Decameter scale irregularities in the polar ionosphere

Master Thesis

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Abstract

From the Sun to the Earth’s upper atmosphere, particles and energy are transported through several key processes. Many of these we know well, and some we are still learning about. In this thesis we will study one of the last processes the energy takes part in before dissipating in the upper atmosphere, namely the production of deca-meter scale irregularities in the high latitude ionosphere.

We make use of NorSat-1, the Longyearbyen SuperDARN radar and ground-based magnetometers and All-Sky Camera to conduct a case study on the difference in ionospheric conditions and structures between a period of low backscatter and one with significant backscatter.

The SuperDARN backscattered signal comes from regions where the emitted, and later refracted, signal hits the geomagnetic field lines in the ionosphere perpendicularly. The amount of backscattered signal can vary significantly from one day to the next, even though the general conditions in the ionosphere should be similar for the two periods. The structure of the plasma being hit by the signal has been shown to be important, and to see this and build on the knowledge we need accurate, small scale measurements of the electron density in the ionosphere. NorSat-1’s m-NLP instrument is capable of sampling the density at 1 kHz sampling frequency and will give us down to decameter scale measurements of the irregularities. Combining this with the SuperDARN radar network we explore the differences between one period of minimal backscatter and one with significant backscatter. Through Fourier analysis we find that NorSat-1 encountered more structures of all measurable scale sizes during a pass through backscatter, as compared to a pass through the same location with no backscatter. This is found as evidence for the energy cascade model stating that energy is transported through decreasingly sized structures in turbulent flows. In relation to this we use results from previous studies on the matter to discuss the role of the KH and GD instabilities in the production of deca-meter scale irregularities in the polar ionosphere.

More research on this subject is encouraged, as a statistical analysis is necessary for any strong conclusion to be made.
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1 Introduction

Space around Earth, near-Earth space, is much like the atmosphere divided into different parts. The broadest division is between the ionosphere and the magnetosphere, but we can further subdivide these spheres into regions such as the plasmasphere, being the lower part of the magnetosphere, the tail lobes found on the nightside of Earth, the cusp found at high latitudes on the dayside, and so forth. All of these regions are connected, and they interact through exchange of momentum, energy and mass. They have in common that they are all within the boundaries of the magnetic field of Earth, the geomagnetic field, outside of which we find interplanetary space. Although often believed to be empty, this region of our solar system is relatively dynamic, filled with particles traveling radially outward from the Sun. It is this solar wind that transports the energy ultimately manifested as northern and southern lights here on Earth, and which fuels the processes discussed in this thesis.

The part of near-Earth space directly above the atmosphere is called the ionosphere. This region begins about 90-100 km above the surface of Earth, and stretches to beyond 1000 km. The name comes from the fact that gas occupying this region is partly ionized through processes like photo-ionization and collisions with high-energy particles. Ionized gas, plasma, interacts with electromagnetic fields and waves, which means it interferes with our main type of communication: satellites. When an electromagnetic signal is sent from a satellite, it has to travel through the ionosphere before it reaches the ground, and during this voyage it will be disturbed. When it comes to GPS signals guiding ships and aircraft to their destination or any service in need of precise coordinates, this disturbance can cause major problems, and the ability to correct for such disturbances is highly valued. For most signals, however, like a phone call or any online map service using any approximate location, this disturbance is rarely of any concern. There are ways to correct for these disturbances in the ionosphere, but to do this we need more detailed knowledge of the origin and behavior of the observed irregularities creating the disturbances. Just as with signals from a satellite, electromagnetic signals from radars on the ground are affected by ionospheric plasma. Using high frequency (HF) signals, it is possible to use the refractive properties of the ionosphere in order to detect deca-meter scale irregularities in the plasma electron density. This is done by the signal scattering off structures and returning to the radar.

After investigating the mechanisms by which radar echoes are generated in the cusp region, Moen et al. (2002)\textsuperscript{17} reported a collocation of high frequency (HF) radar backscatter and auroral precipitation in the cusp. It was proposed that the initial source of the decameter scale features responsible for the backscatter may be a result of fine structures within the precipitation itself, or alternatively from unstable intermediate-scale gradients created in the turbulent plasma. Furthermore, studies have been done on in-situ measurements of HF radar backscatter targets using rockets. Moen et al. (2012)\textsuperscript{16} reported deca-meter scale irregularities being created at kilometer scale electron density gradients in the cusp region of the ionosphere. The ICI-2 (Investigation
of Cusp Irregularities 2) rocket used in the campaign encountered an electron density structure created by precipitating particles. Further investigation into the ICI-2 data was done by Oksavik et al. (2012)[18]. This study looked into the growth rates of the Kelvin-Helmholtz (KH) and the gradient drift instabilities (GDI) in order to determine which of the two dominates. The KHI growth rate was found to be too slow, and the GDI thus dominating the production of the observed irregularities. In addition, due to the timing of strong irregularities versus enhanced aurora, a two-step generation process was proposed. In this, structured precipitation create large-scale irregularities, which the GDI then efficiently break down into deca-meter scale irregularities.

In his excellent master thesis, Spicher (2013)[28] studies ICI-2 measurements in the context of turbulence in the ionosphere. His results also strongly suggest the GDI as being the dominant mechanism for the generation of the observed irregularities. This strengthens the results published by Moen et al. (2012)[16] and Oksavik et al. (2012)[18].

Through the above studies we have strong evidence of ionospheric instabilities being the main producer of electron density irregularities responsible for HF radar backscatter. However, a comparison to periods of low backscatter intensity is lacking, as the above studies are done using rockets during a specific event in the cusp region. It is interesting to know whether the irregularity production is equally high during periods of low HF backscattered power. Therefore, a study on the differences in ionospheric conditions between high intensity HF backscatter and low intensity backscatter time periods is conducted using two passes of the NorSat-1 satellite.

This thesis seeks to be a step towards an increased understanding of ionospheric irregularities. We will look closer at a case study regarding differences in the ionospheric structures present during a few minutes in the early morning on the 23rd and 24th of January 2018 in the high latitude polar cap region. The two time intervals have significant differences in the amount of backscatter detected by the Longyearbyen SuperDARN radar described in section 3.1. We study electron density data from NorSat-1 in relation to the HF backscatter, in an attempt to find structural differences on deca-meter to kilometer scales in the ionosphere between the two dates.

