Alfvén Waves and Spatio-Temporal Structuring in the Auroral Ionosphere

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The cover picture shows the time development of the ionospheric conductivity disturbance in the feedback instability in the ionospheric Alfvén resonator.

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**Abstract**

This thesis is focused on Alfvén waves (AW) and their role for the spatio-temporal structuring of the auroral ionosphere. Three directions of studies are pursued: observations of electron signatures related to AW, statistics of the occurrence of Alfvénic activity, and numerical simulations.

Observations by the Auroral Turbulence 2 sounding rocket show that the energy dispersed magnetic field-aligned electron bursts observed in a localized region at the edge of an auroral arc are periodic in time and are accompanied by AW. The frequency of 0.6 Hz suggests that the ionospheric Alfvén resonator plays a role in the process. Analysis of the electron dispersion locates their source at an altitude of several thousand kilometres. Electron signatures and small transverse scale AWs are also studied using the Freja satellite data. Two distinct energy dispersed electron populations are identified - the wide pitch angle population, often observed prior to the wave, and the field-aligned population seen inside the wavefront. A different study uses a large multi-instrument dataset to reveal the morphology of the premidnight auroral oval during substorm recovery. Periodic field-aligned current sheets are found to propagate westward, producing Pc5 magnetic pulsations on the ground. Accelerated electrons seen in the upward current sheets produce aurora. The event is interpreted in terms of standing AWs excited by substorm injected protons.

A statistical study of Astrid-2 electric and magnetic field measurements shows that extended regions of Alfvénic activity (several hundred kilometres across) constantly exist in the cusp/cleft region, and, during geomagnetically active periods, also in the night-side auroral oval.

Development of the feedback instability in the ionospheric Alfvén resonator is investigated by numerical simulations. It is shown that initial disturbances disperse into wavepackets with backward phase propagation. The spatial frequency at the leading edge of the wavepackets corresponds to the maximum group velocity of the waves in the resonator. The effect of electron collisions on the propagation of small transverse scale AWs is studied. In the presence of collisions the waves are damped and their $E/B$ ratio is modified. Competition of these two effects determines the reflection properties of the topside ionosphere.

**Keywords:** dispersive Alfvén waves, ionospheric Alfvén resonator, small scale auroral structure, auroral particle acceleration.
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The thesis is based on the following papers:


N. Ivchenko had the main responsibility for papers 1, 3, and 5-7. In paper 2 he participated in the interpretation of the data. In paper 4 his contribution was mainly to the experimental part of the paper, and discussion of the results.
Publications with contributions by the author not included in the thesis:


Chapter 1

Introduction

This thesis includes several experimental findings and numerical modelling results on Alfvén waves in the Earth’s ionosphere and magnetosphere. The experimental data presented are mainly from the Auroral Turbulence 2 sounding rocket flight and from the Swedish Astrid-2 and Freja satellites. Observations by the FAST satellite, ground-based radars, and the Polar satellite UVI imager are also used in one of the studies. Numerical simulations are carried out using a two dimensional two fluid model.

The thesis starts with a short introduction to plasma physics, magnetohydrodynamics and Alfvén waves (section 2). A brief description of the formation and main properties of the Earth’s ionosphere is followed by a discussion of two resonators for Alfvén waves - a global one bounded between the opposite hemispheres and the ionospheric one bounded between the conductive ionospheric layer and the Alfvén velocity gradient (section 3). Section 4 surveys briefly some key issues in auroral physics, and the relation of Alfvén waves and the auroral fine structure. The author’s experience gained from processing and analyzing magnetic and electric field data from the Astrid-2 and Freja satellites is summarized in section 5. The numerical model used for the simulations (similar to the one described by [Lysak and Dau, 1983]) is described in detail in Paper 6.

A brief summary of the seven papers contained in this thesis is given in Section 6, with the reproductions of the papers included at the end of the thesis.
CHAPTER 1. INTRODUCTION
Chapter 2

Alfvén waves

A plasma is a conductive ionized medium. Magnetic fields control plasmas in many intricate ways and introduce many phenomena not present in unmagnetized plasmas. At low frequencies magnetohydrodynamics is a useful framework for describing plasmas. The Alfvén wave is one of the fundamental modes in a magnetized plasma, propagating along the magnetic field with the Alfvén velocity proportional to the field strength, and inversely proportional to the square root of the mass density of the plasma. Kinetic effects introduce dispersion and parallel electric fields at small scales transverse to the magnetic field.

2.1 Plasma

A plasma is an ionized gas exhibiting collective electromagnetic interactions. This means that the electric and magnetic fields created by charge separation and currents in plasmas are strong enough to influence its dynamics. An example of collective interaction is Debye shielding, responsible for the quasineutrality of plasmas. An electric charge introduced into a plasma will attract opposite charges and reflect charges of the same sign. A cloud of opposite charge is thus created around the charge in question, shielding its electric field at distances larger than the cloud. The size of the cloud is determined by the temperature and density of the plasma:

\[
\lambda_D = \sqrt{\frac{\epsilon_0 kT}{n e^2}}
\]  

(2.1)

where \( \lambda_D \) - the Debye length, \( k \) - Boltzmann's constant, \( T \) is the temperature, \( n \) the electron density, and \( e \) the charge of the shielding species. For effective shielding the number of particles in the cloud must be large, i.e. \( n\lambda_D^3 \gg 1 \). On spatial scales larger than \( \lambda_D \) the plasma is quasineutral, with equal charge densities of positive and negative species.
A charge separation in a plasma due to different densities of positive and negative charge carriers creates an electric field acting so as to reduce the charge imbalance by accelerating the species into the regions of opposite charge. This creates plasma oscillations. The plasma frequency of each species is defined as

$$\omega_p = \sqrt{\frac{n e^2}{m_0}}$$

where \(m_0\) is the mass of the particle. The electron plasma frequency is the most relevant plasma frequency parameter, as the electrons are much more mobile than the ions.

The magnetic field introduces an anisotropy and a number of new effects into plasmas. The motion of charged particles in the magnetic field is affected by the Lorentz force \(\mathbf{F} = q \mathbf{V} \times \mathbf{B} \), \(q\) being the particle charge, \(\mathbf{V}\) the velocity and \(\mathbf{B}\) the magnetic field. In the simplest case of a homogeneous and constant in time magnetic field electrons and ions gyrate around the direction of \(\mathbf{B}\) at the cyclotron frequencies determined by

$$\omega_{ce} = \frac{eB}{m_e}$$

and

$$\omega_{ci} = \frac{ZeB}{m_i}$$

where \(Z\) is the charge number of the ion. The gyration is in opposite sense for positive and negative charges. It is interesting to note, that the magnetic field created by a gyrating particle of either charge is opposite to the background magnetic field, so that the particle has a diamagnetic effect. The radius of gyration - the Larmor radius - is determined by the particle’s perpendicular velocity: \(r_g = \omega_{ce}r_{\perp}\). The motion along the magnetic field is not affected. In more complicated situations when both electric and magnetic fields are present, or magnetic fields are inhomogeneous or time-dependent, the particles, in addition to gyrating about the magnetic field, will also drift across it.

