal level due to instability. A number of theories have been put forward including streaming instabilities and Langmuir turbulence to explain NEIAL observations. NEIALs occur in two classes distinct by their Doppler features. Observations of the first type, which has been studied more extensively, are generally modelled well by the Langmuir turbulence model. The difficulty in trying to understand the driving mechanism of the instability is the limited spatial resolution of the radar measurements. Observations of the second type, reported on more recently, have been interpreted as evidence for naturally occurring strong Langmuir turbulence by means of their Doppler features.

Aperture synthesis is a technique to increase the spatial resolution of the radar measurements to below beam width of the single receiver antennas. The technique is employed to investigate the structure of NEIALs in the plane perpendicular to the magnetic field at sub-degree scale corresponding to hundreds of meters to a few kilometres at ionospheric altitudes. Calibration of the radar interferometer is necessary and a calibration technique is presented in paper I. Interferometry observations of a NEIAL event with receivers deployed at the EISCAT incoherent scatter radar on Svalbard are presented in paper II. The size of the enhanced backscatter region is found to be limited to $900 \times 500$ m in the plane perpendicular to the geomagnetic field. These observations constitute the first unambiguous measurements giving evidence for the limited size of the enhanced backscatter region.

In paper III observations of strong Langmuir turbulence signatures are presented. The apparent turbulent region in these observations is limited to two narrow altitude regions, 2 km extent, and electron density irregularities caused by the turbulence are thought to reach down to decimeter scale length. The turbulence observations were obtained during energetic electron precipitation thereby differing from other observations during which a low energy component in the electron precipitation is reported. In paper IV a statistical study of strong Langmuir turbulence radar signatures is presented. The study reveals differing local time distributions for these signatures from type I NEIALs indicating differing driving conditions for the two types of NEIALs. It is found that strong Langmuir turbulence signatures are predominantly observed in the pre-midnight sector where auroral break-up aurora prevails.
Sammanfattning


Papper III presenterar observationer av förstärkta spektra som förknippas med stark Langmuirturbulens. Förstärkningar i dessa observationer var begränsade till två tunna höjdskikt (ca 2 km), och turbulensen verkar täcka skalstolpar ner till decimeterskala.

Acknowledgments

I would like to thank all those who supported me and my studies during the last couple of years. Special thanks to those with unstoppable and contagious enthusiasm for science. Two people which carry this infectious enthusiasm with them are my supervisor Nickolay Ivchenko and Björn Gustavsson. I would like to express my gratitude to them.

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<td>ASK</td>
<td>Auroral Structure and Kinetics</td>
</tr>
<tr>
<td>AST</td>
<td>Aperture Synthesis Toolbox</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
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<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>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>IF</td>
<td>Intermediate Frequency</td>
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<tr>
<td>IL</td>
<td>Ion Line</td>
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<tr>
<td>ILE</td>
<td>Ion Line Enhancement</td>
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<tr>
<td>IME</td>
<td>Ionospheric Modification Experiment</td>
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<tr>
<td>IPP</td>
<td>Inter Pulse Period</td>
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<tr>
<td>ISR</td>
<td>Incoherent Scatter Radar</td>
</tr>
<tr>
<td>LP</td>
<td>Lag Profile</td>
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<td>Lag Profile Matrix</td>
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<tr>
<td>LT</td>
<td>Langmuir Turbulence</td>
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<tr>
<td>NEIAL</td>
<td>Naturally Enhanced Ion Acoustic Line</td>
</tr>
<tr>
<td>PAL</td>
<td>Phase Alternation Line</td>
</tr>
<tr>
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<td>Description</td>
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<tr>
<td>---------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>PDI</td>
<td>Parametric Decay Instability</td>
</tr>
<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
</tr>
<tr>
<td>SLT</td>
<td>Strong Langmuir Turbulence</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
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<td>XLPM</td>
<td>Cross Lag Profile Matrix</td>
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I Radar interferometer calibration of the EISCAT Svalbard Radar and a additional receiver station,
Schlatter, N. M., T. Grydeland, N. Ivchenko, V. Belyey, J. Sullivan, C. La Hoz, and M. Blixt,
Contributions to the manuscript were: data analysis and writing the article.

II Observation of a NEIAL event with a radar interferometer system,
Schlatter, N. M., V. Belyey, B. Gustavsson, N. Ivchenko, H. Dahlgren, D. Whiter, and S. Tuttle,
Contributions to the manuscript were: instrumental work, conducting observations, data analysis, interpretation of the data, and writing the article.

III Enhanced EISCAT UHF backscatter during high-energy auroral electron precipitation,
Schlatter, N. M., N. Ivchenko, T. Sergienko, B. Gustavsson, and B. U. E. Brändström,
Contributions to the manuscript were: data analysis, data interpretation, and writing the article.

IV On the relation of Langmuir turbulence radar signatures to auroral conditions,
Schlatter, N. M., N. Ivchenko, and I. Håggström,
Contributions to the manuscript were: research idea, data analysis, data interpretation, and writing the article.

The papers have been reprinted with permission from the copyright holders and are attached at the end of the thesis.
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Chapter 1

Introduction

To us humans the most familiar states of matter are the solid, liquid, and gas states all of which we can observe in our daily life on the earth’s crust. However, more than 99% of ordinary 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 occur 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 is predominantly electrons precipitating down to the ionosphere along the magnetic field. Ground based instrumentation developed over the last centuries has 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.

Figure 1.1. Aurora over Longyearbyen, Svalbard. Image credit: Algot Kristoffer.
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 active fields of research. Complementary measurements with ISRs 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 ISRs. 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 a 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 thesis is focused on naturally occurring plasma instabilities in the ionosphere observed with ground based instrumentation and is an extension of the previously published Licentiate thesis (Schlatter, 2013). 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 relevant 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 arising from open questions is 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 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, i.e. the near earth space where earth’s magnetic field dominates, is described. The inner part of the magnetosphere where the neutral atmosphere is ionized mainly due to solar radiation is referred to as ionosphere and discussed 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.

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 is given by:

\[
F = q(E + v \times B).
\]  

For zero electric field particles gyrate in the plane perpendicular to the magnetic field with the Larmor radius of gyration if they have a velocity component perpendicular to the magnetic field:

\[
r_L = \frac{mv_{\perp}}{|q|B},
\]  

(2.2)

where \( B = |B| \) is the strength of the magnetic field. The angular frequency of the particle gyration is:

\[
\omega_c = \frac{qB}{m}
\]  

(2.3)

5
and $f_c = \frac{\omega}{2\pi}$ is referred to as cyclotron frequency of the particle. The gyration of a charged particle is associated with a magnetic moment $\mu$ due to the current associated with the motion of the particle:

$$\mu = \frac{E_{\perp}}{B} = \frac{mv_{\perp}^2}{2B},$$

(2.4)

where $E_{\perp}$ is the electric field component perpendicular to the magnetic field and $v_{\perp}$ the corresponding velocity component. In a sufficiently slow varying magnetic field the magnetic moment of a particle is constant. Therefore, if the magnetic field increases along the particles trajectory also the perpendicular velocity of a particle will increase. Due to energy conservation 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 magnetic mirroring is useful to think of in case of particles affected by earth’s magnetic field. At the magnetic equator the strength of the magnetic field is at its minimum and increasing along the field lines towards the magnetic poles. Charged particles moving in 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. The drift velocity is given by:

$$v_D = \frac{1}{q} \frac{F \times B}{B^2}.$$  

(2.5)

The force $F$ can be caused e.g. by an electric field ($E \times B$ drift), 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, i.e. an ionized gas with many interacting particles, each of the particles is affected by the other particles due to long range forces. These long range forces are due to the electric charge of the particles. A characteristic length scale for a plasma is the Debye length which describes how well a charge within the plasma is shielded. 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:

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T}{n e^2}},$$

(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:

$$\omega_p = \sqrt{\frac{n e^2}{\epsilon_0 m_e}},$$

(2.7)
2.2. EARTH’S MAGNETOSPHERE

The plasma frequency is independent of the magnetic field and describes how the plasma reacts to charge density fluctuations. It is the oscillation frequency 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:

$$R_m = \mu_0 \sigma v L,$$

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 of plasma.

2.2 Earth’s Magnetosphere

The earth is shielded from the solar wind by the geomagnetic field. 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 and is depicted in Figure 2.2. On the dayside the magnetosphere is compressed due to the magnetic and dynamic pressure of the solar wind and extends about 10 $R_E$ (one earth radius $R_E \approx 6378$ km). In this part of the magnetosphere earth’s magnetic field is roughly dipole shaped. On the nightside earth’s magnetic field is stretched and the magnetosphere extends for about 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 with opposing magnetic field direction.