The text will go through the theoretical basis needed to follow the physics discussed in the thesis. We start with basic plasma physics and introduce single particle motion as a way of describing the motion of individual plasma particles. We then define a fluid description of plasma, called magnetohydrodynamics, which is a central part of space physics. We need these theories in order to understand how plasma behaves in the magneto- and ionospheres. We then go through the journey of a plasma particle from the Sun to the upper atmosphere of Earth, touching onto the coupling between the magnetosphere and the ionosphere, and the aurora. From there we proceed to the Orbital-Motion-Limited theory, describing the environment around an object submerged in plasma. The theory part of the thesis ultimately takes us to instabilities and turbulence in
the ionosphere, in an attempt to understand where the observed irregularities originate.

The next section deals with the instruments used to gather data for the analysis. We write first about the Super Dual Auroral Radar Network (SuperDARN), and specifically the Longyearbyen SuperDARN coherent-scatter radar, before describing the NorSat-1 satellite and the Multi-Needle Langmuir Probe (m-NLP) instrument it carries onboard. The common fluxgate magnetometer is described and we mention the Sony All Sky Camera at the Kjell Henriksen Observatory.

We then describe the method used to analyze the satellite and radar data. An overview of the written scripts is given, and we look closer on the locations and geographic boundaries of the events.

From there we go on to observations. The end products of the analysis is described through figures, and we paint a picture of the ionospheric conditions during the two times of interest.

Lastly, we discuss what we have found and conclude the thesis.
2 Theoretical Background

This section seeks to give the theoretical background necessary to understand the scope and discussions made in the thesis. Starting with a definition of plasma before describing two different ways of calculating the motion of plasma particles. We then follow the plasma on its voyage through the solar system and see how it ends up in our upper atmosphere. Lastly we visit the theory of probes submerged in plasma and the theoretical origin of ionospheric irregularities. A certain knowledge of basic physics and calculus is expected from the reader.

First, a quick overview of terms and names frequently used in space physics and in this text.

\textit{Table 1: Frequently used terms in space physics and this thesis.}

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Plasma</td>
<td>Ionized gas subject to electromagnetic forces</td>
</tr>
<tr>
<td>Magnetosphere</td>
<td>The volume of space influenced by Earth’s magnetic field</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>The ionized part of the upper atmosphere (&gt; 90 km)</td>
</tr>
<tr>
<td>IMF</td>
<td>The Interplanetary Magnetic Field</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Energetic particles colliding with the upper atmosphere</td>
</tr>
<tr>
<td>Backscatter</td>
<td>Electromagnetic radar signals scattered back from targets</td>
</tr>
<tr>
<td>Polar Cap</td>
<td>High latitude region of open magnetic field lines</td>
</tr>
<tr>
<td>Frozen-in</td>
<td>Plasma and magnetic field lines stick to each other</td>
</tr>
<tr>
<td>Reconnection</td>
<td>An abrupt change in local magnetic topography</td>
</tr>
<tr>
<td>NorSat-1</td>
<td>Norwegian scientific satellite</td>
</tr>
<tr>
<td>m-NLP</td>
<td>multi-Needle Langmuir Probe</td>
</tr>
<tr>
<td>SuperDARN</td>
<td>High Frequency radar network monitoring high latitudes</td>
</tr>
</tbody>
</table>
2.1 Definition of a plasma

Plasma is ionized gas made up of both electrically neutral and charged constituents, most commonly free electrons and protons. To ionize a gas it is essentially enough to heat it to a certain temperature where the electrons can be considered free. This condition is met when the particle’s typical potential energy due to its nearest neighbor is much smaller than its random thermal energy (Baumjohann, 1997) \[1\]. The movements of charged particles in a plasma are largely dependent on their neighbors due to the nature of electromagnetism, and less so on other forces like gravity due to the particle’s small mass. This is especially true near Earth, and less true near more massive bodies like the Sun. For near-Earth space physics then, gravity can often be neglected. Although only a few natural plasmas can be found near the surface of Earth, such as flames and lightning strikes, plasma is the most abundant state of matter in the universe with more than 99% of all observable matter falling into the plasma category (Baumjohann, 1997) \[1\].

There are differences between neutral gases, simply ionized gases and proper plasmas. The so called plasma criteria are the following:

1. \( \lambda_D << L \)
2. \( \Lambda = n_e \lambda_D^3 >> 1 \)
3. \( \omega_{pe} \tau_n >> 1 \)

where \( \lambda_D \) is the Debye length, \( L \) is the physical size of the system, \( \Lambda \) is the plasma parameter, \( n_e \) is the plasma density, \( \omega_{pe} \) the plasma frequency and \( \tau_n \) is the time between two electron-neutral collisions.

The first plasma criterion tells us that the physical scale of the system needs to be much larger than the Debye length for quasineutrality to hold. A quasineutral plasma has roughly the same amount of positively and negatively charged particles and appears electrically neutral for an outside observer. In practice, this happens when the electric Coulomb potential field of every charge, \( q \), is shielded by other charges in the plasma and assumes the Debye potential form:

\[
\Phi_C = \frac{q}{4\pi \varepsilon_0 r} \quad \Rightarrow \quad \Phi_D = \frac{q}{4\pi \varepsilon_0 r} \exp \left(-\frac{r}{\lambda_D}\right) \tag{1}
\]

where \( \varepsilon_0 \) is the permittivity of free space. From the above equation it is clear how the Debye length determines where the Debye potential field is cut off \((r > \lambda_D)\). The Debye length is dependent on the plasma temperatures and density, and is given as

\[
\lambda_D = \left(\frac{\varepsilon_0 k_B T_e}{n_e e^2}\right)^{1/2} \tag{2}
\]
If this length is not much smaller than the physical size of the system, $L$, there is not enough space for the shielding effect to occur, and we will not have a plasma but a simple, ionized gas.

The second plasma criterion involves the number of particles contained in a sphere with radius $\lambda_D$ (a Debye sphere). It is vital that there are enough particles within such a sphere since the shielding effect simply does not work with too few particles. The number of particles within a Debye sphere is $\frac{4\pi}{3}n_e\lambda_D^3$ and the second criterion states that the plasma density per Debye sphere must be much greater than one, or $n_e\lambda_D^3 >> 1$.