The role of the magnetic field in controlling plasma dynamics depends on the relative strength of magnetic and non-magnetic forces in the systems. If the scale size of the system is small compared to the gyro radii of the species, magnetic field often can be neglected. Another parameter of importance is the ratio of the Larmor frequency of a species to collision frequency \(\nu\) of this species’ particles with particles of other kinds. If \(\omega_{ci}/\nu \ll 1\) then the species can be considered unmagnetized. Finally, the ratio of the thermal energy of plasma to the energy of the magnetic field, referred to as plasma \(\beta\), determines the character of the interaction between the plasma and the magnetic field. If \(\beta \ll 1\) the magnetic field configuration controls the dynamics of plasmas, whereas in the opposite case, the plasma dynamics determines the distribution of the magnetic field.
2.2 Magnetohydrodynamics

Electromagnetic processes in plasmas are governed by Maxwell’s equations:

\[ \text{div} \mathbf{E} = \frac{\rho}{\varepsilon_0} \]  
\[ \text{div} \mathbf{B} = 0 \]  
\[ \text{rot} \mathbf{B} = \mu_0 \mathbf{j} + \varepsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} \]  
\[ \text{rot} \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  

and equations describing the evolution of the charge density $\rho$ and the current density $\mathbf{j}$ in self-consistent electromagnetic fields.

The most general theoretical approach to describing plasmas is in terms of distribution functions. The distribution function of a partice species $i$ $f_i(\mathbf{r}, \mathbf{v}, t)$ gives the phase space density of particles of the species at a point in phase space $(\mathbf{r}, \mathbf{v})$ at time $t$. This approach is exact, as the distribution function can represent any discrete distribution of particles, by choosing:

\[ f_i(\mathbf{r}, \mathbf{v}, t) = \sum_j \delta(\mathbf{r} - \mathbf{r}_j(t))\delta(\mathbf{v} - \mathbf{v}_j(t)) \]  

where $(\mathbf{r}_j(t), \mathbf{v}_j(t))$ describes the trajectory of $j$-th particle in the phase space. The charge and current densities in this approach are given by moments of the distribution functions:

\[ \rho = \sum_i \int q_i f_i(\mathbf{r}, \mathbf{v}, t) \, d\mathbf{v} \]  
\[ \mathbf{j} = \sum_i \int q_i \mathbf{v} f_i(\mathbf{r}, \mathbf{v}, t) \, d\mathbf{v} \]

respectively.

The evolution of the distribution function is described by the kinetic equation:

\[ \frac{\partial f}{\partial t} + \mathbf{v} \frac{\partial f}{\partial \mathbf{r}} + \frac{q}{m} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \frac{\partial f}{\partial \mathbf{v}} = \left( \frac{\partial f}{\partial t} \right)_c \]

where $\frac{\partial}{\partial \mathbf{r}}$ and $\frac{\partial}{\partial \mathbf{v}}$ denote gradients in configuration and velocity spaces, respectively. The right hand side describes the evolution of the distribution function due to collisions.

Equations for macroscopic quantities can be obtained from the kinetic equation by taking its moments in velocity space. The quantities governed by the equations are moments of the distribution function, number density, current density, pressure tensor, heat flux tensor etc. Each of the moment equation
contains a higher order moment of the distribution function, and the system of equations can be truncated in some situations. For example, in the cold plasma limit the pressure and heat flux tensors equal zero. In other cases, if the distribution functions are close to a Maxwellian distribution, \( f \sim \exp\left(-\frac{m(v - U)}{2kT}\right) \), the heat flux can be neglected, as well as the non-diagonal elements of the pressure tensor.

For low frequency (\( \omega \ll \omega_c \)) and large scale (\( L \gg r_g \)) perturbations the moment equations are simplified further. The resulting magnetohydrodynamic (MHD) equations include the mass conservation equation:

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{U}) = 0, \tag{2.13}
\]

the momentum equation:

\[
\rho \frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla) \mathbf{U} = -\nabla P + \mathbf{j} \times \mathbf{B}, \tag{2.14}
\]

and the Ohm’s law:

\[
\mathbf{j} = \sigma (\mathbf{E} + \mathbf{U} \times \mathbf{B}). \tag{2.15}
\]

The system is completed by Maxwell equations and an energy equation (the equation of state). In the ideal MHD approximation, the plasma conductivity is assumed to be infinite, and Ohm’s law reduces to \( \mathbf{E} = -\mathbf{U} \times \mathbf{B} \).

### 2.3 MHD waves

In the framework of the equations of magnetohydrodynamics three types of waves exist: shear waves, and two branches of compressional waves: the fast and the slow magnetosonic modes. The existence of shear magnetohydrodynamical waves in conductive fluids was predicted by Alfvén, [1942].

Assuming a homogeneous background magnetic field \( \mathbf{B}_0 \) in the \( z \) direction, the linearized MHD equations lead to the dispersion relation for shear perturbations (with the wave-related magnetic and electric fields polarized perpendicularly to the background magnetic field):

\[
\omega = k_z V_A, \tag{2.16}
\]

where \( k_z \) is the component of the wavevector along the \( z \) axis, and the Alfvén velocity is given by

\[
V_A = \frac{B_0}{\sqrt{\mu_0 \rho}}, \tag{2.17}
\]

with \( \rho \) being the mass density of the medium. Both phase and group velocities are equal to the Alfvén velocity, and are directed along the \( z \) axis, meaning
that AWs are guided along the background magnetic field. In the ideal MHD limit the wave is not dispersive, i.e. the propagation is not dependent on the wavelengths along or across the magnetic field.

For a wave propagating in the positive z direction, assuming the wave magnetic field lies in the y direction, the electric field disturbance is in the z direction, and is related to \( B_y \) by

\[
\frac{E_z}{B_y} = V_A. \tag{2.18}
\]

The disturbance of the fluid velocity is in the \( y - z \) plane (which contains the magnetic field), and is antiparallel to the wave magnetic disturbance:

\[
\nu_y = -\frac{B_y}{\sqrt{\rho_0}}. \tag{2.19}
\]

This means that there is no compression related to the wave, and the fluid follows the magnetic field lines, being "frozen" to them.

The other two types of MHD waves - the fast and the slow modes - involve compression of the fluid. In the fast mode the compressional component of the magnetic field and the density disturbance are in phase, whereas for the slow waves they are in antiphase, meaning that the elastic properties of the fluid and the magnetic field add up in the former case, and work against each other in the latter case, making the fast mode velocity higher than that of the slow mode. Being compressional waves, the magnetoacoustic waves are similar to the sound waves in gases. They are not guided along the magnetic field as the AWs are, but the propagation speed depends on the angle to the magnetic field in the general case.

### 2.4 Kinetic and inertial Alfvén waves

In a plasma the transverse current in the AWs is carried primarily by the polarization drift of the ions, while the parallel current is carried by electrons. In the ideal case the divergences of the currents are balanced, and there is no parallel electric field. In the real case, kinetic effects, such as finite ion gyroradius, non-zero electron mass, and thermal effects, introduce an electric field parallel to the magnetic field, and the waves become dispersive. The two most common for the Earth’s magnetosphere cases are those where the effects of electron inertia or thermal effects dominate. The former happens in low-temperature plasmas, where the mean thermal velocity of electrons is below the Alfvén speed (this is typical for the topside ionospheric plasma up to about \( 10^4 \) km altitude). The term inertial Alfvén waves is used to refer to this special case. Higher up, the electron thermal velocity exceeds the Alfvén speed, and AWs are said to be in the kinetic regime [Slasiewicz et al., 2000].
CHAPTER 2. ALFVÉN WAVES

For a plasma with $\beta \ll m_e/m_i$ the motion of plasma electrons along the magnetic field is controlled by the parallel component of the electric field $E_1$:

$$m_e \frac{\partial v_e |}{\partial t} = -eE_1$$  \hfill (2.20)

The rate of change of the field-aligned current is thus proportional to $E_1/m_e$. If the transverse wavelength is comparable to or smaller than the electron skin depth $\lambda_e = c/\omega_{pe}$, $E_1$ becomes significant:

$$\frac{E_1}{E_\perp} = \frac{k_1 k_\perp \lambda_e^2}{1 + k_\perp^2 \lambda_e^2}. \hfill (2.21)$$

The dispersion relation of the waves is also modified at short transverse scales:

$$\omega = k_1 V_A \sqrt{1 + k_\perp^2 \lambda_e^2}. \hfill (2.22)$$

so that the phase velocity decreases. The wave is backward propagating transverse to the magnetic field.