The main mechanism for solar wind plasma to enter the magnetosphere is thought to be magnetic reconnection at the 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 so called open field lines which extend far into space. The open field lines created on the dayside are pulled along by 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 tail lobes can reconnect. The tension in the magnetic field causes the newly created closed field lines to snap back towards earth into a more dipole shaped form. This process is referred to as 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 and from outside the magnetosphere, bremsstrahlung emitted from deceleration processes and photons emitted from within the ionosphere. On the dayside of the earth’s ionosphere, photoionization by solar photons (10 nm to 100 nm wavelength) is the dominating source of ionization.

The dominating neutral species in the ionosphere are N₂, O₂, 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. In Figure 2.2 the number density of neutrals in the lower ionosphere is plotted. The flux of photoelectrons on the other hand is increasing with altitude, therefore the ionization has 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 electron density profile of the ionosphere.

![Figure 2.2. Number density of neutral species in the lower ionosphere.](image)

The first layer was experimentally found in 1925 by E. V. Appleton and M. A. F. Barnett after being postulated by A. E. Kennelly and O. Heaviside in 1902 and was named E layer because of its ability to reflect radio waves. Radio waves are reflected when the local plasma frequency is larger than the wave frequency, see Chapter 3. The E layer is at about 90 km to 150 km altitude. By reflection of radio waves from other altitudes also the D and F region were found, at 70 km to 90 km and 150 km to 600 km respectively. In Figure 2.3 the ionospheric ionization profile is shown schematically.

In the ionosphere the neutral density is much larger than the density of the plasma. Therefore the dynamics of the plasma are strongly influenced by the neutral particles however not vice versa. The motion of charged particles is affected by neutrals due to collisions.

### 2.4 Current Systems

Electric fields, associated with magnetospheric convection, map down to the ionosphere along the magnetic field lines. Ionospheric currents perpendicular to the magnetic field are generated where the electric field provides the force balanced by collisions of the charge carriers with neutrals (Paschmann et al., 2003). The
E region currents are coupled to the magnetosphere via field-aligned currents often referred to as Birkeland currents, see Figure 2.4.

At high altitudes the collision frequency of charge carriers with the neutral gas is low and above 200 km the ionosphere is a good electric conductor along the magnetic field lines. The motion of charge carriers perpendicular to the magnetic 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 the charged particles with neutrals is of the order of the gyration frequency, they 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 acceleration 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 transiting an 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 observed as atoms and molecules in the ionosphere are excited by precipitating particles and emit photons in the relaxation process. As the composition of the ionosphere is changing with altitude also the observed colours 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 (see energy deposition profiles for different electron populations and different electron energies: Rees, 1989). Due to the altitude dependence of energy deposition with precipitation energy also the excited auroral emissions vary with precipitation energy. 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>
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<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>$N_2(B^3Π_g)$</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>$N^+_2(B^2Σ^+_g)$</td>
</tr>
<tr>
<td>844.6</td>
<td>$O(3p^3P)$</td>
</tr>
</tbody>
</table>
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 for example 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. Langmuir turbulence occurring both naturally and in ionospheric modification experiments is covered in section 3.3.

3.1 Electromagnetic Waves

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

\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \epsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} \]  \hspace{1cm} (3.1)

\[ \nabla \times \mathbf{E} = -\frac{1}{\epsilon_0} \frac{\partial \mathbf{B}}{\partial t} \]  \hspace{1cm} (3.2)

\[ \nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \]  \hspace{1cm} (3.3)

\[ \nabla \cdot \mathbf{B} = 0 \]  \hspace{1cm} (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. In the following 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 assume small perturbations, 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 is $E$. 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 $s$ refers to the particle 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 taken to be in $z$-direction. It is useful to transform Eqn.(3.5) to Fourier space, in vector notation it then becomes:

$$-i\omega m_s \tilde{v}_{sx} = e_s [\tilde{E}_x + \tilde{v}_{sy} B_0],$$

$$-i\omega m_s \tilde{v}_{sy} = e_s [\tilde{E}_y + \tilde{v}_{sx} B_0],$$

$$-i\omega m_s \tilde{v}_{sz} = e_s \tilde{E}_z. \quad (3.6)$$

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 given by:

$$\sigma = \sum_s \frac{n_s e_s^2}{m_s} \begin{bmatrix} -i\omega & \omega^2 - \omega_c^2 & 0 \\ \omega^2 - \omega_c^2 & -i\omega & 0 \\ 0 & 0 & \sigma_{zs} \omega_c^2 \end{bmatrix}.$$ \quad (3.7)

The dielectric tensor is given by $K = 1 - \frac{\sigma}{i\omega\varepsilon_0}$ and has the form:

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

where

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

$$ik \times k \tilde{E} = -(-i\omega) \tilde{B}$$

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

\[ \mathbf{k} \times (\mathbf{k} \times \vec{E}) + \frac{\omega^2}{c^2} \mathbf{K} \cdot \vec{E} = 0. \]  

(3.12)

The definition of the refractive index is \( n = \frac{c}{\omega \mathbf{k}} \) and is used to simplify the equation above to:

\[ n \times (n \times \vec{E}) + \mathbf{K} \cdot \vec{E} = 0. \]  

(3.13)

For simplicity the coordinate system is chosen such that \( \mathbf{k} \) and therefore also \( n \) lie in the x-z plane, \( \mathbf{B}_0 \) is along the z axis. The angle between \( \mathbf{B}_0 \) and \( n \) 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:

\[
\begin{bmatrix}
S - n^2 \cos^2 \theta & -iD & n^2 \sin \theta \cos \theta \\
iD & S - n^2 & 0 \\
n^2 \sin \theta \cos \theta & 0 & P - n^2 \sin^2 \theta
\end{bmatrix}
\begin{bmatrix}
\vec{E}_x \\
\vec{E}_y \\
\vec{E}_z
\end{bmatrix}
= 0.
\]  

(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:

\[ \tan^2 \theta = -\frac{P \left( n^2 - R \right) \left( n^2 - L \right)}{\left( Sn^2 - RL \right) \left( n^2 - P \right)}. \]  

(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.

For waves parallel to the magnetic field (\( \theta = 0 \)) the matrix Eqn.(3.15) simplifies to:

\[
\begin{bmatrix}
S - n^2 & -iD & 0 \\
iD & S - n^2 & 0 \\
0 & 0 & P
\end{bmatrix}
\begin{bmatrix}
\vec{E}_x \\
\vec{E}_y \\
\vec{E}_z
\end{bmatrix}
= 0.
\]  

(3.17)

for which three non-trivial solutions exist:

\[ P = 0, \quad \vec{E} = (0, 0, E_0) \]  

(3.18)

\[ n^2 = R, \quad \vec{E} = (E_0, iE_0, 0) \]  

(3.19)

\[ n^2 = L, \quad \vec{E} = (E_0, -iE_0, 0) \]  

(3.20)

where

\[ R = 1 - \sum_s \frac{\omega^2_{ps}}{\omega(\omega + \omega_{cs})} \quad \text{and} \quad L = 1 - \sum_s \frac{\omega^2_{ps}}{\omega(\omega - \omega_{cs})}. \]  

(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 \( \mathbf{k} \). 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 this 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.

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:

\[
\begin{align*}
    n^2 &= P, \quad \tilde{E} = (0, 0, E_0) \quad \text{(3.22)} \\
    n^2 &= RL, \quad \tilde{E} = \left( \frac{iD}{S} E_0, E_0, 0 \right) . \quad \text{(3.23)}
\end{align*}
\]

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, described in section 3.2.1, play a significant role. By measuring Doppler shifted radar backscatter containing the signature of ion acoustic waves important plasma bulk properties can be deduced such as the electron temperature. Another important type of thermal excited waves are Langmuir waves which are described in section 3.2.2.