The typical oscillation frequency of a fully ionized plasma is the plasma frequency

$$\omega_{pe} = \left( \frac{n_e e^2}{m_e \epsilon_0} \right)^{1/2}$$

with the subscript $e$ denoting electrons.

If an external force is exerted on the plasma, and the quasineutrality is disturbed, the electrons, having a much smaller inertia than the heavier ions, are accelerated in an attempt to restore the charge neutrality resulting in an oscillating motion around an equilibrium position. If the plasma is not fully ionized and we have neutral particles present, the electrons might collide with those particles and end up in an equilibrium with the neutrals. This is an example of what can happen in the lower ionosphere, where the plasma is only partially ionized. For the electrons to be regarded as unaffected by this, the average time between collisions must be much smaller than the plasma frequency. If the opposite where to be true and the electrons fall into equilibrium with the neutrals, the plasma would behave like a neutral gas. Hence, the third plasma criterion is as stated above $\omega_{pe}\tau_n >> 1$.

An important issue to discuss is how electromagnetic waves interact with plasma particles and how this interaction alters the wave. Any electromagnetic wave is affected when passing through a plasma. When the wave hits the free electrons, these will oscillate around an equilibrium position. They are held in place by a restoring force set up by the resulting polarization field that arises when the electrons move in relation to the ions. The ions themselves are so heavy that their movement can be neglected in comparison to the movement of the electrons. The electron oscillation frequency is what we call the plasma frequency, given by equation [3]. The oscillating electrons, being charge carriers, will themselves emit electromagnetic radiation, and these secondary waves will be superimposed on the main wave, changing its behavior. This is the refractive property of the ionosphere. The main electromagnetic wave is evidently affected by having its propagation direction, velocity and amplitude changed. How much these characteristics are altered depends on the wave frequency and the electron density.

When dealing with this type of refraction the Appleton-Hartree equation is worth mentioning. The equation describes the refractive index for an electro-
magnetic wave propagating in a plasma. In essence, the equation is as follows

\[ \eta^2 = 1 - x^2 \]  

where \( \eta \) is the refractive index and \( x \) is some given function dependent on the plasma frequency. As we know from above the plasma frequency depends on the electron density, and thus the refractive index depends on the electron density. As we shall see later in the thesis, the electron density in the ionosphere changes with altitude, which causes the electromagnetic waves to bend and change direction. This is in appliance with Snell’s law, stating that any electromagnetic wave experiencing a change in refractive index has its direction changed. This has obvious consequences for radar signals, and the Appleton-Hartree equation and Snell’s law are both key parts in how we measure backscatter from the ionosphere.

### 2.2 Single Particle Motion

An electrically charged particle is affected by any present electromagnetic field. This includes electric forces from nearby charged particles and background magnetic fields. A moving charge carrier like an electron can be viewed as a small current element, and through Maxwell’s equations we know that currents produce magnetic fields. So any moving, charged particle is contributing to the total field in its vicinity, while also being strongly affected by it.

Through Newton’s second law we can write for the motion of a charged particle in a magnetic field:

\[ m \frac{d\vec{v}}{dt} = \vec{F} + q \vec{v} \times \vec{B} \]  

with \( m \) as the mass of the particle, \( \vec{F} \) an external force and \( q \vec{v} \times \vec{B} \) the Lorentz force describing moving charge carriers. We separate the above equation into components parallel and perpendicular to the magnetic field

\[ m \frac{d\vec{v}_\parallel}{dt} = \vec{F}_\parallel \]  

\[ m \frac{d\vec{v}_\perp}{dt} = \vec{F}_\perp + q \vec{v}_\perp \times \vec{B} \]

where the Lorentz force in the parallel equation vanishes because the vectors point in the same direction. The perpendicular equation is a differential equation, and has several solutions depending on the configuration of the magnetic field. As stated by Prölls (2004)\[20], the motion of the particle can be broken down into its individual components, which are nearly independent of each other because they evolve at very different time scales. We shall look closer at the components corresponding to gyration, bounce and drift.

In a uniform magnetic field, with \( \vec{F}_\perp = 0 \), electrons and ions will gyrate, meaning they move in a circle around a guiding center. The magnetic force
(Lorentz force) on the right side of equation\[7\] will accelerate the particle toward the guiding center, and must be balanced by a centrifugal force for energy to be conserved. From this we can derive the so called \textit{gyro radius}, $r_g$

$$|q|v_\perp B = m \frac{v_\perp^2}{r_g} \Rightarrow r_g = \frac{mv_\perp}{|q|B} \tag{8}$$

Further we can calculate the gyration period, $\tau_g$, and the \textit{gyrofrequency}, $\omega_g$

$$\tau_g = \frac{2\pi}{v_\perp r_g} \Rightarrow \omega_g = \frac{2\pi}{\tau_g} = \frac{|q|B}{m} \tag{9}$$

So far we have been looking at charged particles in a homogeneous magnetic field with no other external forces. We now include a non-zero force, $\vec{F}_\perp$, perpendicular to the magnetic field. Assuming a particle starting at rest, it will be accelerated in the direction of $\vec{F}_\perp$. As the particle moves it feels the magnetic field and gyrates because of this. Since the direction of movement changes, the particle will inevitably move against the external force at some point in its gyration. This decelerates the particle and ultimately turns it back in the direction of $\vec{F}_\perp$. This is the same situation we had before, only now the particle has moved away from its starting position. This lateral shift is what we call drift. We shall next derive the drift velocity, and take a closer look on the situation when the external force is an electric field. This will give us the expression for the $\vec{E} \times \vec{B}$ drift velocity.