If $\beta \gg m_e/m_i$ the parallel electric field balances the parallel electron pressure gradient:

$$E_1 = -\frac{T_e}{e n_e} \frac{\partial n_e}{\partial z}, \hfill (2.23)$$

assuming a constant electron temperature $T_e$ along the field. The factor in the right-hand side can be written as $e\mu_0 \rho_e^2 V_A^2$, where $\rho_e = c_s/\omega_{ce}$, and the sound speed is given by $c_s = \sqrt{T_e/m_i}$. The dispersion relation of the kinetic AW is:

$$\omega = k_1 \sqrt{1 + k_\perp^2 \rho_e^2}. \hfill (2.24)$$

Again, the wave becomes dispersive at scales small compared to $\rho_e$, but is forward propagating transverse to the magnetic field.

For both inertial and kinetic AWs the ratio of the wave electric to magnetic field depends on the transverse wavevector. For the inertial AW the dependence is:

$$E_\perp/B_\parallel = V_A \sqrt{1 + k_\perp^2 \lambda_e^2}, \hfill (2.25)$$

i.e. at short scales the ratio can be much larger than the local Alfvén speed.
Chapter 3

Alfvén waves in the Earth’s ionosphere

The space environment of the Earth above approximately 100 km contains partially ionized plasmas. The upper part of the Earth’s neutral atmosphere is ionized by solar radiation and cosmic rays, and, at high latitudes, by energetic auroral particles, forming the ionosphere. It is subdivided into the D, E and F layers, with different ionization sources and sinks operating in each of them. Due to the collisions of electrons and ions with the neutral atmosphere, the plasma in the E and F layers has a non-zero conductivity across the magnetic field. This leads to the reflection of downward propagating Alfvén waves. Above the F layer the ionosphere merges with the magnetosphere, the region where the dynamics of the charged particles is dominated by the geomagnetic field, which is close to dipolar at distances below about 8 \( R_E \) (one Earth radius \( R_E \approx 6400 \) km). On such closed field lines standing waves exist, captured between the reflecting ionospheres in the opposite hemispheres. A fast decrease of the plasma density with altitude in the top-side ionosphere leads to the formation of the ionospheric Alfvén resonator, bounded between the conducting ionospheric layers and the gradient in the Alfvén velocity.

3.1 Structure of the ionosphere

The atmosphere of the Earth consists primarily of molecular nitrogen (78 \%) and oxygen (21 \%) at sea level. The composition is constant up to altitudes of about 100 km, while the density decreases exponentially with a 8 km scale height (altitude difference at which the neutral density changes e-fold). Above 100 km, the turbulent mixing in the atmosphere is less efficient, and the concentration
of each of the different gases decreases with altitude:
\[
n(h) = n(0) \exp(-h/H)
\]  
(3.1)
with its own scale height \(H = kT/mg\). This relation is known as the barometric law. Atomic oxygen, formed by photodissociation of oxygen molecules becomes a major component above 150 km, and dominates up to several hundred kilometres.

The main sources of ionizations are solar EUV radiation and cosmic rays (high energy particles and gamma quanta). Formation of an ionization layer by the ionizing irradiation can intuitively be understood in the following terms, assuming one ionospheric species. The photoionization rate \(Q\) is proportional to the intensity of the radiation, and decreases downwards as the incident radiation is absorbed in the ionization. On the other hand, the number density of the neutrals decreases with altitude according to the barometric law. The competition of this two processes produces a maximum in the ion production rate. Above the maximum, the atmosphere is optically thin (transparent) for the radiation, and the decrease in \(Q\) with altitude is due to the falling density of the neutral component. Below the maximum, the atmosphere becomes optically thick (opaque), and the decrease in \(Q\) downward is due to the decay in the radiation intensity. This reasoning is summarized by the Chapman formula for the altitude dependence of the ion production rate:
\[
Q = Q_m \exp(1 - z - \sec(\chi) \exp(-z))
\]  
(3.2)
where \(Q_m\) is the maximum ion production rate, \(\chi\) is the solar zenith angle, and
\[
z = (h - h_m)/H
\]
3.1. STRUCTURE OF THE IONOSPHERE

![Diagram of the vertical structure of the upper atmosphere and the ionosphere](image)

Figure 3.2: Vertical structure of the upper atmosphere and the ionosphere ([Kivelson and Russell 1995]).

with $h_m$ is the altitude at which the maximum ion production occurs (where the optical depth is equal to unity), and $H$ is the scale height. The equilibrium electron concentration $n_e$ is determined by the balance of the ion production and losses. In a real atmosphere the situation is more complicated than the simple model described above, because several species are involved, with different ionization energies and relative abundances changing with altitude. The "sinks" for the electrons are also multiple, including radiative recombination, dissociative recombination and diffusion.

The Earth’s ionosphere has a maximum electron concentration of the order of $10^5$-$10^6$ cm$^{-3}$ at altitudes around 200-300 km. This maximum is denoted as F layer, and it is dominated by $O^+$ ions produced in the ionization of atomic oxygen by solar EUV radiation. Below the F layer there is a secondary maximum between 90 and 130 km denoted as the E layer, where $O_3^+$ and $NO^+$ ions dominate. The primary ionization mechanism here is due to the solar EUV emissions at wavelengths 100-150 nm (including the $L_\alpha$ line) and solar X-rays. Typical plasma densities are an order of magnitude lower than in the F layer, but can assume density values similar to the F region maximum at times of energetic auroral particle precipitation. At altitudes below 90 km (ionospheric D layer) ion densities are still lower, $10^3$ cm$^{-3}$. Here the ionization is mainly due to hard x-rays and cosmic rays. In this layer there are a number of ion species (including negative ions), with a complicated photochemical balance controlling their relative abundances. At night the plasma concentration in the F layer is an order of magnitude lower than during daytime, and for the E layer the decrease is even more dramatic.

Above 1000 km the composition and dynamics of plasmas become less co-
plied to the neutral atmosphere. The region, where the behaviour of the plasma is determined by the magnetic field of the Earth, is called the magnetosphere. It extends about 10 \( R_E \) in the sunward direction, where the magnetopause and bow shock separate it from the solar wind flow, and to over 100 \( R_E \) in the anti-sunward direction, where it forms a long tail. Plasma densities and temperatures in the magnetosphere cover a broad range of values in different regions. The magnetospheric particles are of mixed ionospheric and solar wind origin, and undergo a number of heating and acceleration processes. In the inner regions of the magnetosphere the magnetic field configuration is close to dipolar, dominated by the Earth’s magnetic field, whereas further away from Earth the field is controlled by the magnetospheric current systems. In the magnetotail the field lines are stretched, forming two lobes of oppositely directed magnetic fields and dilute plasmas (with densities of the order of 0.1 \( \text{cm}^{-3} \)) separated by the neutral sheet having a very weak magnetic field and a relatively dense plasma. The magnetosphere interacts with the solar wind - the supersonic plasma outflow from the solar corona. This interaction drives the magnetospheric convection, and is the ultimate energy source for the auroras. The energy input from the solar wind is most efficient when the interplanetary magnetic field is oriented opposite to the Earth dipole magnetic field ("southward"), resulting in a high geomagnetic activity level.