In order to describe plasma with a non zero temperature a statistical approach is needed which is called kinetic theory. The Boltzmann equation describes the evolution of the particle distribution function \( f \) in phase space:

\[
\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \frac{\mathbf{F}}{m} \cdot \nabla_\mathbf{v} f = \frac{\delta \omega}{\delta t} f . \quad \text{(3.24)}
\]
3.2. ELECTROSTATIC WAVES

where \( \nabla_v \) is the gradient operator in velocity space and the term \( \delta_c f / \delta t \) 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:

\[
\frac{\partial n_s}{\partial t} + \nabla \cdot (n_s U_s) = 0,
\]

(3.25)

where \( U_s \) 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:

\[
m_s n_s \frac{dU_s}{dt} = n_s q_s [E + U_s \times B] - \nabla \cdot P_s + \frac{\delta_c P_s}{\delta t},
\]

(3.26)

where the second term on the right hand side describes the momentum change per unit volume due to pressure \( (P_s) \) gradients and the third term is 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):

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

(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) can be made if the ion temperature is assumed to be small, i.e. \( C_i = 0 \):

\[
1 - \frac{\omega^2_i}{\omega^2} = \frac{\omega^2_{pe}}{\omega^2 - \gamma e C_e^2 k^2} = 0.
\]

(3.29)

Furthermore limiting the phase velocity to less than the electron thermal velocity \( \omega^2 \ll \gamma e C_e^2 k^2 \) yields:

\[
\omega^2 = \frac{1}{1 + \gamma e C_e^2 k^2} \left( \frac{\gamma_e k_B T_e}{m_i} \right) k^2.
\]

(3.30)
This dispersion relation is plotted in Figure 3.1(a). For long wavelengths i.e. 
\( k\lambda_{De} \ll 1 \) Eqn.(3.30) simplifies to:
\[
\begin{align*}
\omega_S &= \pm kv_S, \\
v_S &= \sqrt{\frac{\gamma_e k_B T_e}{m_i}}.
\end{align*}
\]
For ion acoustic waves the oscillation of electrons and ions is almost in phase and 
density perturbations are thus 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 \( \gamma_D \):
\[
E = E_0 e^{-i\omega_r t} e^{-\gamma_D t}.
\]
With kinetic theory the damping coefficient \( \gamma_S(k) \) for ion acoustic waves can be 
derived (Stix, 1992):
\[
\gamma_S(k) = \omega_S(k) \left( \frac{\pi \gamma_e}{8} \right)^{1/2} \left[ \left( \frac{m_e}{m_i} \right)^{1/2} + \gamma \left( \frac{T_e}{2T_i} \right)^{3/2} \exp \left( -\frac{\gamma T_e}{T_i} \right) \right].
\]

Damping of ion acoustic waves depends on the electron to ion temperature ratio 
and is one parameter which can be derived from Incoherent Scatter Radar (ISR) 
measurements as will be shown in chapter 4.

### 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:
\[
1 - \frac{\omega^2_{pe}}{\omega^2 - \omega^2 C^2_e k^2} = 0.
\]
Here the ion motion was neglected, due to the slow response of ions to electric fields. 
Rewriting the above equation in terms of \( \omega \) and using the relation \( C_e = \omega_{pe}\lambda_{De} \) for 
the electron thermal velocity leads to the dispersion relationship for the Langmuir 
mode:
\[
\omega^2_L = \omega^2_{pe} \left( 1 + \gamma_e \lambda^2_{De} k^2 \right),
\]
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 a large part to 
electrons which move at a velocity close to the phase velocity of the wave. From
Figure 3.1. Dispersion for (a) the ion acoustic mode and (b) the Langmuir mode. Also shown in (b) is the short wavelength approximation $\omega \sim k \sqrt{\frac{e_0 T_e}{m_e}}$. Both dispersion relations are plotted for typical values of the Tromsø E-region.
kinetic theory the damping rate $\gamma_L(k)$ can be derived for a Maxwellian plasma (Stix, 1992):

$$\gamma_L(k) = \omega_p \left( \frac{\pi}{8} \right)^{1/2} (k\lambda_D)^{-3} \exp \left( -\frac{1}{2k^2\lambda_D^2} \right)$$

(3.37)

for $(k^2\lambda_D)^2 \ll 1$.

Although the Langmuir wave spectrum, i.e. the plasma line, is not routinely measured in ISR (section 4) experiments it can be used for density calibration of ISR. Observation of Langmuir wave activity is also crucial in modification experiments and the study of Ion Line Enhancement (ILE).

### 3.3 Nonlinear Wave-Wave Interaction

Ion acoustic waves are associated with plasma density fluctuations and thereby change the index of refraction. Langmuir waves propagating in a plasma with ion acoustic fluctuations 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 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:

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

(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:

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

(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:

$$\nabla \cdot \left( i\frac{\partial}{\partial t} + \frac{3C_e^2}{2\omega_p} \nabla^2 + i\gamma_L \right) E = \nabla \cdot \left( \frac{\omega_p\delta n_e}{2n_e} E \right),$$

(3.40)

with $\gamma_L$ 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:

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

(3.41)

is omitted here. A closed system of equations must include the effect of Langmuir waves on density perturbations. The Langmuir waves act on the density perturbations via a 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):

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

(3.42)

Due to the inverse dependency of the force on the particles mass \( m \), this force is much stronger for electrons than for the heavy 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:

\[
\left( \frac{\partial^2}{\partial t^2} + 2 \gamma S \frac{\partial}{\partial t} - v_S^2 \nabla^2 \right) \delta n_e = \frac{\varepsilon_0}{4m_i} \nabla \nabla |E|^2.
\]  

(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 |\( E \)| is not necessarily stable. Zakharov et al. (1985) showed that five instability regimes, defined by \( k \) and the ratio of electrostatic to thermal energy, exist including the electrostatic decay instability and the Modulational Instability (MI). In the regime of the electrostatic decay instability or the Parametric Decay Instability (PDI) 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 PDI describes the decay of a mother wave into daughter waves. A demonstrative scenario of PDI is given by ionospheric modification experiments PDI. In these experiments energy is fed into the system at a fixed frequency and wavevector defined by an electromagnetic pump wave. At the pump 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. The decay scenario is depicted in Figure 3.2. The secondary wave \(\omega_1\) driven by \(\omega_0\) eventually grows until the threshold of instability is reached. Then the wave further decays into daughter Langmuir and ion acoustic waves depicted by dashed lines in Figure 3.2.

PDI of Langmuir waves excited by bump-in-tail instability are considered as a possible mechanism to enhance the level of ion acoustic waves in the ionosphere in regions of auroral precipitation (Forme, 1999). 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 3.3. For a wave with phase velocity $v_{ph}$, indicated in Fig. 3.3, the velocity distribution function of the plasma has a positive slope. More particles have a slightly higher velocity $v_{ph} + dv$ than particles which have a slightly lower velocity $v_{ph} - dv$ and energy is transferred from the particles to the wave. The transfer of energy from particles to a wave is called inverse Landau damping. In the auroral ionosphere Langmuir waves are thought to be enhanced on magnetic field lines where the precipitating electrons cause a bump-in-tail of the electron velocity distribution.

![Figure 3.3. Velocity distribution of a plasma with a so called bump-in-tail. Waves with phase velocity $v_{ph}$ gain energy from the particles.](image)

In the regime of MI localized wave packets occur in addition to propagating Langmuir and ion acoustic waves. These waves packets consist of a Langmuir wave field trapped in non-propagating density depletions referred to as cavitos. The Langmuir wave field acts on the density depletion via a ponderomotive force causing the depletion to collapse and dissipate. Radar scatter from these stationary density depletions may be observed as zero Doppler shift backscatter if the Bragg condition is fulfilled. Observation of a zero Doppler feature is well known in ionospheric modification experiments (DuBois et al., 1990). The zero Doppler feature is also observed in radar measurements of aurora (Isham et al., 2012; Akbari et al., 2012) and thought to be an indication of naturally driven Langmuir Turbulence (LT).
Chapter 4

Incoherent Scatter Radars

Incoherent Scatter Radar (ISR) date back to the 70’s when the Doppler backscatter spectrum from the ionosphere was measured with a radar. Backscatter measurements of the ionosphere were envisaged much earlier, however, first measurements were delayed due to great challenges. One challenge is the little backscatter cross section which makes it necessary to employ large antennas and high transmitter powers. To measure the Doppler spectrum resolved in altitude is yet another problem as the ionosphere is a so called *overspread* radar target. Since the beginning of ISRs the technique has been refined and ISRs become powerful instruments for measurements of ionospheric plasma bulk properties such as electron density, electron and ion temperature and ion drift velocity based on the radar Doppler spectrum.

Section 4.1 describes how plasma properties can be derived from the backscatter spectrum. The refinement of ISR technique of has lead to increasing time and altitude resolution of the measurements. Section 4.3 gives a short introduction in the ISR techniques used in current experiments. A limiting factor in the spatial resolution of ISR measurements is the beam cross section (typically > 1°). Recent attempts to advance ISR measurements include radar interferometry techniques, a brief introduction to which is given in section 4.4.

4.1 The ISR Backscatter Spectrum

The radar backscatter spectrum from a plasma can be calculated either as scattering from a continuous medium or as superposition of scattering from single particles. Here the electric field scattered from a cloud of electrons is derived (following Farley and Hagfors, 1999).