To find the drift velocity we first assume the gyration of the particle is constant, which implies that the drift velocity is constant. In other words, the time average of the particle velocity equals the drift velocity. For this to be true, the magnetic and external forces must cancel when averaged over time (Prölls (2004)[20]), and we can write the following equation.

$$\langle \vec{F}_\perp + q\vec{v}_\perp \times \vec{B} \rangle = \vec{F}_\perp + q\vec{v}_D \times \vec{B} = 0 \tag{10}$$

The trick now is to cross both sides by $\vec{B}$

$$\vec{F}_\perp \times \vec{B} + q \left( \vec{v}_D \times \vec{B} \right) \times \vec{B} = 0 \tag{11}$$

and use the vector identity $(\hat{c} \times \hat{b}) \times \hat{a} = (\hat{a} \cdot \hat{c})\hat{b} - (\hat{a} \cdot \hat{b})\hat{c}$. Through this the second term of equation\[11\] turns into $(\vec{B} \cdot q\vec{v}_D)\vec{B} - (\vec{B} \cdot \vec{B})q\vec{v}_D$. Remembering that $\vec{v}_D$ is a velocity perpendicular to $\vec{B}$ it follows that the first term equals zero, and we are left with

$$\vec{F}_\perp \times \vec{B} - q\vec{v}_DB^2 = 0 \tag{12}$$
which leads us to an expression for the drift velocity

\[ \vec{v}_D = \frac{\vec{E}_\perp \times \vec{B}}{qB^2} \]  

We see from the above equation that the drift velocity is usually dependent on the charge of the particle. In this general case this means the electrons and ions drift in opposite directions, consequently creating a current. Notice that the drift velocity is not dependent on the particles mass.

When we now assume the external force is an electric field, \( \vec{F}_\perp = q\vec{E} \), equation 13 turns into

\[ \vec{v}_D = \frac{\vec{E}_\perp \times \vec{B}}{B^2} \]  

which is not dependent on charge. This is the \( \vec{E} \times \vec{B} \) drift velocity. In a collisionless plasma it is not associated with a current, since the electrons and ions drift in the same direction with the same drift velocity. Figure 1 shows an illustration of the situation.

Since Earth’s magnetic field is dipole-like, a uniform magnetic field is not a good approximation for charged particles in near-Earth space. When we introduce a gradient in the magnitude of \( \vec{B} \), \( \nabla B \), we get two more components to the motion of the particle, namely the gradient drift and bounce motions. These arise when the gradient is directed perpendicular or parallel to the magnetic field, respectively.

Consider a gradient in magnetic magnitude directed perpendicular to the field itself, \( \nabla B \perp \vec{B} \). A particle gyrating around a field line will experience a different intensity in \( \vec{B} \) during different parts of its gyration. From equation 8 we see how the radius is dependent on the magnitude of \( \vec{B} \), meaning the particle will change its gyroradius throughout its motion, having a larger radius where the magnetic field is weaker. This results in a drift motion where the guiding center of the particle drifts in a direction perpendicular to both \( \vec{B} \) and \( \nabla B \). The expression for the gradient drift is the following
 excellently derived by most introductory books on plasma physics, e.g. Baumjohann (1997)[1] and Prößl (2004)[20]. From the above equation it is clear how the gradient drift is dependent on the charge of the drifting particle. This means the ions and electrons drift in different directions, creating a current. Notice also how the gradient drift is proportional to the particles perpendicular kinetic energy, $E_{k\perp} = \frac{1}{2}mv_{\perp}^2$. This can be used to define the magnetic moment as the ratio between the kinetic energy and the magnetic field

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

which we will now use in the derivation of the mirror force responsible for the bounce motion of the particle.

Before describing a magnetic mirror, we define the so called pitch angle. This describes the inclination angle between a moving particle and the magnetic field, when the velocity of the particle contains both a perpendicular and parallel component. It is defined as $\alpha = \tan^{-1}\left(\frac{v_{\perp}}{v_{\parallel}}\right)$ (Baumjohann, 1997) [1]. The pitch angle essentially tells us how much of the total velocity of the particle is directed along the magnetic field.

With a gradient in the intensity of the magnetic field directed along the field lines, $\nabla B \parallel \vec{B}$, a particle gyrating toward increasing magnetic magnitude will feel a mirror force, $\vec{F}_M$, directed in the opposite direction

$$\vec{F}_M = -\frac{E_{k\perp}}{B} \nabla B = -\mu \nabla B$$

with $\nabla B$ denoting the gradient parallel to $\vec{B}$ (Baumjohann (1997)[1], Prößl (2004)[20]).

We have now introduced different components of the motion of a charged particle in an inhomogeneous magnetic field. A plasma particle in the ionosphere and magnetosphere will gyrate, drift and bounce its way around Earth, and its exact trajectory is complicated.

To accurately describe a plasma by single particle motion it is necessary to calculate the position, velocity and acceleration of every plasma particle at any given time, take into consideration collisions with neutral particles, background electromagnetic fields and the interaction between a particle and all of its neighbors. It is clear that this requires an immense amount of computing power and is in most cases not a viable option. Considering also that a plasma is not just a few particles, but rather a large collection of them, it is a natural option to describe it as a fluid, which is what we will be describing in the next section.
2.3 Magnetohydrodynamics

Magnetohydrodynamics (MHD) is the description of a plasma as a fluid. In this
theory we will look at macroscopic changes in various parameters of a plasma
packet rather than the motion of single particles. MHD is derived from fluid
mechanics with applied electromagnetism and has proved to be a rigid tool for
space physicists.

In order to describe a plasma through MHD it is necessary to introduce a
set of equations. In the simple case of ideal, incompressible MHD we consider
the plasma as one continuous medium with infinite conductivity, cold and not
magnetized. As with other gases, we describe the plasma through Navier-Stokes
equations, a continuity and a momentum equation. In addition we need to make
use of Maxwell’s equations in order to describe the electromagnetic terms and
obtain a closed set of equations. We begin with an equation of state. For ideal,
incompressible MHD this becomes

\[ \nabla \cdot \vec{v} = 0 \quad (18) \]

When assuming no creation or loss of particles, and using the above equation
of state, our continuity equation becomes

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\vec{v} \rho) = \frac{\partial \rho}{\partial t} + \vec{v} \cdot \nabla \rho = 0 \quad (19) \]

where \( \rho \) is the mass density and \( \vec{v} \) is bulk flow velocity. As we assume the plasma
behaves like a fluid with electromagnetic properties, we can for our momentum
equation use a Navier-Stokes equation

\[ \rho \left( \frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} \right) = -\nabla p + \vec{J} \times \vec{B} \quad (20) \]

where \( \nabla p \) is a pressure gradient and \( \vec{J} \times \vec{B} \) is a force density originating from
the fact that currents in the plasma creates magnetic fields which will affect
the plasma. The force due to gravity is neglected as we assume a proximity to
Earth (see explanation in section [2.1]), in which case the electrons and ions in
our plasma are too light. If we extend our research to e.g. near the Sun, gravity
would need to be included.