### 3.2 Reflection of Alfvén waves

Due to collisions of charged particles with neutrals the ionospheric plasma has finite conductivities both transverse and parallel to the ambient magnetic field. (In a collisionless plasma the parallel and transverse conductivities are formally infinite and zero, respectively). In a coordinate system where the magnetic field is along the \( z \) axis, the current density is related to the electric field by

\[
\mathbf{J} = \sigma \mathbf{E},
\]  

(3.3)

where \( \sigma \) is the conductivity tensor:

\[
\sigma = \begin{pmatrix} \sigma_P & \sigma_H & 0 \\ -\sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_\parallel \end{pmatrix}.
\]  

(3.4)

The component of the current in the direction of the electric field component perpendicular to the magnetic field is called the Pedersen current \( \mathbf{j}_P = \sigma_P \mathbf{E}_\perp \), and the component perpendicular to both \( \mathbf{B} \) and \( \mathbf{E}_\perp \) is called the Hall current \( \mathbf{j}_H = \sigma_H \mathbf{B} \times \mathbf{E}_\perp \).

In a collisional plasma the conductivities are given by:

\[
\sigma_P = \sum_{\gamma = e, i} \frac{n_e q_e^2}{m_e} \frac{\nu_e}{\nu_e^2 + \omega_{e,z}^2},
\]  

(3.5)
3.2. REFLECTION OF ALFVÉN WAVES

Figure 3.3: Vertical profiles of Pedersen, Hall and parallel conductivities [Hanson, 1965].
\[ \sigma_H = - \sum_{s = e, i} \frac{n_s q_s^2 \omega_c s}{m_s \nu_s^2 + \omega_c^2 s}, \quad (3.6) \]

\[ \sigma_I = \sum_{s = e, i} \frac{n_s q_s^2}{m_s \nu_s}, \quad (3.7) \]

Here \( \nu_s \) is the effective collision frequency of species \( s \).

For large scale currents the ionosphere can be treated as a sheet conductor, with perpendicular conductivities given by the height-integrated values:

\[ \Sigma_{H, P} = \int_{h_1}^{h_2} \sigma_{H, P} dh, \quad (3.8) \]

where \( h_1 \) and \( h_2 \) cover the height interval with the bulk of the conductive layers. The vertical profiles of \( \sigma_P, \sigma_H \) and \( \sigma_I \), as well as the integrated values \( \Sigma_P \) and \( \Sigma_H \), are determined by the vertical profiles of the plasma concentration and the collision frequencies, and vary, depending on the time of the day, solar activity, and auroral precipitation. A typical value of \( \Sigma_P \) in the dayside ionosphere is of the order of 5 S and it is mainly controlled by the zenith angle of the Sun, while on the nightside the variation is between 0.1 S and 40 S, with high conductivities in the regions of energetic particle precipitation.

If the Alfvénic impedance is not equal to the impedance of the conductive layer, Alfvén waves impinging on the ionosphere are reflected. Assuming a uniform Alfvén velocity in the magnetosphere, the reflection coefficient is given by:

\[ R = \frac{\Sigma_A - \Sigma_P}{\Sigma_A + \Sigma_P}, \quad (3.9) \]

where \( \Sigma_A = 1/\mu_0 V_A \) [Mallinckrodt and Carlson, 1978]. If \( \Sigma_A = \Sigma_P \) the wave is fully absorbed.

### 3.3 Standing MHD waves in the magnetosphere

Geomagnetic pulsations have been observed on the ground for several decades. The pulsations are classified according to the character of the field variation - continuous or irregular, and their period. The lowest frequency pulsations, with periods over 100 seconds, are the manifestation of standing Alfvén waves in the magnetosphere.

Magnetic field lines connected to Earth at both ends are called closed field lines, whereas field lines connected to Earth only at one end are called open field lines. The latter typically exist at high geomagnetic latitudes (>70°). The ionospheres act as reflecting layers for Alfvén waves. A resonator is formed between the two conjugate ionospheres on closed field lines, which can support...
standing Alfvén waves. At the ionospheres the wave electric field is small (for high conductivity conditions) and the field line length can accomodate an integer number of half-wavelengths. The fundamental frequency of the standing wave (when the field line spans one half-wavelength) is at a location determined by the length of the field line between the ionospheres and the distribution of Alfvén velocity along it. For an axisymmetric system (which is a good approximation for the dipolar inner part of the magnetosphere) this frequency is constant at lines of equal magnetic latitude ($L$ shells), and normally decreases with latitude. Typical frequencies lie in the ultralow frequency band (1-4 mHz).

The field variation in a standing wave is given by $\exp(i(m\phi - \Omega t))$, where $\Omega$ is the eigenfrequency of the resonator and $\phi$ is the azimuthal coordinate. Two polarization modes are distinguished - the toroidal mode (with $\delta B_\perp$ in the azimuthal direction) and the poloidal mode (with radial $\delta B_\parallel$). The modes decouple completely only for $m = 0$, when the toroidal oscillations exist independently for each $L$ shell, and the poloidal mode has a global nature, being trapped between the turning points at the resonant toroidal $L$ shell and the magnetopause. For non-zero $m$ the toroidal and poloidal oscillations couple [Walker et al., 1992].

The resonant pulsations are often detected in a narrow range of latitudes with

Figure 3.4: Relation between the field line length, equatorial plasma density and resonant frequency [Walker et al., 1992].
constant frequency across it, and a phase shift of about 180° centered at the latitude of the maximum pulsation amplitude. This common pattern is interpreted in terms of the field line resonance (FLR) concept [Southwood, 1974], where a generator (e.g. a Kelvin-Helmholtz instability at the flank magnetopause, or a solar wind pressure pulse impinging on the magnetosphere [Lee and Lysak, 1989, Lessard et al., 1999]) launches a compressional wave inside the magnetosphere at a certain frequency, which couples to toroidal oscillations in the vicinity of the L shell with the same eigenfrequency. The latitudinal phase shift is due to the phase lag (lead) between the driver and the driven damped oscillation on field lines with eigenfrequencies slightly off the resonance frequency. The phase decreases poleward, as the resonant frequency decreases. The azimuthal phase variation in FLRs typically shows antisunward phase propagation and relatively low m-numbers (normally below 15), consistent with a source on the flank magnetopause [Fennrich et al., 1995].

A class of long period magnetic pulsations with properties different from those of FLRs has been observed [Yeoman et al., 1992, Grant et al., 1992], having higher azimuthal m-numbers, and exhibiting westward and equatorward phase propagation instead of poleward and antisunward, and having a total latitudinal phase shift exceeding 180°. These pulsations are localized in the afternoon and premidnight sector. There is no general consensus on the nature of these waves.

3.4 Ionospheric Alfvén resonator

A jump in the impedance of a medium traversed by a wave leads to reflection of the wave. This is true not only for sharp transitions, but also for smooth gradients. In this case the reflection is distributed in space.

In the topside ionosphere the plasma density decreases monotonically above the F-layer maximum. The Alfvén speed increases until the decrease in the magnetic field starts to dominate the dependence at altitudes above 1 \( R_E \). This leads to the formation of a resonator for Alfvén waves, bounded between the conductive layer of the ionosphere and the gradient of the Alfvén speed above it [Lysak, 1991]. The resonator has no well-defined upper boundary, and is coupled to the higher altitude portions of the field line.