An electromagnetic wave incident on a plasma accelerates the charged particles within. In turn, the accelerated particles radiate (e.g. Landau and Lifshitz, 1975). The phase of the scatter by an electron located at \( \mathbf{r}_p \), measured at \( \mathbf{R}_s \) and caused
by a plane wave originating from $\mathbf{R}_i$ is described by:

$$e^{i \phi(t)} = e^{-i(\omega_0 t - (\mathbf{k}_i - \mathbf{k}_s) \cdot \mathbf{r}_p)} e^{i(\mathbf{k}_i \cdot \mathbf{R}_i + \mathbf{k}_s \cdot \mathbf{R}_s)},$$

(4.1)

where $\mathbf{k}_i$ is the wave vector of the incident wave and $\mathbf{k}_s$ is the wave vector of the scattered wave. Dropping the last factor, which is a constant phase term, the electric field at the receiver can be written as:

$$E_s(t) = \frac{r_e}{r_s} E_0 \sin \chi e^{-i(\omega_0 t + \mathbf{k} \cdot \mathbf{r}_p)}.$$

(4.2)

Here $\mathbf{k} = \mathbf{k}_s - \mathbf{k}_i$, $r_e$ denotes the classical electron radius and $\chi$ is a polarization angle. For linear polarization $\chi$ is the angle between the incident wave electric field and $\mathbf{r}_s$.

In order to compute the scatter from all electrons within a volume $V$ of the plasma Eqn.(4.2) can be thought of as a Green’s function describing the field at $\mathbf{R}_s$ due to scatter by a single electron. The electron number density distribution of the single electron is:

$$N_p(r, t) = n_0 + \Delta N_p(r, t) = \delta(|\mathbf{r} - \mathbf{r}_p(t)|).$$

(4.3)

To compute the total electric field measured at $\mathbf{R}_s$ the scatter contribution from all electrons $N_s$ need to be accounted for:

$$E_s(t) = r_e E_0 e^{-i\omega_0 t} \sin \chi \sum_{p=1}^{N_s} \left| \frac{1}{\mathbf{R}_s - \mathbf{r}_p(t')} \right| e^{-i\mathbf{k} \cdot \mathbf{r}_p(t')}$$

$$\approx \frac{r_e E_0}{R_s} e^{-i\omega_0 t} \sin \chi \sum_{p=1}^{N_s} e^{-i\mathbf{k} \cdot \mathbf{r}_p(t')}$$

$$= \frac{r_e E_0}{R_s} e^{-i\omega_0 t} \sin \chi \int_V \sum_{p=1}^{N_s} \delta(|\mathbf{r} - \mathbf{r}_p(t')|) e^{-i\mathbf{k} \cdot \mathbf{r}_p} d^3r$$

$$= \frac{r_e E_0}{R_s} e^{-i\omega_0 t} \sin \chi N_V(\mathbf{k}, t'),$$

(4.4)

with $t'$ being the appropriately retarded time. Here $N_V(\mathbf{k}, t')$ is the spatial Fourier spectrum of the plasma which is related to the density fluctuations. The frequency spectrum of the electric field is computed by time domain Fourier transformation of Eqn.(4.4) and gives:

$$E_s(\mathbf{R}_s, \omega_0 + \omega) = \frac{r_e E_0}{R_s} \sin \chi N_V(\mathbf{k}, \omega).$$

(4.5)

The density fluctuations in the plasma are the property of interest in incoherent scatter radar measurements. The spectrum of these fluctuations contains the
signature of the electrostatic ion acoustic and Langmuir waves. In Figure 4.1 the schematic Doppler spectrum of a radar measurement is depicted. The part of the ISR spectrum containing the ion acoustic signature is referred to as Ion Line (IL). The part of the ISR spectrum containing the signature of Langmuir waves is referred to as Plasma Line (PL).

![Schematic backscatter spectrum of a ISR](image)

**Figure 4.1.** Schematic backscatter spectrum of a ISR, where $f_s$ and $f_p$ are the ion acoustic and plasma frequency respectively.

In practice measurements are obtained at a fixed wavevector $k$ determined by the transmitted wavelength and the observation geometry. For a monostatic radar, where the transmitter and receiver antenna are the same, the wavevector of observation is $k = 2 \cdot k_{\text{radar}}$.

![Relation of the ISR ion line spectrum to plasma bulk properties](image)

**Figure 4.2.** Relation of the ISR ion line spectrum to plasma bulk properties. Image credit: T. Nygrén.
Fitting the radar backscatter spectrum with model spectra yields estimates of the electron temperature, electron to ion temperature ratio, electron density and line of sight ion velocity. Figure 4.2 shows a number of ion line spectra computed for different plasma bulk properties of a Maxwellian plasma.

4.2 NEIAL echoes

Non-thermal ionospheric backscatter are occasionally observed and can result in backscatter enhancements of several orders of magnitude. These backscatter enhancements are thought to be caused by enhanced levels of wave activity in the ionospheric plasma due to wave instability. Enhancement of the IL can be triggered in artificial modification experiments by powerful High Frequency (HF) waves (e.g. Rietveld et al., 2000; Kohl et al., 1993; Dubois et al., 1993). Backscatter enhancements are also observed during disturbed geomagnetic conditions, during which the enhanced IL is referred to as Naturally Enhanced Ion Acoustic Line (NEIAL) (e.g. Rietveld et al., 1991; Sedgemore-Schultess and St. Maurice, 2001; Isham et al., 2012). The Power Spectral Density (PSD) of a typical NEIAL echo is compared to the spectrum of thermal backscatter in Figure 4.3.

Several models have been proposed to explain NEIALs. These models can be grouped into streaming instabilities directly exciting ion acoustic waves and cascade from Langmuir waves driven to instability (e.g. Rietveld et al., 1991; Forne, 1999; Sedgemore-Schultess and St. Maurice, 2001). In addition a model 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. In this model ion acoustic instability is driven by the ion cyclotron waves.

First observations of NEIALs were reported by Foster et al. (1988) and since then studied to understand their driving mechanisms. Except for the Sondrestrom
radar (1290 MHz) NEIALs have been observed with all ISRs in the auroral zone and a large number of papers have been published on the topic. In the following some of the most important findings and typical observational features are summarized. The summary distinguishes between “classical” NEIALs and NEIALs thought to be evidence for naturally occurring Strong Langmuir Turbulence (SLT). Observations of “classical” NEIALs are summarized as follows:

**Spectra:** Power enhancements are observed at the ion acoustic frequencies. Typically the spectra are asymmetric with higher power in the downshifted ion line (Ogawa et al., 2011, e.g.).

**Range:** The enhancements are typically observed between 300 to 700 km altitude, but have been observed at altitudes as high as 1600 km and low as 150 km (Rietveld et al., 1991, 1996; Ogawa et al., 2006, 2011). Enhanced power is observed over an altitude range of hundreds kilometers simultaneously.

**Scale size:** NEIALs are coherent echoes arising from volumes limited in size in the plane perpendicular to the magnetic field. The scale size of the enhanced region has been estimated to hundreds of meters on an event basis (Grydeland et al., 2003).

**Local time:** The local time distributions of the echoes vary with the observation site. At the EISCAT Svalbard Radar (ESR) the peak occurrence frequency is observed around local magnetic noon (Ogawa et al., 2011).

**Aurora:** NEIALs are observed during auroral activity with optical aurora in vicinity of the radar measurement volume. The question whether optical aurora is observed on the same magnetic field line as the one from which the power enhancements occur has not been resolved (Blixt et al., 2005; Michell et al., 2008). However, optical aurora typically has a strong red component during NEIALs indicating a low energy component in the electron precipitation.

In recent years NEIALs have been reported with characteristic features predicted by SLT (Isham et al., 2012; Akbari et al., 2012). These features are enhanced power at zero Doppler shift, corresponding to backscatter from non-propagating density depletions, and observation of enhanced plasma lines simultaneously to the NEIALs. The reported observations can be summarized as follows:

**Spectra:** Enhanced power occurs at the ion line frequencies and at zero Doppler shift. Enhanced plasma lines are observed simultaneously (Isham et al., 2012; Akbari et al., 2012).

**Range:** The enhancements are observed at altitudes around 250 km (Ekeberg et al., 2012; Schlatter et al., 2014) with a small range extent of few kilometers to tens of kilometers (Schlatter et al., 2013b, 2014).

**Local time:** The local time distribution of the enhancements has been reported for one radar only with a peak around 19 MLT (Schlatter et al., 2014).

**Aurora:** The auroral conditions during these enhancements have been studied
little and the relation to optical observations has to be established yet.

4.3 Radar Experiments

The following short introduction to radar codes is inspired by Farley (1996) and the interested reader is referred to it.