To get a closed set of equations, we need to introduce the Maxwell equations
and Ohm’s law (equations [21][24] and [25]). These link the electric fields, magnetic
fields and currents.

\[ \nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0} \quad \text{(Gauss' law for electricity)} \quad (21) \]

\[ \nabla \cdot \vec{B} = 0 \quad \text{(Gauss' law for magnetism)} \quad (22) \]

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \text{(Faraday's Law)} \quad (23) \]
\[ \nabla \times \vec{B} = \mu_0 \vec{J} \quad \text{(Ampère's Law)} \]  

In Ampère’s law above we have neglected the displacement current. We can do this because we assume \( \frac{\dot{E}}{c^2} \ll 1 \), that is the fluctuations of the electric field is a lot smaller than the square of the speed of light, \( c \). In addition to those we need a manipulated Ohm’s law where we use the assumption regarding infinite conductivity to force the currents to stay finite

\[ \vec{J} = \sigma (\vec{E} + \vec{v} \times \vec{B}) \quad \Rightarrow \quad \vec{E} = -\vec{v} \times \vec{B} \]  

where \( \sigma \) is the conductivity.

Magnetohydrodynamics describe the interaction between magnetic fields and conductive fluids. It is the basis for most of space and plasma physics, and we will need it later in the thesis to understand the movement of plasma packets from the Sun to the ionosphere. Furthermore, in the next section we will visit the frozen-in concept, a consequence of ideal MHD described above. This is a central part of our assumption that we can detect the same wavelength structures at two different altitudes in the ionosphere.

### 2.4 Frozen-in

The frozen-in theorem is a consequence of ideal MHD, discussed in the previous section, where the assumption of infinite conductivity implies that there are no electric fields in the frame moving with the plasma. This can also be seen from equation (25). Slightly rewritten we get \( \vec{E} + \vec{v} \times \vec{B} = 0 \) from which we can state that any electric field component parallel to the magnetic field must vanish (Baumjohann (1997) [1]). Another consequence of frozen-in is that in non-diffusive plasmas any plasma packet on a given magnetic field line will find itself on the same field line at a later time. Even through translation and distortion of the magnetic field, the plasma particles will follow. Thus in our assumptions the plasma particles are only able to move along the field lines, although they are allowed to gyrate in the perpendicular direction, as described in section 2.2 on single particle motion. The assumption of infinite conductivity is a good approximation in most space plasmas.

### 2.5 The Solar Wind

Dynamic as it is, our Sun is constantly flinging high-energetic charged particles into the solar system in all directions. In addition to this the Sun’s magnetic field extends far into the solar system and is often known as the Interplanetary Magnetic Field (IMF). The particles in the solar wind are closely tied to the magnetic field, unable to move across the magnetic field lines. The physics behind this phenomenon, the frozen-in concept, is explained in section 2.4. In this section we will look at key parameters of the solar wind, and explain how it interacts with the geomagnetic field, ultimately being the source of energy.
for the ionosphere. Although the solar wind can display large fluctuations in its parameters, the mean values gives a good picture of how it behaves. Solar wind plasma mostly comprises protons (Hydrogen nuclei) and electrons, with a few α-particles (Helium nuclei) present as well. The densities of protons and electrons are approximately equal each other, at 6 particles per cubic centimeter, and the temperature is on the order of $10^5$ Kelvin. This hot, dilute plasma travels outwards from the Sun with a mean velocity of about 470 kilometers per second (Prölls (2004)[20]).

Table 2: Mean values of solar wind parameters. Adapted from Prölls (2004) [20]

<table>
<thead>
<tr>
<th>Composition</th>
<th>96% H⁺, 4% He²⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>6 cm⁻³</td>
</tr>
<tr>
<td>Velocity</td>
<td>470 km/s</td>
</tr>
<tr>
<td>Temperature</td>
<td>$\approx 10^5$ K</td>
</tr>
</tbody>
</table>

The IMF, as mentioned propagating outward in the solar system, can at any one point be described as a vector, that is it has a direction and a magnitude. Due to the Sun’s rotation, the direction of the IMF creates what is known as a Parker Spiral, spiraling out from the Sun in the center, shown in Figure 2.

Figure 2: Parker spiral with slow solar wind. Sun is in the middle, and the dashed line is the orbit of the Earth. From Parker (1963), adapted from Kivelson and Russell (2004).

A portion of the solar wind is directed towards Earth, and it interacts with
the geomagnetic field as it reaches our planet. The pressure it puts on the day-side magnetopause is balanced by the pressure set up by the geomagnetic field. This balance is always maintained, though the location of the magnetopause is not constant. A common assumption of the distance is 10 Earth radii, $R_E$, but this fluctuates with the solar wind intensity. On the nightside of Earth, the magnetosphere is prolonged. This so called magnetotail is several hundreds of $R_E$ long and a few tens of $R_E$ wide.

The IMF has a direction, though in contrast to the geomagnetic field it rapidly changes. We can decompose the IMF $\vec{B}$ vector into its components, $B_x$, $B_y$ and $B_z$. We are here using the Geocentric Solar Ecliptic (GSE) coordinates, with $x$ pointing from the Earth towards the Sun, $z$ pointing north in the ecliptic plane and $y$ fulfilling a right-hand system, pointing out from Earth towards dusk. The $B_z$ component is the most impactful. This is because two parallel magnetic fields impinged on each other will simply push on the other field, but two anti-parallel fields reconnect. Figure 3 is an illustration of a reconnection event. This happens on the dayside of the Earth when the IMF $B_z$ is negative, or pointing south in the GSE system. A magnetic reconnection event changes the topography of the magnetic field locally. As the name suggests, field lines connect to each other, resulting in plasma particles on one field line now having access to a previously inaccessible line.

![Figure 3: Illustration of a magnetic reconnection event. Arrows show the direction of the magnetic field lines. Different colors depict different magnetic regions.](image)

For this study, magnetic reconnection is a key process, as it makes it possible for charged particles to cross into areas they were previously not able to reach, as in this case where they find their way from interplanetary space into Earth’s magnetosphere and ultimately the ionosphere. Although important, magnetic reconnection is not fully understood.