The spectrum of eigenfrequencies of the resonator depends on the Alfvén velocity profile, the fundamental frequency being of the order of \( \omega = H/V_{Al} \), where \( H \) is the scale height of the Alfvén velocity increase, and \( V_{Al} \) is the Alfvén velocity at the ionospheric level. For typical ionospheric conditions the fundamental frequency is 0.1-1 Hz. As the reflection at the upper boundary is distributed in space, the frequencies of the resonator harmonics are not equidistant. There are two loss processes in the resonator - imperfect reflection at the ionospheric boundary, and leakage through the upper boundary. The iono-
3.4. **IONOSPHERIC ALFVÉN RESONATOR**

![Background Density Profile](image1)

**Figure 3.5:** Vertical profile of electron density in the topside ionosphere according to satellite measurements [Hilgers, 1992]

![Reflection Coefficient](image2)

**Figure 3.6:** An example of the reflection coefficient modified by the presence of the ionospheric Alfvén resonator [Lysak, 1991]. At the resonant frequencies the reflection is worse than for low frequency AWs.
spheric losses depend on the mismatch of the impedance of the plasma and the conductive layer, while the leakage depends on frequency, the minimum value (for eigenfrequencies) being determined by the "depth" of the resonator cavity - the ratio between the values of the Alfvén velocity at the ionospheric end and at the "upper boundary". The ionospheric reflection coefficient, defined earlier as the ratio of the electric fields in the reflected and the incident waves at the magnetospheric level, becomes frequency dependent, exhibiting large deflections from the nominal value near the resonator eigenfrequencies.

The reflection properties of the ionospheric boundary of the IAR depend on the Pedersen conductivity, which, in its turn depends on the electron concentration profile. It is known that the field aligned currents change the altitude distribution of plasma density. In the regions of upward field aligned current, the electrons carrying the current increase the number of charge carriers in the conductive layer, both directly, and by additional ionization (when the electrons are accelerated to sufficiently high energies). In the regions of downward current the evacuation of ionospheric electrons creates "holes" in the plasma density [Karlsson and Marklund, 1998].

The changes in the ionospheric Pedersen conductivity due to the field-aligned currents work in two ways. Firstly, the inhomogeneity in the reflection coefficient shifts the energy in higher transverse wavevector parts of the spatial spectrum due to nonlinear interaction. Secondly, and even more importantly, in the presence of a background electric field in the ionosphere, spatial gradients in the Pedersen conductivity launch field-aligned currents upward from the ionosphere. If the phasing is appropriate, the reflected wave can be amplified by the field-aligned currents generated by the conductivity variation. This can result in the feedback instability [Lysak, 1991].
Chapter 4

Aurora and particle acceleration

Northern lights, common at high latitudes, are produced by emissions of atmospheric particles excited by high energy electrons guided by the magnetic field towards Earth’s upper atmosphere. The acceleration of auroral electrons is intimately coupled to the low number of charge carriers to carry the imposed auroral current. The most common electron populations are the inverted-V population peaking at energies of 1-10 keV and having a broad pitch angle distribution, and the supra-thermal electron bursts, mostly field aligned and often covering a broad energy range from thermal energies up to several keV. Observations and theoretical studies suggest that the latter population is related to Alfvén waves and is intimately linked to the small-scale structure in the aurora, which can be as narrow as tens of metres transverse to the magnetic field.

4.1 Aurora

The aurora is a spectacular natural light phenomenon. It is created by emissions of atoms, molecules and ions in the upper atmosphere at high latitudes (at altitudes of about 100-250 km), excited by the impact of energetic particles (electrons or protons). The most intense auroras, the discrete auroras, are created by precipitating electrons with energies of several keV. The electrons are closely guided by the magnetic field lines, resulting in the ray structure of the displays. The different colours of the aurora correspond to the transitions between different energy levels in the emitting atoms/molecules. The strongest auroral emissions are the green and red oxygen lines at wavelengths of 557.7 nm, 630.0 nm and 636.4 nm. Among other spectral components of the aurora are lines of hydrogen, nitrogen and other atmospheric constituents. Besides the
visible emissions, aurora produces spectral lines in the ultraviolet and soft x-rays. These emissions can be observed from space.

Auroras are normally observed at geomagnetic latitudes between 60 and 75 degrees, forming at any instant an oval around the magnetic pole in each hemisphere. The oval is roughly located at the boundary between closed magnetic field at low latitudes and open magnetic field lines in the polar cap (which maps out to the lobes of the magnetotail). It is in this region that the magnetospheric current systems connect by magnetic field-aligned (Birkeland) currents to horizontal ionospheric currents (Pedersen and Hall currents). The field-aligned current patterns form two concentric rings that follow the auroral oval. Discrete auroras - bright structured displays - are typically observed in regions of upward Birkeland current, carried by precipitating accelerated electrons.

The intensity and dynamics of the aurora are related to the overall geomagnetic activity. Auroras are brighter and move to lower latitudes when the energy input to the magnetosphere from the solar wind is efficient during periods of southward interplanetary magnetic field. The brightest displays are observed during magnetic storms. A magnetic storm is caused by the passage past Earth of a magnetic cloud in the solar wind, a formation with high-speed flow and strong magnetic field created by coronal mass ejections from the solar corona.

A very important phenomenon in auroral physics is the substorm. In the course of a substorm the magnetosphere undergoes a major reconfiguration, releasing the energy stored in the magnetotail towards Earth. Stretched magnetic field lines become more dipolar-like, and plasma is injected towards the Earth from the magnetotail. The auroral oval brightens up near local midnight and expands in the westward and eastward directions, after which it gradually fades. The duration of the expansion phase is usually less than an hour, and the process repeats itself with a 1-1.5 hour interval during periods of southward interplanetary magnetic fields.

4.2 Electron acceleration

In situ satellite observations have established that aurora is caused by downward accelerated electrons, often detected as so-called inverted-V structures [Frank and Ackerson, 1971] (the name originates from the appearance of the time dependence of the energy peak in such events, maximizing in the centre of the structure). The electrons typically have a broad pitch angle distribution, characteristic of the plasmasheet population, and a relatively narrow energy peak. It is now well established that the electrons are accelerated within quasistatic potential structures associated with an upward magnetic field-aligned electric field in the regions of upward field-aligned current [Mozer et al., 1980, McFadden et al., 1999]. Recently, similar structures accelerating ionospheric electrons upward have been discovered in the downward current regions, cor-
Figure 4.1: Aurora over Oulu, Finland, on March 19, 2001 (photographer P. Kekkonen).
Figure 4.2: Auroral oval seen by the UV imager onboard the Polar satellite.

Figure 4.3: "Inverted-V" auroral electrons and upward accelerated electrons in the return current region (courtesy of M. Berthomier). The top panel is the energy-time spectrogram of the electron energy flux, the two bottom panels show pitch-angle distributions in two energy ranges (0° pitch angle is downwards).
4.2. ELECTRON ACCELERATION

responding to dark regions between the auroral arcs [Marklund et al., 1994, Marklund et al., 1997, Carlson et al., 1998d]. The acceleration regions in the auroral potential structures are located at altitudes between 4000 and 15000 km, while the acceleration region in positively charged potential structures responsible for upward electron acceleration are located lower, at 1000 to 3000 km altitude.

The ultimate reason for both downward and upward electron acceleration is the lack of charge carriers at some location on the magnetic field lines when the current is imposed by the other elements in the magnetospheric current circuit. The discrete aurora, corresponding to the most energetic electron precipitation, is more common during nighttime winter conditions, when the ionospheric density is low [Newell et al., 1998]. The altitude of the acceleration regions depends strongly on the ambient plasma density, extending to lower altitudes for low plasma density conditions. The evolution of the potential structures is coupled to the time history of the associated field-aligned current, at least for the downward current regions, as suggested by multipoint Cluster measurements [Marklund et al., 2001b] showing the growth of the acceleration potential in close association with plasma cavity formation in the ionosphere.