In radar jargon one distinguishes between over- and underspread targets. For overspread targets, such as the ionosphere, the Nyquist sampling rate can not be fulfilled by probing the target with pulses separated in time by the sampling period without range ambiguities of the measurements. To cover the ion line spectrum a sampling bandwidth of about 50 kHz is required. Therefore, samples of the backscatter signal need to be taken every 20 $\mu$s to provide spectra free from aliasing. 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 achieve the necessary spectral bandwidth and spatial resolution one can take advantage of the fact that measurements from disjoint regions are uncorrelated. When designing a radar experiment 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, alternating codes, and random 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.

4.3.1 Uncoded Pulses

The basic transmission scheme for a radar is to transmit a single pulse of suitable duration 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.

In Figure 4.4(a) 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 $\text{env}(t)$, one can sample the whole altitude region from which the backscatter is arising. It is also possible to oversample the backscattered signal with a receiver filter having a shorter impulse response function than the duration of the transmitted pulse. In order to measure the Auto Correlation Function (ACF) of the backscatter target one can use oversampling to get lagged samples for a given range.
4.3. RADAR EXPERIMENTS

The range resolution of the uncoded long pulse experiments is limited by the length of the transmitted pulse. By the use of inverse theory it is however possible to increase the range resolution of the estimated parameters by including assumptions for the backscattered signal (Hysell et al., 2008). This technique is used at the Jicamarca radio observatory and the AMISR radars amongst other techniques.

4.3.2 Coded Pulses

Coded pulses are a technique to increase the range resolution of the measurements and are in use at many ISR facilities. The coding 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 sequence in a code. During each transmission cycle a specific code sequence is transmitted. Consider the case where the signal has the bit sequence \( a_0 \) to \( a_3 \) as shown in Figure 4.4(b). The code can be described as a series of bits with value ±1. At reception the data are decoded with the bit scheme used at transmission. The lagged product of the first two samples \( V_0 = V(t_0) \) and \( V_1 = V(t_1) \) is formed by their complex multiplication:

\[
a_0 V_0 a_1 V_1^* = a_0 (a_0 s_h + a_1 s_{h-1} + a_2 s_{h-2} + a_3 s_{h-3})
\times a_1 (a_0 s_{h+1}^* + a_1 s_h^* + a_2 s_{h-1}^* + a_3 s_{h-2}^*)
\]

(4.6)

where \( s_h \) is the signal contribution from height \( h \). We can now take advantage of \( a_2^2 = 1 \) and \( \langle s_{h+\alpha} s_{h+\beta}^* \rangle = 0 \) if \( |\alpha - \beta| \geq 2 \) since backscatter from different volumes are uncorrelated. The notation \( \langle ... \rangle \) is used for the expectation value implicating averaging over a number of measurements. For the lagged product of samples \( V_0 \)
and \( V_1 \) the expectation value is:

\[
\langle a_0 V_0 a_1 V_1^* \rangle = \left( s_h s_h^* \right) + \langle a_0 a_2 \rangle \left( s_h s_{-1} s_{h-1} \right) + \langle a_0 a_1 a_2 a_3 \rangle \left( s_h s_{-2} s_{h-2} \right) \\
+ \langle a_0 a_1 \rangle \left[ \left( s_h s_{h+1}^* \right) + \left( s_h s_{-1} s_h^* \right) + \left( s_h s_{-2} s_h^* \right) + \left( s_h s_{-3} s_h^* \right) \right] \\
+ \langle a_1 a_2 \rangle \left( s_h s_{h-1}^* \right) \\
+ \langle a_0 a_3 \rangle \left( s_h s_{-1} s_{h-2} \right). 
\] (4.7)

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. This technique is called coded long pulse. With the transmitted code being random (random codes) these expectation values will even vanish for a large number of transmitted pulses (Sulzer, 1986). Another approach is to chose the transmitted codes in such way that the expectation values of the clutter terms minimizes for a limited code set. The latter technique is referred to as 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 as in Eqn.(4.7).

### 4.4 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 with the radar measurements. Radar interferometry is a technique to estimate the cross beam structure of the scattering medium at sub beam scales. The technique of radar interferometry has first been utilized for ionospheric studies by Farley et al. (1981) and Kudeki et al. (1981) and since been further developed (e.g. Hysell and Chau, 2006). By measurement of the backscatter signal with receivers located at \( R_i \) the moments of the arrival-angle distribution of the backscatter medium can be found and the cross beam structure of the backscatter medium investigated. Computing the cross beam structure from the interferometric measurements is referred to as imaging.

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 \( b \), where \( b = R_2 - R_1 \) will observe the same signal \( S \), scattered from a point in the sky, 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 referred to as cross-phase, is a measure of the time lag. With the assumption that the length of the baseline is negligible as compared to the range of the backscatter target the
cross-phase depends solely on the angle of arrival:
\[ \phi = \frac{2\pi}{\lambda} \mathbf{s} \cdot \mathbf{b}, \]
where \( \lambda \) is the wavelength of the signal and \( \mathbf{s} \) is a unit vector pointing from the radar towards the backscatter target, as depicted in Figure 4.5. In practice the measure of the cross phase is limited to \( \pm \pi \), thereby introducing a \( 2\pi \) ambiguity. The two receiver chains will also introduce a phase offset due to filtering, mixing and the difference in the internal signal path length. 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:
\[ \phi + \delta_0 = \frac{2\pi}{\lambda} \mathbf{s} \cdot \mathbf{b}. \] (4.8)

Figure 4.6 depicts the cross-phase as a function of look direction defined by \( \mathbf{s} \). The cross-phase varies between \( \pm \pi \) along the direction of the baseline whereas it remains constant in the perpendicular direction. The phase offset introduced in the receiver systems acts as displacement of the cross-phase pattern and needs to be calibrated for in order to determine the angle of arrival by measuring \( \phi \).

In practice the data which are used for imaging are complex cross-spectral measurements, i.e. cross-correlation measurements resolved in the frequency domain. These measurements are derived in the same way as the single receiver measurements (e.g. Eqn.(4.7)), however, with voltage samples obtained with two different receiver antennas. Normalization of the cross-spectral measurements \( \hat{S}_{1,2} \), by the geometrical mean of the power spectra \( \hat{S}_i \), of the two involved receivers gives the visibilities:
\[ \hat{V} = \frac{\hat{S}_{1,2}}{\sqrt{\hat{S}_1 - N_1 \hat{S}_2 - N_2}}, \] (4.9)
where the $N_i$ are the noise estimates of the corresponding receiver. The visibilities, or coherences, are a measure of how well the measurements obtained on two receivers correlate. Based on the coherence, baseline geometry, and antenna patterns the extent of a backscatter object can be estimated (e.g. Grydeland et al., 2003).

The relation between the visibilities, and the scattered power density (a function of look direction) called brightness is given by Thompson (1986):

$$V(kb) = \int_{4\pi} A_N(s) B(s) \exp(jkb \cdot s) d\Omega. \quad (4.10)$$

Here $A_N$ is the normalized two-way antenna pattern, $B$ is the brightness, and $k$ the wavenumber. In practice the transmitting antennas are highly directive and the power in the first side-lobe of the transmitting antenna is much smaller then the power in the main-lobe. Therefore the integration in Eqn.(4.10) can be limited to look directions defined by the main-lobe of the transmitting antenna.

In case of visibility data obtained with receivers having differing antenna pat-
terns these need to be included in the forward model explicitly. The antenna pattern of the transmitting antenna $A_T$, common to all observations, can be included in the effective brightness distribution $B^{eff} = A_T B$. $B^{eff}$ is the function to be derived from the measurements by means of inversion techniques. The discretized forward model can be written as Hysell and Chau (2006):

$$V_j = \sum_i B^{eff}_i H_{ij},$$

(4.11)

where $H$ is the point spread function, and the indices $j$ and $i$ denote the baseline and look direction. The point spread function is defined by:

$$H_{ij} = \sqrt{A_{R1,ij} A_{R2,ij}} \exp(\imath k \mathbf{b}_j \cdot \mathbf{s}_i).$$

(4.12)

Here $A_{R1}$ and $A_{R2}$ are the two receiver beam patterns corresponding to the receivers of baseline $j$.

**Imaging Implementation**

At the ESR a total of 5 receivers are in operation on a campaign basis in order to allow for imaging of strong backscatter targets, see section 5.2 for instrumental details. Here some of the implementation details for imaging with this system are discussed and examples of radar images presented.

The resolution of the point grid defined by $s_i$ (Eqn.(4.12)) can be chosen such that the resolution is increased until new details in $B^{eff}$ cease to emerge. The size of the smallest resolved features is defined by the baseline configuration. For imaging at ESR the point grid defined by the pixels of supporting optical instrumentation is chosen. The resolution of this point grid is approximately 1.5 arc minutes.