The Sun drives the solar wind which consist of the IMF and frozen-in plasma moving along the magnetic field lines. Under the right conditions, the IMF and the geomagnetic field reconnect when the solar wind reaches Earth, and the
plasma particles now find themselves on field lines connected to both the Sun and the Earth. The next step is to look at the movements of the plasma and magnetic field lines within the magnetosphere.

2.6 The Dungey Cycle

The Dungey cycle is a model describing how the magnetic field lines around Earth change and move under the influence of the solar wind and the interplanetary magnetic field connected to it. First introduced by J. W. Dungey in 1962, it has proven to be a rigid approximation to the magnetic topography of near Earth space.

Figure 1 shows a simple illustration of the Dungey cycle. Duskside view of the Earth with the Sun to the left. The numbers correspond to time steps in the motion of the field lines, meaning line number two would be where line number one is after a certain time. Primed numbers are the corresponding field lines in the southern hemisphere. The smaller circle at the bottom is a view down towards the north polar region looking from the dusk side of Earth. It shows the foot points of the field lines connected to Earth, as well as the modeled plasma flow with arrows showing the direction. The numbers in small circles in this part of the figure correspond to the numbers along the field lines.

As the supersonic solar wind approaches Earth, it slows down at the bow shock. A bow shock can be found in front of any obstacle located in a supersonic flow, and it defines the boundary at which the flow decelerates from super- to subsonic due to the necessary deviation from its original path (Pröß (2004)).

Assuming the direction of the IMF has a negative z component, it will reconnect with the geomagnetic field (1), creating so called open field lines with one foot point on Earth and the other in the Sun. As the solar wind is still blowing, numbers (2-4) in the figure show how the field lines get dragged along toward the magnetotail. At (5) field lines are stacked in the tail, increasing the magnetic pressure in this region. The same process happens in the southern tail lobe where the field lines have the opposite direction. On the border between the northern and southern tail lobes there is a possibility for another reconnection event. This event is shown at (6) in the figure. Numbers (7) and (7’) show already reconnected field lines now accelerated towards and away from Earth, respectively. Between (8) and (9) convection of the magnetic field lines are illustrated around the sides of the Earth at lower latitudes back to the dayside, where they are ready to begin a new cycle.
As shown by the smaller top-down view of the north polar region in Figure 4, the magnetic footpoints follow a relatively straight path over the pole from the day to the nightside, before turning toward dusk and moving back towards the dayside. We say that the plasma following the field lines are convecting across the polar cap. The polar cap is defined as the high latitude region where the magnetic field lines are open, that is with one footpoint on Earth and the other in the IMF. This corresponds to lines (1-6) in Figure 4 with the Earth-connected footpoint of (1) and (6) marking the day and nightside edges of the polar cap, respectively. As is indicated in the figure, there is a second cell of convection on the dawn side of the Earth. This cell is similar to the one shown in full, only mirrored. Monitoring this twin cell convection pattern is the main scientific mission of the SuperDARN network.

While the IMF $B_z$, as mentioned in the previous section, decides where reconnection happens on the dayside, the IMF $B_y$ has an impact on the structure
of the convection pattern over the polar cap.

After convecting over the polar caps and reconnecting in the magnetotail, the now closed magnetic field lines of Earth are populated with accelerated particles. The particles will move along the lines as mentioned in section 2.2 on single particle motion. In the next section we shall see how this helps drive the coupling between the magnetosphere and the ionosphere, and how the particles ultimately end up in the ionosphere where both SuperDARN and NorSat-1 can measure them.

2.7 Structure of the Ionosphere

There are several ways of categorizing the regions of the ionosphere. The different definitions are based on different parameters. In this section we will briefly take a look at the most common way of defining the different regions, which is based on the electron density. We see a clear difference in electron density between the different regions, between night and day, and even between solar maximum and minimum. Figure 5 shows the electron density profile of the ionosphere for night versus day during solar maximum. Although the following altitudes are given exactly, the borders between the regions are naturally fluctuating, and some uncertainties must be expected.

The common altitude at which the ionosphere is thought to begin is approximately 90 km. Here the electron density is low and the neutral components are still dominating. This region is called the D-region, marking the beginning of an alphabetical naming scheme. The E-region follows at about 120 km, stretching to around 250 km altitude. This is where the main parts of the aurora occurs, and the electron density here is higher than in the D-region. Above the E-region we find the F-region, with the highest electron density. The F-region is the uppermost part of the ionosphere, bordering the magnetosphere at around 1000 km altitude. NorSat-1, orbiting at 600 km, is within the upper F-region.
2.8 Magnetosphere-Ionosphere Coupling

The plasma, now inside Earth’s magnetosphere, continues to be glued to the magnetic field lines. Assuming those are closed within the magnetosphere, we essentially have trapped particles. Due to the topography of the magnetic field and all the electromagnetic forces present, the plasma particles gyrate, drift and bounce around the Earth, as described in section 2.2. When there is a certain separation of the direction or speed of the positive and negative charges, we get currents. As we have seen, the different individual motions of the plasma particles can give rise to currents, and we will in the following describe this in greater detail. Figure 6 shows a simple illustration of the ionospheric current systems.

The solar wind, acting as a form of dynamo, is the source of the energy necessary to maintain the observed current systems in the ionosphere. When plasma convects over the polar caps as described in section 2.6 an electric field is set up fulfilling equation 2.5. This electric field is directed from dawn towards dusk. Now under the influence of both an electric and a magnetic field, the charged particles will $E \times B$ drift. As described in section 2.2 this drift is not associated with a current under the assumption of a collisionless plasma. In the ionosphere, however, the neutral particle density is so high that
this assumption breaks down. When the collision frequency between a plasma particle and a neutral is approximately equal to the ion gyrofrequency (equation 9) we get charge separation, and thus currents. In fact, due to collisional $\mathbf{E} \times \mathbf{B}$ drift we get the so called Hall and Pedersen currents. The Pedersen current is directed along the electric field, and originates from the ions not being able to complete a full gyration loop before colliding with a neutral. This results in the ion having its velocity reset, and then again accelerated by the electric field, gyrating, again colliding and so forth. The electrons, being a lot more agile than the heavy ions, are able to complete several gyration loops before colliding, and the motion closely resembles that of the collisionless $\mathbf{E} \times \mathbf{B}$ drift. This results in the electrons moving faster in the direction perpendicular to the Pedersen current, and from the conventional current definition, the Hall current flows in the direction opposite of the electron motion.