Figure 4.4: A sketch of auroral potential structures (after Marklund et al., [1997]).
4.3 Small-scale auroral structure and Alfvén waves

Measurements of the widths of discrete auroral arcs have shown that they can be as thin as 0.1-1 km across the magnetic field [Trondsen and Cogger, 1998]. Of the many theories addressing the origin of auroral arcs [Borovsky, 1993], the theories involving the AW interactions come closest to explaining the observed thickness of the auroral structures. The scale of around 100 m corresponds to the electron skin depth in the topside ionosphere, and dispersive AWs carry a parallel electric field, which can accelerate the electrons.

Alfvén waves can be identified from the observations by analyzing the mutually perpendicular electric and magnetic field perturbations. If due to field-aligned current structures, they should be related by the Pedersen conductivity of the ionosphere, whereas if due to a propagating AW the ratio of $\delta E_\perp / \delta B_\perp$ is close to local Alfvén speed [Akiio et al., 1996]. The situation is more complicated for interfering upward and downward propagating AWs. Electromagnetic fluctuations consistent with Alfvén waves have been observed in a number of satellite and sounding rocket experiments (see a review by Stasiewicz et al., [2000a]). The dependence of the $\delta E_\perp / \delta B_\perp$ ratio on the transverse wavelength consistent with that of the inertial AWs has been reported from the Freja satellite observations [Stasiewicz et al., 2000b]. Suprathermal electron bursts often accompany the small-scale dispersive AWs, suggesting that the electrons are accelerated by the wave electric field.

Though a general consensus exists on the relation of small-scale auroral structure to the dispersive AWs, the physics of this relation is a subject of ongoing research. Several theoretical developments have been put forward in order to explain the electron acceleration in AWs. Most of the early works concentrated on the estimation of parallel electric fields, speculating on the possibility that these fields accelerate electrons to the energies of several hundred eV. Other studies approached the problem in a more self-consistent way, suggesting various scenarios for the acceleration process. A downward propagating inertial Alfvén wave front partially reflects a portion of the electron distribution function with parallel velocities below the Alfvén velocity [Kletzing, 1994]. The velocity gain for an electron is twice its velocity in the wave front reference frame, if its energy in this frame is below the parallel potential ramp in the wave front. Small amplitude wave fronts will only affect a small portion of the distribution function close to the $v_\parallel = V_A$, whereas large amplitude ones are potentially capable of accelerating the bulk of the electron distribution to velocities of twice the Alfvén velocity. Thompson and Lysak [1996] considered electron motion in a wave field in the ionospheric Alfvén resonator by following test particles with various initial conditions. Time-energy dispersions and electron conic distributions resembling the observed electron features can be obtained in this way. Another scenario is related to nonlinear breaking of AWs [Hai and Seyler, 1992], when a portion of the cold electrons is accelerated to velocities close to $2V_A$. 
Chapter 5

E and B measurements on spinning satellites

Much of the work in this thesis is based on in situ satellite measurements of electric and magnetic fields, and particle distributions in the auroral ionosphere. Processing of electric and magnetic field data from the EMMA instrument on-board the Astrid-2 Swedish microsatellite [Marklund et al., 2001a] was done at the Alfvén laboratory. Here the principle of the electric field measurements is described briefly, followed by a more detailed description of the procedure and concerns in the analysis of the data. Generally speaking, there are two reasons for having spinning satellites. The first is to stabilize the satellite attitude (the other large class of passively stabilized low-Earth orbit satellites use gravity stabilized platforms). The second reason (of importance for scientific missions with plasma and field instruments) is to use the centrifugal force from the spinning to stretch out the wire booms carrying the electric field probes. Both the Freja and Astrid-2 satellites were Sun-pointing in order to achieve the best illumination of the solar panels and to keep certain instruments in the satellite shadow. Other orientations are used too, for example the Cluster satellites have the spin plane close to being parallel to the Earth equatorial plane; whereas the FAST [Carlson et al., 1998b] and the Viking satellites use the cartwheel mode with the spin plane being close to the orbital plane.

5.1 Measurement technique

The electric field measurements on most satellite missions are carried out using the double probe technique [Fahleson, 1967]. The essence of the method is to measure the potential difference between two opposite probes extended from the satellite on the tips of booms. By dividing the potential difference with the
distance between the probes one obtains the electric field component along the
direction defined by the probe separation:

\[ E_{12}^{\text{rel}} = (U_1 - U_2)/l \] (5.1)

where \( U_1 \) and \( U_2 \) are the potentials of the probes 1 and 2 respectively, and \( l \) is
the distance between the probes.

This simple method assumes that the probes are in good electric contact with
the plasma (i.e. the potential differences between the probe and the plasma are
the same on all probes), and no disturbances are introduced into the plasma by
the satellite, booms and the probes. To achieve the latter, the booms are made
as thin and as long as possible (often realized as wires), and the satellite body
is made conducting to reduce the effects of differential charging. The former
requirement needs more illumination.

The potential of a probe in plasma is determined by a balance of currents
towards the probe:

\[ I_e + I_{ph} + I_i + I_b = 0 \] (5.2)

where \( I_e \) and \( I_i \) are the ambient electron and ion currents to the probe, \( I_{ph} \)
is the photoelectron current, and \( I_b \) is the bias current to the probe. All the
currents depend on the potential of the probe with respect to the plasma (except
the bias current, which is controlled from the satellite), the shape and surface
properties of the probe. The dependence on shape is reduced by making the
probes spherical, and homogeneous surface properties are achieved by special
treatment of the probe surface. By selecting a bias current \( I_b \) to put the working
point at the steepest part of the voltage-current characteristic of the probe the
effects of spurious current variations on the probe potential can be reduced.

The EMMA instrument on Astrid-2 for measuring the electric field consists
of four identical spherical probes (40 mm in diameter) placed 3.3 m away from
the satellite centre at the tips of wire booms. The satellite was spin-stabilized,
with the spin period being around 7 seconds, and the spin axis oriented towards
the Sun. During the first two months of the mission no bias current was fed to
the EMMA probes and for the remainder of the mission the bias current to the
probes was set to +20 nA.

The measured electric field is in the reference frame moving with the space-
craft, and differs from the Earth fixed electric field by the induction contribu-
\[ \mathbf{v} \times \mathbf{B} \], which can amount to 0.3 V/m for a low orbit satellite.

5.2 In-flight magnetometer calibration

To convert the raw data from the magnetometer into physically useful measure-
ments, they must be calibrated and transformed into geophysical coordinates.
5.2. IN-FLIGHT MAGNETOMETER CALIBRATION

The calibration is given by a matrix relating the physical and engineering units, and a vector of zero offsets:

\[ \mathbf{B} = \mathbf{C} \mathbf{B}_{\text{raw}} + \mathbf{O} \]  \hspace{1cm} (5.3)

The diagonal elements of the calibration matrix give the "scales" along the magnetometer axes, and the off-diagonal elements (sometimes called cross-talk) appear due to non-orthogonality of the sensor axes. The calibration matrix for the magnetometer is supplied by a pre-flight calibration, but it is known to change with time slightly. The improper calibration combined with the satellite rotation results in a residual spin modulation of the data. To correct for this effect, the procedure of in-flight calibration is used.