For practical reasons the real and imaginary part of the complex valued point spread function and the measurements are assigned to different visibility indices:

$$V_n = \Re \left\{ \sum_i B^{eff}_i H_{ij} \right\}, \text{ and } V_{n+1} = \Im \left\{ \sum_i B^{eff}_i H_{ij} \right\}.$$  

(4.13)

The first baseline is assigned to the baseline with zero length $|\mathbf{b}| = 0$ with a uniform receiver pattern giving a visibility of 1. It is this baseline which determines the total brightness $\sum_i B^{eff}$ of the radar image. The remaining baselines constitute of all possible combinations of the 5 receivers giving 10 baselines each providing a complex valued measurement, i.e. in total 21 visibility data.

In order to compute the $B^{eff}_i$ from the visibility data inversion of $H_{ij}$ is necessary. The pseudo inverse of $H$ can be computed by using singular value decomposition. Other inversion techniques used in radar imaging employ regularization functions and a-priori probabilities for $B^{eff}$ (e.g. Hysell and Chau, 2006). Here singular value decomposition of $H$ is used to compute the brightness estimate $B^{eff}$. 
Imaging results of highly coherent backscatter obtained at the ESR are presented in Figure 4.7. A satellite transit is observed in the supporting optical instrumentation due to scattering of sunlight off the satellite. The satellite transits the main lobe of the transmitting antenna and radar backscatter is observed from a range of approximately 605 km. Panel (a) illustrates the ambiguities involved in image reconstruction with a limited number of baselines. To produce the image data from only two receivers were used resulting in a periodic brightness estimate in the direction of the baseline. Since there is no moment in the direction perpendicular to the baseline the brightness estimate results in a stripe pattern. Due to $B^{cf} = A_T B$ the antenna pattern of the transmitting antenna is clearly noticeable. The visibilities are shown in the lower plot together with the visibilities modeled by the obtained brightness distribution. Visibilities of baselines not employed for the imaging are underestimated. In panel (b) data from 5 receivers were used reducing the ambiguities significantly and giving a good location estimate of scatterer. Note also that all visibilities are reproduced by the brightness distribution. The position of the satellite, as observed with optics, is indicated by a white marker.

![Figure 4.7](image)

**Figure 4.7.** ASK grayscale image (FOV of 6.2° × 6.2°) with overlayed radar brightness distribution for a satellite transit. A white + highlights the position where the satellite is seen with ASK. In the left image only the 32m/42m baseline was used for imaging while in the right image all EASI baselines were used. Radar data were obtained with the *beata* experiment and integrated over 50 ms.

Backscatter targets with non-zero size in the baseline direction result in reduced coherence in the measurements. Figure 4.8 illustrates the effect of an extended backscatter object on the radar brightness estimate. Using the same satellite transit as above, however, with increased time integration results in backscatter arising...
from a range of look directions due to the satellite motion. During the integration period the satellite covers a considerable distance as indicated by the white track seen in the plot and highlighted with the two white markers. The estimate of the radar brightness distribution resembles the path of the satellite well.

![Figure 4.8](image)

**Figure 4.8.** ASK grayscale image with overlayed radar brightness distribution for a satellite transit. Both radar and optical data were integrated over 400 ms. The white + markers indicate the path of the satellite during the integration period. In the bottom panel the visibility data (red) and the visibility computed from the brightness estimate (dashed black) are plotted.
Chapter 5

Instrumentation

Observations with the EISCAT radars are the basis of studies presented here. The EISCAT radars and radar programs used for observations are described in section 5.1. 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. Supplementary optical observations were conducted with the Odin and ASK imagers installed at the EISCAT Svalbard Radar (ESR) site. Section 5.4 describes the ASK optical instrument. Section 5.5 describes the Odin imager.

5.1 EISCAT Radars

The principle of Incoherent Scatter Radar (ISR) measurements is to transmit a powerful radar wave and measure the Doppler shifted ionospheric radar 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 shown in Figure 5.1(a). In the receiver chain the signal is pre-amplified at the antenna by a pre-amplifier which is protected from saturation during transmission. After amplification the signal is mixed down to the Intermediate Frequency (IF), possibly in several steps, followed by digitization. At this point of the receiver chain raw data can be saved to memory if wanted. In the next step the Lag Profile (LP) are formed from lagged data products, as described in section 4.3.2, and saved to memory in form of a Lag Profile Matrix (LPM). In case of phase coded experiments, the LPMs are calculated from data measured during at least one complete code cycle. To minimize the amount of data LMPs are integrated over a few code cycles and then 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). Radar interferometry with EASI is done in post-processing requiring storage of the raw data.
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). During campaigns 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 variety of radar programs exist for the UHF radar each with its advantages and shortcomings. The arc1 experiment is of interest for high time and range resolution which comes at the cost of reduced data quality. 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

Figure 5.1. Overview of the ESR and EASI radar receiver systems.
is described in detail in section 5.1.2.

5.1.2 ESR

The ESR facility 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. While the 32m dish is fully steerable the 42m dish is fixed in the direction of magnetic zenith corresponding to 184.5° azimuth and 81.6° elevation. 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.

LT2

LT2 is the most recent experiment which has been used for interferometry observations. It is a long pulse experiment designed by B. Isham and P. Gallop to study enhanced plasma lines. Of interest for observations with EASI is the long pulse which is transmitted at 499.9 MHz every millisecond. On reception the signal is sampled at different frequencies and frequency bands in order to cover ion line and plasma line frequencies with great detail. Only downshifted plasma line frequencies are covered, however, on both ESR dishes enabling plasma line interferometry. For ion line interferometry with EASI the ion line spectrum is sampled at 20 µs covering a bandwidth of 50 kHz centered at the transmitter frequency. During each cycle also a short pulse is transmitted to obtained profiles with high altitude resolution. The experiment has been tested and validated during a campaign in November, 2014.

LT4

LT4 is a very basic radar program used in early interferometry campaigns with EISCAT Aperture Synthesis Imaging (EASI). 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, as depicted in Figure 5.2. While sampling backscatter at frequencies $\nu_1$ and $\nu_2$ background samples can be taken on receiver channels for $\nu_3$ and $\nu_4$ for background noise reduction. It is possible to connect one additional receiver antenna to the ESR plasma line channel to record ion line data during this experiment.

The LT4FL 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. At 6250 µsec the next subcycle is started. A total number of 64 code 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 $d_{data}$ vector and raw data samples are saved in the $d_{raw}$ vector. A summary of the $beata$ program which has been used in interferometry campaigns is given in Table 5.1.

**Arc_slice**

$Arc_slice$ is a 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 a high time resolution of 0.5 sec. Based on this program is $arc_slice ASK$ which includes storing of raw data samples for reception on the 32m and 42m antenna.

$Arc_slice ASK$ 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. After 10 cycles, corresponding to an integration period of 5 sec, the LPM is dumped.
5.2 EASI

EISCAT Aperture Synthesis Imaging (EASI) (Grydeland et al., 2005a) is an interferometry system with three additional receiver antennas to the ESR radar facility (Goodbody, 2013). Each of the three antennas is a phased array with $4 \times 4$ antennas. The signal of the 16 UHF TV antennas with a gain of $\sim 12.5$ 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 on one of the ESR antennas. 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.

Due to inaccuracies in the time stamp in data recorded with EASI a post-processing technique has been developed to synchronize data recorded with the Echotek receiver and the ESR receiver system. The technique takes advantage

in the data vector and raw data samples are saved in the raw data vector. A summary of the arc_sliceiASK program is given in Table 5.1.

The mainland radar arc1 experiment is similar to the arc_slice, but has the duration of a code cycle of 0.44 s and the range coverage between 96 and 422 km.

**Figure 5.3.** Alternating code of the beata and arc_sliceiASK experiment.
Table 5.1. Summary of the radar programs at ESR suitable for interferometric radar observations with EASI.