As shown in Figure 6, the Hall current is closing on itself, flowing anti-parallel to the plasma convection across the polar caps and around the Earth at lower latitudes. The Pedersen current, on the other hand, flows from dawn to dusk across the polar cap. In the auroral oval south of the cap, however, it flows north (south) on the dusk (dawn) side. This creates regions where charges seem to build up or deplete, respectively. To close the current circuit a third system is necessary. This is the so called field aligned (FAC), or Birkeland, currents. These are divided into the Region 1 and Region 2 FACs. The Region 1 current is closing in the magnetopause current, while the Region 2 current closes in the ring current. A brief explanation of these two current systems is given in the following.

The plasma accelerated towards Earth by magnetic reconnection in the tail experiences a gradient in the intensity of the magnetic field directed perpendicular to the field itself. As explained in section 2.2 this gives rise to the gradient drift. Equation 15 shows how this is dependent on the charge, $q$, of the particle. This results in the electrons and ions drifting in opposite directions around Earth, creating the ring current.

The magnetopause current originates from the plasma particles in the solar wind experiencing a gradient in the magnetic field intensity as it reaches the geomagnetic field. In the simplest case, we can approximate the IMF as a region with $\mathbf{B} = 0$, the geomagnetic field as a static, uniform field and charged particles traveling in a straight line towards Earth. Upon interaction with the magnetic field the charged particles will complete one half gyration loop and return in the direction it came. As electrons and ions gyrate in opposite directions in a magnetic field, this results in a net current flowing in the direction of the ions gyration motion. This approximation is named the Chapman-Ferraro current.
2.9 The Aurora

So far our plasma has traveled from the Sun, found its way into Earth’s magnetosphere through magnetic reconnection, and convected over the poles. In the magnetotail another reconnection event accelerated the particles towards Earth, and those with enough energy are now precipitating onto the ionosphere and upper atmosphere. The density of neutral particles increases with inverse altitude, so the further down a plasma particle penetrates, the higher the chance for a collision. Aurora borealis/australis, northern/southern lights, are the optical consequence of plasma particles precipitation in the ionosphere.

Neutral particles hit by energetic electrons and ions absorb energy and get excited. From particle physics we know that excited atoms fall back into their original state, and in doing so emit photons. The type of atom and the amount of energy absorbed decide what wavelength is emitted. For the ionosphere, oxygen is the main constituent, followed closely by nitrogen. The wavelength emitted by a first stage excited oxygen atom is 557.7 nanometers, which corresponds to the common green aurora. A second stage excited oxygen atom emits a photon at 670.0 nm, corresponding to the less visible red aurora often seen above the green. The aurora span a relatively large range of altitudes, namely

Figure 6: Current systems of the polar ionosphere. Figure after Le (2010) [15]. See text for full explanation.
approximately 120-250 km for the green aurora, and above 250 km for the red. The nitrogen contributes with a wavelength of 427.8 nm, which is observed as the elusive blue aurora. This lesser known type of aurora can be seen below the green (<120 km) during high intensity auroral events, but is often hard to detect due to the much higher intensity of the green aurora.

Aurora manifests itself as a range of different structures, with the curtained arc being the most prominent and well known. The timescales on which the auroral structures change is seconds on small scales, that is the twisting and turning of specific sections of an arc. On larger scales, e.g. the movement of the auroral boundary across the sky, the time scale is typically on the order of minutes.

![Figure 7: Aurora over Hiorthfjellet close to Longyearbyen, Svalbard. Personal picture.](image)

2.10 Instabilities and Turbulence

Irregularities in the ionosphere are found at a wide range of scales, and is still poorly understood, though efforts have been made to use turbulence theory (e.g. Frisch (1995) [8]) and instabilities (Moen et al. (2002) [17]/(2012) [16], Oksavik et al. (2012) [18]) in order to describe them. Turbulence is usually thought of as chaotic, swirling motion and is famously present in e.g. smoke and air flowing around an obstacle. Instabilities are regarded as the source of turbulent flows. We shall look closer at the Kelvin Helmholtz Instability (KHI) and the gradient drift instability (GDI).

The KHI is a velocity shear driven instability known since Hermann von Helmholtz and Lord Kelvin’s work in the second half of the 1800’s. It originates
from small natural fluctuations in the boundary between two fluids of different
densities with oppositely directed flows, or parallel flows with different speeds.
Assume a small wave-like structure in the boundary between the two flows.
After Bernoulli’s principle, the wave creates faster flows and lower pressures in
the fluid it intrudes on, since the flow is forced around the obstacle. This must
increase the amplitude of the wave-structure which further increases the flow
speed and decreases the pressure. Ultimately, the instability materializes as
structures resembling breaking waves, creating vortexes and whirls which turn
the flow turbulent. As will be discussed later, the KHI is interesting because of
our location near the flow reversal region of the ionosphere.

The gradient drift instability (GDI) arises from charge separations occurring
when an external force acts on a volume of plasma already under an enhanced
density gradient (Schiffler (1996)[24]). The charge separation introduces a polar-
izing electric field which increases any initial disturbance because of the presence
of a magnetic field. For the E-region ionosphere, the condition for the growth of
the GDI is met when an electric field is parallel to the plasma density gradient.
The electrons will move perpendicular to the electric field (Hall drift) and ions
will move along the electric field (Pedersen drift). This creates a charge separa-
tion along an initial disturbance. For the F-region ionosphere the condition
for GDI is that the electric field is directed perpendicular to the magnetic field.
This is due to the lower collisional frequency in this higher altitude region. The
charge separation instead arises from the larger Pedersen drift component of the
ions, directed along the electric field.

These instabilities have been detected several times in the ionosphere (e.g.
Keskinen et al. (1987)[13], Moen et al. (2012)[16], Oksavik et al. (2012)[18]),
and their role in the production of deca-meter scale irregularities is still a big
research topic.