The general idea of the procedure is to use as a reference field the measured magnetic field itself, and its change of direction in the rotating satellite frame. (Normally, to calibrate a magnetometer, a set of measurements is taken with orientations of the magnetic field in the magnetometer frame covering uniformly the whole sphere of the solid angle, while the magnetic field magnitude is monitored by a precision scalar magnetometer [Menyo et al., 2000]). To carry out the in-flight calibration a calm interval in the data is selected (typically at low latitudes, far from auroral currents). A set of calibration parameters is found, for which the modulation of the magnitude of the measured signal at the spin frequency and its harmonics is minimal. This assumes a smooth variation of the actual magnetic field. The absolute scale of the signal can be determined by comparing the measured magnitude of \( \mathbf{B} \) to the Earth's magnetic field, as given by the International Geomagnetic Reference Field (IGRF).

For processing the Astrid-2 microsatellite data the calibration procedure was divided into three major steps: calibration of the axes in the spin plane (application of the offsets, scale factors and cross-talk with the spin axis), alignment of the magnetometer in the spacecraft coordinates, and application of the calibration for the spin axis component. The reason for this division is that the various groups of the components of the calibration matrix and offsets change together and/or can be easily determined together.

The alignment of the \( z \) axis of the magnetometer with the spin axis is accomplished by multiplying the magnetic field vector with a rotation matrix, describing the misalignment of the magnetometer:

\[ \mathbf{B}_1 = \begin{pmatrix} \cos \alpha_y & 0 & -\sin \alpha_y \\ 0 & \cos \alpha_z & -\sin \alpha_z \\ \sin \alpha_y & \sin \alpha_z & \cos \alpha_y \end{pmatrix} \mathbf{B}_0. \]  \hspace{1cm} (5.4)

Here \( \mathbf{B}_0 \) is the vector of magnetometer measurements after application of the calibration parameters obtained from the in-flight calibration of the axes in the spin plane. The angles \( \alpha_x \) and \( \alpha_y \) are the rotation angles around the \( x \) and \( y \) axes to align the \( z \) axis with the spin axis of the spacecraft. Typically the
Figure 5.1: Alignment angles between the magnetometer and the satellite coordinate systems. Note the changes when the satellite enters into and exits the Earth shadow (once every orbit, with the period of about 100 minutes).

Figure 5.2: Changes of the spin rate during the same time interval as in Figure 5.1. In the periods in the Earth shadow the spin frequency increases, to decrease again in the sunlight.
5.3. ATTITUDE AND SPIN RATE

angles are small, some $10^{-3}$ radian. The alignment angles change when the spacecraft goes into Earth shadow, as its inertia tensor changes due to thermal contraction of satellite parts. The opposite change occurs when the spacecraft enters sunlight again. After the axes are aligned, a correction to the in-flight calibrations, including the spin axis offset, is applied as:

$$B_2 = \begin{pmatrix} c_1 & 0 & 0 \\ 0 & c_1 & 0 \\ 0 & 0 & c_3 \end{pmatrix} B_1 + \begin{pmatrix} 0 \\ 0 \\ a_3 \end{pmatrix}. \quad (5.5)$$

All these parameters are determined from the data. In order to determine the alignment angles $\alpha_x$ and $\alpha_y$, the $z$ component of the magnetometer signal is Fourier-transformed on an interval with an integer number of spin periods. The complex Fourier coefficient at the spin frequency is related to the Fourier coefficients of the $y$ and $x$ magnetometer signals by:

$$(b_z)_{\text{spin}} = -\sin \alpha_x (b_y)_{\text{spin}} - \sin \alpha_y (b_x)_{\text{spin}}. \quad (5.6)$$

When the $z$ axis is aligned with the spin axis, the corrections to the preflight calibration for the $x$ and $y$ axes can be obtained, by requiring that the squared signal in the spin plane $b^2 = b^2_x + b^2_y$ has no modulation at the spin frequency. This would mean that the scales and the offsets on these axes are consistent, and the axes are orthonormal to the spin axis. To find the corrections to the corresponding matrix elements $\Delta c_{ij}$ and the offsets $\Delta o_i$ the deflection:

$$\epsilon = \frac{b^2}{2} - \bar{b}^2, \quad (5.7)$$

where $\bar{b}^2$ is the spin average of $b^2$, is fitted by the least square methods to the $\frac{\partial \epsilon}{\partial c_{ij}}$ and $\frac{\partial \epsilon}{\partial o_i}$. Only the components pertaining to the spin plane axes are corrected (i.e. $c_{11}$, $c_{12}$, $c_{13}$, $c_{22}$, $c_{23}$, $o_1$ and $o_2$).

The corrections to the spin axis scale $c_3$ and offset $o_3$, and the common scale for the $x$ and $y$ axes $c_1$ (see eq. 5.5) are obtained by least square fitting of the measured $b^2$ to the model $b^2_{\text{GHF}}$. The fitting is done on time intervals covering a large portion of the orbit, so that the direction of the field changes the direction relative to the spin axis significantly.

5.3 Attitude and spin rate

The attitude of the spacecraft is given by the direction of the spin axis in space and the spin phase. This information can, for example, be provided by the star camera, but can also be reconstructed from the magnetic field measurements, as this was done for the Astrid-2 satellite.

The direction of the spin axis changes slowly due to the gravity torque, and has to be corrected when necessary by attitude manoeuvres to keep it within
30 degrees from the direction towards the Sun. To determine the spin axis direction, a model of its change was used to calculate the projection of the IGRF magnetic field along the spin axis and in the spin plane in the course of several orbits. This variation was then compared to the observed $\hat{b}_2$ and $\hat{b}_3$, and the attitude model was improved iteratively by the fastest descent method.

In vacuum the angular momentum of a rotating solid body is conserved. In practice, the spin rate of a low orbit satellite decreases slowly due to the aerodynamic friction. Besides, if the moment of inertia of the spacecraft changes, the spin rate adjusts so as to keep the angular momentum constant. Variations of the inertia tensor are due to thermal contraction/extension of the satellite parts. The largest variations occur after entering the Earth’s shadow, and after exiting into sunlight. When in sunlight, the spin rate can be estimated from the sunpulses, generated whenever the sun sensor points to the Sun once every spin. Otherwise, it is possible to estimate the spin phase from comparing the measurements to the model magnetic field. This method works well in regions with small magnetic fields disturbances, whereas in auroral regions the spin phase should be interpolated through the regions where Birkeland currents flow. This is especially difficult if the spacecraft either enters or exits the Earth’s shadow in that region.

When the measurements are calibrated and the attitude information is known, the background geomagnetic field is subtracted, and the field variations due to the ionospheric and magnetospheric currents can be studied. The described processing steps apply in general for analyzing magnetometer data from sounding rockets as well. There, however, the situation is complicated by a more complex motion of the payload (beside the spinning, a sounding rocket undergoes coning...
rotation, or, in other words, the spin axis is not fixed in the payload body), and by the fact that only a relatively short (≈1000 s) interval of measurements in a region of disturbed magnetic fields is available.

5.4 Data reduction into geomagnetic coordinates

To be scientifically useful the data must be transformed into a geophysical coordinate system. For low-altitude satellites a coordinate system used frequently is the magnetic field coordinate system, while the electric field is best treated in the spin-plan related coordinate system. In the latter, referred to as the "magnetic - spin plane" (MSP), \( \mathbf{e}_3 \) is chosen along the spin axis, \( \mathbf{e}_1 \) in the spin plane along the projection of the magnetic field, and \( \mathbf{e}_2 \) completes the right-hand orthogonal set. In the field aligned coordinates, referred to as the "magnetic - east - equatorward" (MEE), \( \mathbf{e}_1 \) is along the model magnetic field, \( \mathbf{e}_2 \) is in the east direction perpendicular to the magnetic field, defined as \( \mathbf{B} \times \mathbf{R} \), and \( \mathbf{e}_3 \) completes the right-hand orthogonal basis, pointing equatorward.