<table>
<thead>
<tr>
<th>Program</th>
<th>LT2</th>
<th>LT4</th>
<th>beata</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transm. freq.</td>
<td>499.3 MHz</td>
<td>499.35 + 0.3 MHz</td>
<td>499.3 MHz</td>
</tr>
<tr>
<td>Backgr.</td>
<td>50 kHz</td>
<td>40 kHz</td>
<td>384 µs</td>
</tr>
<tr>
<td>Sampling freq.</td>
<td>50 kHz</td>
<td>40 kHz</td>
<td>384 µs</td>
</tr>
<tr>
<td>Bit length</td>
<td>-</td>
<td>-</td>
<td>7.5 km</td>
</tr>
<tr>
<td>No. of bits</td>
<td>-</td>
<td>-</td>
<td>64</td>
</tr>
<tr>
<td>Pulse length</td>
<td>980 µs</td>
<td>2 × (360 µs)</td>
<td>384 µs</td>
</tr>
<tr>
<td>Range resolution</td>
<td>147 km</td>
<td>3.75 km</td>
<td>57.6 km</td>
</tr>
<tr>
<td>Sampling range</td>
<td>168 km − 1608 km</td>
<td>P1 190.5 − 1368 km</td>
<td>P2 135 − 1368 km</td>
</tr>
<tr>
<td>Dump length</td>
<td>2 s</td>
<td>6 s</td>
<td>6 s</td>
</tr>
<tr>
<td>IPP</td>
<td>10 ms</td>
<td>6.25 ms</td>
<td>3.906 ms</td>
</tr>
<tr>
<td>No. of subcycles</td>
<td>1</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Duration of cycle</td>
<td>10 ms</td>
<td>0.4 s</td>
<td>0.5 s</td>
</tr>
<tr>
<td>Plasma line</td>
<td>x (interferometry)</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

 entrada, algo, trasmit. Ant. 

Transmit. line
Plasma line
Duration of cycle
No. of subcycles
 IPP
Dump length
Sample range
Range resolution
Pulse length
No. of bits
Bit length
Sample freq.
Transmit. freq.
radio observations with EASL.

Table 5.1. Summary of the radar programs at ESR suitable for interferometric
5.2. EASI

![Image of EASI array A in front of the 42m antenna (Image credit: Hanna Dahlgren, 2009).](image1)

![Normalized beam patterns of the 42m, 32m and EASI antennas.](image2)

![EASI Antenna positions at the ESR.](image3)

**Figure 5.4.** EASI receiver system at ESR.

- a) Image of EASI array A in front of the 42m antenna (Image credit: Hanna Dahlgren, 2009).
- b) Normalized beam patterns of the 42m, 32m and EASI antennas.
- c) EASI Antenna positions at the ESR.

of the phase code modulated onto the transmitted radar pulse. This code can be recognized in the received signal scattered back from a target such as a satellite and thereby providing accurate pulse synchronization between the two receiver systems.

In 2006 only one EASI antenna panel, labeled EASI-A in Figure 5.4, was operational with a somewhat different setup then described above. The antennas used were 18-element Yagi UHF antennas (manufactured by Triax Denmark) with a gain of $\sim 14.5$ dBi. Data obtained with this system configuration is used in Paper I. Due
to problems with wind and snow drift the Yagi antennas were replaced with the TV panel antennas. EASI antennas B and C were completed in 2010. Figure 5.4(c) shows the beam pattern of the EASI antennas in comparison to the ESR antennas.

5.3 Radar Data Handling

At the EISCAT radars data are 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). In case of raw data storage the file also contains these data in the $d_\text{raw}$ vector.

![Flow diagram of radar data handling](image)

Figure 5.5. Radar data handling.

Figure 5.5 depicts the flow diagram of the radar data handling. 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 ion temperature ratio and the ion line of sight 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 each antenna pair. XLPM are equivalent to LPM where lagged products are formed from samples $V_0$ and $V_1$, described in section 4.3.2, measured on two different receivers. Interferometric parameters, such as coherence and cross-phase, are then calculated with software labeled Aperture Synthesis Toolbox (AST) in Figure 5.5, from the XLPMs.

5.4 ASK

The Auroral Structure and Kinetics (ASK) optical instrument (see Dahlgren et al., 2008) is a powerful tool for auroral studies. It consists of three imagers and two photometers. The core of the imagers are sensitive Electron Multiplying Charge
Coupled Device (EMCCD) sensors for high resolution observations of aurora. Each of the three imaging channels (ASK1, ASK2, ASK3) is equipped with a $6.2 \times 6.2^\circ$ Field Of View (FOV) lens and an optional galilean telescope to reduce the FOV to $3.1 \times 3.1^\circ$. A set of optical filters for observation of particular auroral emissions are available for the imagers. Optical observations presented in paper II were conducted with the setup outlined in Tab. 5.2.

<table>
<thead>
<tr>
<th>Imager</th>
<th>Emission</th>
<th>Wavelength</th>
<th>FOV</th>
<th>sensitive to</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASK1</td>
<td>$N_2(B^4\Pi_g)$</td>
<td>673.0 nm</td>
<td>$6.2 \times 6.2^\circ$</td>
<td>high energy precip.</td>
</tr>
<tr>
<td>ASK2</td>
<td>$O(2P)$</td>
<td>732.0 nm</td>
<td>$3.1 \times 3.1^\circ$</td>
<td>low energy precip.</td>
</tr>
<tr>
<td>ASK3</td>
<td>$O(3p^3P)$</td>
<td>777.4 nm</td>
<td>$6.2 \times 6.2^\circ$</td>
<td>high and low energy precip.</td>
</tr>
</tbody>
</table>

5.5 Odin

During the observation season 2005/2006 the Odin imager was installed outside the ESR facility for white light observations of aurora. 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 $720 \times 576$ pixel resolution. The imager’s FOV is $14.3^\circ \times 10.9^\circ$. 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 (GPS) time. Optical data from the Odin imager was used for calibration of the radar interferometer (paper I).
Chapter 6

Summary of Papers

Paper I reports on a calibration technique for ISR interferometry systems and is summarized in section 6.1 and presented in paper I. The developed calibration technique is of great value for future studies with EASI and was applied in the NEIAL interferometry study summarized in section 6.2 and presented in paper II. In Paper III, summarized in section 6.3, we report on EISCAT UHF observation of a Naturally Enhanced Ion Acoustic Line (NEIAL) event. In Paper IV, summarized in section 6.4, a statistical study of SLT like radar signatures in data obtained with the ESR. The statistical results highlight the difference between the “classical” NEIAL signatures and SLT like signatures not only in terms of their spectral characteristics, but also their different local time occurrence distributions.

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

The ESR interferometer consists of the two parabolic dishes and its extension the three phased array receivers (EASI). Several science goals exist for EASI the primary is to study NEIALs, their relation to optical aurora and the spatial relation between the up- and down-shifted ion line enhancements. 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 of meters. Narrow field of view imagers provide the possibility to study the aurora at this scale size. The observation of NEIALs with radars is however limited by the width of the radar beam typically about 1° corresponding to 2 km at 120 km range. Employing multi-baseline interferometry to synthesize a larger receiver aperture increases the resolution to sub-degree scales.
In order to do aperture synthesis imaging and compare the radar images with measurements from optical imagers, calibration of the radar interferometer system is necessary. In this paper a phase calibration technique for the EASI system is presented. The calibration technique employs coherent scatter from satellites passing through the radar beam. Optical signatures of the satellite transits provide an accurate measure of the angle of arrival of the backscatter. By using a number of satellite transits sufficient for mapping the beam perpendicular plane, the interferometric cross-phase model is fitted to the observations. Figure 6.1 shows the measurements and fit residual for the 32m/42m as well as the 42m/A baseline. The advantage of the technique over others is that not only the phase offsets can be computed, but the baseline for each antenna pair is found with accuracy better than 1 m. This accuracy is difficult to achieve by other means since the phase center of the dish antennas are not well known.

Figure 6.1. Cross-phase measurements and fit residuals for the 32m/42m baseline as well as the 42m/A baseline. Image credit: Schlatter et al. (2013a).
6.2 Paper II - Observations of a NEIAL event with a radar interferometer system

Paper II discusses first observations of a NEIAL event with EASI. The observations were made on December 17, 2012 with the beata experiment (section 5.1.2). Based on coherence estimates derived from the radar measurements an upper limit of the size of the enhanced backscatter volume is derived. Four baselines of EASI are employed for the analysis and Figure 6.2(a) shows the relation of coherence to the scale size of the enhanced scattering region. The larger the scattering region is the smaller the coherence gets and for long baselines the coherence decreases more rapid (see section 4.4). In Figure 6.2(b) the coherence estimates for the four baselines are plotted over the event duration. Based on these values the scattering region has a size of less than $900 \times 500$ m in the plane perpendicular to the geomagnetic field. The altitude extent is about 150 km.

![Dependence of Coherence from Structure Size](image-1)

**Figure 6.2.** Panel (a) shows the dependence of backscatter coherence from the size of the enhanced backscatter region for four EASI baselines and an altitude of 400 km. Panel (b) shows observed coherences in the down- and upshifted ion line at 400 km, color annotation as in panel (a). Image credit: Schlatter et al. (2015).

Using aperture synthesis images of the radar brightness distributions are computed. The derived brightness distributions show that the enhanced backscatter region is aligned with the geomagnetic field. Furthermore, the brightness distributions indicate the enhanced backscatter to arise approximately 4 km east of the radar beam center.

Simultaneous optical observations were conducted with the ASK optical instrument (section 5.4). Optical emissions of an auroral arc are observed with ASK just outside the FOV of the radar. Mapping the radar brightness distributions to altitudes where optical emissions are observed relates the enhanced backscatter vol-
ume to regions of auroral precipitation. Figure 6.3 shows a combination of optical and radar data. In panel (a) the 32m/42m power spectrum is plotted, showing the enhanced backscatter in the down-shifted ion line at altitudes between 330 to 450 km range. Panel (b) shows ASK1 images integrated over the same time period as the radar data, 06:38:35.8 - 06:38:36.4 UT. Optical emissions from an auroral arc are observed just outside the radar beam. The radar brightness distribution mapped to an altitude of 120 km is plotted in panel (c) and (d) for the down- and upshifted ion line respectively. The geomagnetic field line passing through the maximum radar brightness is indicated in the ASK1 image (panel (b)) for altitudes of 100, 120, 160, and 240 km in red. Although optical emissions are observed from a region outside the radar beam the imaging results show that the enhanced backscatter region and optical emissions possibly arise from the same geomagnetic field lines.

![Figure 6.3](image.png)

**Figure 6.3.** Optical and radar data for the time period 06:38:35.8 to 06:38:36.4 UT. Panel (a) shows the 32m/42m radar power. Panel (b) shows the radar brightness distribution mapped to an altitude of 120 km for the down-shifted ion line. ASK1 data integrated over the same time period is shown in panel (c). The red circle indicates 42m main lobe and the red line the field line passing through the highest radar brightness with altitudes 100, 120, 160, and 240 km marked. Image credit: Schlatter et al. (2015).
6.3 Paper III - Enhanced EISCAT UHF backscatter during high-energy auroral electron precipitation

In recent years a class of NEIAL echoes was reported on which is thought to be evidence for naturally occurring Strong Langmuir Turbulence (SLT). First observations of SLT signatures were reported by Isham et al. (2012) and later by Akbari et al. (2012).

![Figure 6.4. Time history of radar data of the UHF enhancements and snapshots of optical data. In panel (a) the backscattered power or apparent electron density is plotted for altitudes where the enhancements were observed. In panel (b) the E region apparent electron density is plotted. In panel (c) the mean power from the altitudes regions shown in (a) and (b) is plotted. Panel (d) shows a close up of panel (c). In panel (e) snapshots of optical image data is shown. Image credit: Schlatter et al. (2013b), reprinted with permission.](image)

In paper III observation of ion line SLT signatures in EISCAT UHF data is reported. Enhanced backscattered radar power is observed simultaneously from two limited altitude regions, see Figure 6.4. Besides enhancement at the ion line shoulders also a distinct zero Doppler shift feature is observed as shown in Figure 6.5. The zero Doppler shift feature is associated with non-propagating electron density irregularities due to cavitation. 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 $L$. For observations with the EISCAT UHF system the scale size is of the order of decimetres. With the high range resolution of the observations it has furthermore been possible to show that the altitude extend is limited to $\sim 2$ km. The enhancements occurred close to the F region peak with little gradient in the background electron density.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{UHF_spectra.png}
\caption{SLT signature in UHF ion line data. Image credit: Schlatter et al. (2013b).}
\end{figure}
6.4 Paper IV - On the relation of Langmuir turbulence radar signatures to auroral conditions

The statistical occurrence of anomalous radar echoes thought to be signature of naturally occurring SLT is investigated in paper IV. For the study a large, and nearly continuous, data set obtained with the ESR during the International Polar Year (IPY, 2007-2008) was employed. The IPY data set consists of over 3.4 million data files each containing the LPM for the ion line and the down- and upshifted plasma line channel. A search algorithm was developed to identify possible SLT signatures based on the ion line signature. That is, observation of enhanced power at the down- and upshifted ion line as well as at zero Doppler shift was required. Approximately 0.02% of the data files were identified to show the ion line SLT signature.

![Figure 6.6](image.png)

The identified events occur predominantly in the pre-midnight sector and only few events were observed in the pre-noon sector. Figure 6.6 shows the magnetic local time distribution of the event occurrence. For comparison the local time distribution of “classical” NEIALs (Ogawa et al., 2011) is also plotted in the same Figure. The two distribution significantly differ from each other. Around local magnetic noon the characteristic energies of electron precipitation are low energetic precipitation, typically hundreds of eV. The aurora observed during evening hours, however, is typically aurora due geomagnetic substorms with energetic electron precipitation, with energies of keV. Therefore, it is argued that “classical” NEIALs and SLT signatures are not caused by the same driving mechanism. That is, naturally occurring SLT is not driven by low energy electron precipitation.

From the events identified in the study it could also be shown that SLT signa-
tures indeed occur close to the F region peak, a finding which was indicated by the reported events and by Ekeberg et al. (2012). Figure 6.7 shows the altitude distribution of identified events. The grey shaded region is not covered by the search algorithm, due to difficulties in identifying SLT signatures in the highly variable E region.

![Figure 6.7. Altitude distribution of SLT signatures and plasma line enhancements at ESR. Image credit: Schlatter et al. (2014), reprinted with permission.](image)

Plasma line enhancements were consistently observed within several seconds of the SLT ion line signatures. Two types of plasma line enhancements were identified. The first, wide in frequency and range extent at a frequency of about 3 MHz and altitudes between about 150 to 220 km. The second, narrow in frequency and range extent at altitudes between about 200 to 250 km. The altitude distribution of both types is shown in Figure 6.7. The first type is thought to occur due to a electron distribution function unstable at energies of 2-4 eV. At these energies excitation of vibrational levels of $\text{N}_2$ causes a marginal unstable electron distribution function (Nilsson et al., 1996). The second type occurs at altitudes of the ion line SLT signatures and is thought to be the Langmuir counterpart to the enhanced ion lines.
Chapter 7

Outlook

This chapter gives a brief overview of studies planned in the near future. The ideas for these studies originate in yet unfinished work which needs to be followed up and involvement in projects which are expected to result in valuable scientific data in the months to come.

I Follow up of the statistical study presented in paper IV

In paper IV the statistical occurrence of LT signatures in ESR data which indicate SLT has been studied. The events which have been identified in one year of continuous observations is a rich dataset to be explored further. The event occurrence can be studied to derive the parameter regime in which SLT is observed at the ESR. Further possible investigations are the occurrence frequency of SLT signatures in aurora, i.e. occurrence frequency during periods with electron precipitation around magnetic zenith, and the dependence of observations on precipitation energies.

II Langmuir wave enhancements

The statistical study of SLT signatures observed with the ESR revealed complex plasma line enhancements. The data set underlying the study was obtained with an alternating code experiment with the drawback of instrumental clutter in the data. A long pulse radar experiment with high frequency resolution would be suitable to study the occurrence of enhanced Langmuir wave activity in aurora. Such an experiment is now available at the ESR including the possibility of plasma line interferometry with two receivers and ion line interferometry with EASI.

III Sounding rocket measurements

Sounding rockets experiments involving wave electric field measurements have revealed a large number of complex wave-wave and wave-particle interactions in auroral precipitation regions. Drawback of these observations is the single point nature of rocket observations leading to space-time ambiguities. With
respect to investigations of the nature of radar SLT signatures existing rocket data have another drawback which is the little coverage of the altitude region of interest. A sounding rocket equipped with free flyers to conduct multipoint measurements at 250 km altitude could significantly contribute to the understanding of naturally occurring Langmuir turbulence. Science questions to address with such an experiment would be:

- How does the turbulence spectrum look like - is it scale-free (Gaelzer et al., 2003)?
- What is the horizontal structure of the turbulence layers and its relation to the auroral arc precipitation?
- Why are SLT signatures in radar measurements narrow in altitude? Is this an instrumental effect or is the turbulence confined in altitude?
- What is the relation of the turbulence to the electron distribution function (Akbari et al., 2015)?

**IV NEIAL interferometry studies**

To date only few NEIAL events have been recorded with the EASI interferometer. The deep solar minimum in recent years was the main reason for the observational difficulty resulting in low occurrence of NEIALs during observation campaigns. The ongoing active period should be used for further observations and to increase the recorded number of NEIAL events with a sufficient Signal to Noise Ratio (SNR) in the phased array receivers. Using these observations in conjunction with supporting optical data could advance the understanding of driving mechanisms and conditions for NEIALs.
Bibliography