The use of the MSP coordinates is motivated by the fact that the electric field is only measured in the spin plane, while the component along the spin axis is unknown. To transform the electric field data into the magnetic field related coordinate system, an assumption has to be made concerning the unmeasured spin axis component \( E_{3m,p} \). The commonly used assumption is that the electric field component perpendicular to the magnetic field is much larger than the parallel component, so that \( \mathbf{E} \cdot \mathbf{B} = 0 \). Then the third component of the electric field is

\[
E_{3m,p} = -E_{1m,p} / \tan \alpha,
\]

where \( \alpha \) is the angle between the magnetic field and the satellite spin plane. Now the full vector of the electric field can be transformed into the MEE system.

When the value of \( \alpha \) is small, the measurement of the electric field becomes difficult for two reasons. Firstly, any spurious signal is amplified by a factor of \( (\tan \alpha)^{-1} \). Secondly, when the magnetic field is close to the spin plane, the presence of the satellite body on the same field lines as the electric probes disturbs the measurements [Ivchenko et al., 2001]. In these cases, only the \( E_{2m,p} \) component of the electric field is measured reliably.
CHAPTER 5. E AND B MEASUREMENTS ON SPINNING SATELLITES
Chapter 6

Summary of the papers

Paper 1: Quasiperiodic oscillations at the edge of an auroral arc

This paper presents electric and magnetic field observations from the Auroral Turbulence 2 sounding rocket. The rocket carried three separate payloads through an auroral arc at an altitude of 500 km. Periodic fluctuations with a frequency of 0.6 Hz at the edge of the auroral arc were observed in the electric and magnetic fields on all three payloads, accompanied by bursty field-aligned particle electron precipitation. Oscillations were observed within about 7 km of the edge of the inverted-V structure. The three point measurements show that the signature is coherent at least on scales of 3 km. Two sub-regions in the oscillations can be identified in the pulsation region, the inner, with high electric field amplitudes and elliptical polarization, and the outer with smaller electric field and polarization close to linear. Based on the frequency of the fluctuations and their harmonic appearance, it is suggested that these are a manifestation of the ionospheric Alfvén resonator.

Paper 2: Multiple-point electron measurements in a nightside auroral arc

The second paper focuses on the particle data from the Auroral Turbulence 2 crossing of the same auroral arc as in Paper 1. Analysis of the timing of the particle boundaries observed on the three payloads showed that the auroral arc had a proper motion of 550 m/s in the northern direction. The time-energy dispersed field aligned electron bursts come from a source extended in altitude, with the upper boundary around 10000 km. Comparison of derived injection
times and source altitudes between the payloads is used to estimate the motion of the electron bursts along the arc. The velocity of the structures along the arc separates two distinct regions, with westward and eastward motion respectively. This is in general consistence with the variation of the DC electric field at the edge of the arc.

**Paper 3: Low frequency electromagnetic activity at 1000 km altitude**

This paper presents a statistical study of the occurrence of low frequency (below 8 Hz) electromagnetic disturbances at 1000 km altitude, as observed by the Astrid-2 microsatellite. The database consists of over 1000 auroral oval crossings during 6 months of 1999. It is shown that large (several hundred kilometres across) regions of broadband Alfvénic activity are persistently observed in the cusp/cleft region, and, during geomagnetically active periods, in the pre-midnight sector of the oval. Small regions of electromagnetic disturbances are seen throughout the oval with a tendency to follow the average distribution of the upward current region. During periods of high geomagnetic activity both the extended and the smaller scale regions of Alfvénic activity shift to lower latitudes. The observed ratios of $\delta E/\delta B$ are generally higher at the nightside, and during the winter conditions, than they are in the dayside ionosphere, and during the summer.

**Paper 4: Electron signatures and Alfvén waves**

In this paper Freja observations of particles, and electric and magnetic fields are analyzed in detail for a number of events when small-scale Alfvén waves were observed concurrently with time-dispersed electron signatures. Two distinct populations are identified in the dispersed signatures - a population with a broad pitch angle distribution, often observed before the main disturbance in the electric and magnetic fields, and a field-aligned population, coinciding with the field disturbance itself. Tracing of the energy and pitch angle dispersion to the source show that the two distributions originate from different source altitudes. A simplified model of electron acceleration by Alfvén waves is used to reproduce the observed signatures.
Paper 5: Pc5 pulsations during substorm recovery

This paper presents a multi-instrument study of a geomagnetic pulsation event observed in the evening sector of the auroral oval during a substorm recovery. The structure in the auroral oval was investigated using in situ satellite measurements, ground-based coherent scatter radar data, and auroral imaging from the ground as well as from space. Quasi-periodic geomagnetic pulsations with a period of 10 minutes were observed on the ground in the geomagnetic latitude range between 70 and 75 degrees in the northern hemisphere. Radar data showed spatially quasi-periodic, westward propagating patches of alternating flows in the same latitudinal band. Several simultaneous satellite crossings of both the southern and the northern auroral ovals revealed a periodicity in the field-aligned currents and the accompanying electron fluxes. The Polar UV imager showed westward propagating patches at the poleward edge of the northern auroral oval, and a ground-based all-sky camera detected periodic brightening of the aurora, propagating equatorward. The picture emerging from all the datasets is that spatially periodic current sheets extending from NW to SE (SW to NE) covered the entire oval width in the northern (southern) auroral oval. The current sheets propagated westward and equatorward, producing magnetic pulsations on the ground. In the upward current regions accelerated electrons were present, with energies sometimes exceeding 1 keV, and energy fluxes capable of producing aurora. Field-aligned electron bursts accompanied by electromagnetic disturbances (similar to those described in Papers 1 and 2) were detected at the edges of the current sheets. The event is interpreted as resonant Alfvén waves excited by the westward drift of substorm-injected protons.

Paper 6: Simulations of feedback instability

This paper presents the model and the first results of the simulation of the feedback instability in the ionospheric Alfvén resonator. At short transverse scales the behaviour of the instability is determined by the dispersion properties of the resonator. A dispersive wave train is formed in the transverse to the magnetic field direction, propagating in the direction opposite to the large scale electric field. The phase velocity of single spatial components is opposite to the group velocity. At the leading edge of the wave train the spatial scale is that which corresponds to the maximum group velocity, while both smaller and larger scales lag behind. In the original formulation the instability grows fastest for the shortest transverse wavelengths. In the real ionosphere a number of processes suppresses the growth at the shortest scales.
CHAPTER 6. SUMMARY OF THE PAPERS

Paper 7: Reflection of small-scale Alfvén waves

The final paper addresses the question of reflection of small transverse scale Alfvén waves from the ionosphere. The dispersion relation for Alfvén waves in a cold plasma in the presence of electron and ion collisions shows that for wave frequencies below the electron collision frequency, the effect of parallel resistivity dominates over electron inertia. Applied to the Earth’s ionosphere this means that the collisional dispersion relation should be used under about 1000 km. At large electron collision frequencies, the $E/B$ ratio exceeds that of the inertial Alfvén waves. As the electron collision frequency increases downward, waves with perpendicular scales between 10-100 electron inertial lengths can be partially reflected from the collisional region of the ionosphere, before they reach the conductive E and F layers in the ionosphere. Waves with shorter transverse scales are strongly damped, and are not reflected. A numerical simulation is used to illustrate this effect.
Bibliography


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