Common characterizations of turbulent flows are that they are strongly dif-
fusive. In other words they are an efficient way of transporting and mixing
fluids. They have a high number of degrees of freedom and they need some sort
of energy source. Their origin is usually thought of as instabilities in laminar
flows, evolving to vortexes and whirls on different scales (Spicher, 2013)[28].

As shown in Figure 8, given an energy input to sustain structures on large
scales, the energy will be transported to smaller and smaller structures until
being dissipated at a certain scale through the vorticity of the fluid in question.
This phenomenon was first proposed by Richardson in 1922 [21]. For insta-
bilities and irregularities in the ionosphere, the source of energy is the solar
wind. Through field aligned currents the energy is channeled into the iono-
sphere, where it drives current systems and plasma flows. The flowing plasma is
turbulent and is subject to the situation in Figure 8. At some point as the struc-
tures in the plasma gets smaller, they will be of a scale that is detectable by our
SuperDARN radar. Turbulence in ionospheric plasma is thus a key phenomenon
in our study.
A great study on turbulence was done by Kolmogorov in a series of papers from 1941, in the community only known as "K41". Kolmogorov introduces a hypothesis about the energy transport in turbulent flows. The conclusion is that if plotted in Fourier space, the energy as a function of wave number will decay with a constant slope of \(-\frac{5}{3}\), until the scale of dissipation is reached.

2.11 Window Functions and Welch’s Method

When working with Fourier transforms (FFT), as we will be doing when analyzing electron density data from NorSat-1, we must be aware of the process called spectral leaking. The FFT algorithm assumes repetitive signals, which is not true for our sets of data. When repeating the signal, sharp discontinuities are created at the end of each sequence. This results in a spreading of the energy over the different frequencies (Spicher (2013) [28]), and essentially blurs out the resulting plot. To reduce this effect we apply a so called window function to the signal. This essentially dampens the magnitude of the measurements near the edges of the sequence, depending on which window function we choose. The clean signal itself can be thought of as convoluted with a perfectly rectangular window, not dampening any measurement point. In this thesis we are using a Hamming window. The choice of window function is made based on its popularity. The Hamming window was used by Solberg (2018) [26] when doing spectral analysis of NorSat-1 electron density data, and this window function has similarities with the Hann window function used by Spicher (2013) [28] when analyzing electron density data from the m-NLP on board the ICI-2 rocket.
Welch’s method is used for estimating power spectra. It works by dividing the signal into blocks, or bins, and averaging the periodogram for each bin. A periodogram of a time signal is further based on the definition of power spectral density. It is defined as the averaged squared magnitude Fourier transform of a windowed signal (Smith (2011) [25]). In mathematical terms:

\[ P = \frac{1}{M} \left| \text{FFT} \left( x(t) \right) \right|^2 \]  

(26)

where \( M \) is the size of the time signal and \( x(t) \) is the time signal convoluted with a window function. Welch’s method differ from other periodogram methods (e.g. Bartlett’s method) by allowing the bins to overlap.

Beginning with our definition of a plasma as ionized gas, we have seen how electromagnetic forces interact with plasma and its movements. We have discussed the different components of the motion of plasma particles in the geomagnetic field, and the consequence of the gyration, bouncing and different drifts. Through magnetohydrodynamics we have described a plasma as a macroscopic fluid rather than individual particles, and we have used its resulting frozen-in concept to explain how plasma from the solar wind only get access to the magnetosphere during certain conditions. With the solar wind as the main source of energy we follow the plasma through the Dungey Cycle and into the ionosphere. The ionospheric plasma maintain large scale turbulent structures due to the input of energy from the solar wind, and through the energy cascade the structures decrease in size until they are of a scale that is detectable by the SuperDARN radar. With the solar wind constantly blowing past Earth, we could assume these detectable structures to be present at all times. This is however not the case as SuperDARN often has periods of no backscatter. During this thesis, we hope to shed some light on why this is.
3 Instrumentation

In this thesis, the key instruments are the Longyearbyen SuperDARN radar and the NorSat-1 satellite, though other instruments are also used to give a wider view of the events discussed, namely fluxgate magnetometers and the Sony All-Sky Camera located at Kjell Henriksen Observatory (KHO) outside Longyearbyen on Svalbard.

In this section we describe the different instruments.

3.1 SuperDARN

SuperDARN, the Super Dual Auroral Radar Network, is, as its name implies, a network of high frequency coherent-scatter radars whose fields-of-view combine to cover extensive regions of both the northern and southern polar ionosphere. The main goal of SuperDARN is to measure the global convection of ionospheric plasma in order to study the structures, patterns and dynamics of large scale convection, as described in section 2.6. This is done through the use of signals in the high frequency (HF) regime, scattering off ionospheric irregularities described in section 2.10. The Doppler velocity of the backscatter targets moving with the ambient plasma at $\vec{E} \times \vec{B}$ drift velocities is measured. Even though each individual radar only gets information about the plasma velocity in its line of sight, through the network of overlapping fields of view it is possible to create detailed two-dimensional maps of the plasma moving over the poles.

A SuperDARN radar is a coherent-scatter radar sensitive to Bragg scattering from decameter scale electron density irregularities (Greenwald et al. (1995)[9]). Coherent-scatter radars make use of the refractive properties of the ionosphere, mentioned in section 2.1, to have their signal hit targets perpendicularly. It then follows that the reflected wave follows the same path back down to the radar, and can be measured. Any signal impinging at other angles will not be sent back to the radar.

A given coherent-scatter radar is sensitive to backscatter from targets having a wavelength of half the radar wavelength (Greenwald et al. (1995)[9]). In the case of the Longyearbyen SuperDARN radar transmitting at approximately 9.8 MHz, corresponding to a wavelength of 30.6 meters ($\lambda = c/f$), this means a target wavelength of 15.3 m.

The first SuperDARN radar was built in Goose Bay, Canada, in October 1983, though this was before the SuperDARN collaboration was a reality (Chisham (2017)[3]). This phased array, electronically steerable HF radar comprises a main array of 16 antennae which transmit and receive in the 8-20 MHz frequency range. Its field of view extends about 52° in azimuth and from 200 km to more than 3000 km in range. The range resolution is 45 km, determined by the 300$\mu$s pulse length. The backscattered signal is sampled and processed to produce multi-lag complex auto-correlation functions (ACFs) as a function of range.

Figure 9 shows a picture of the Longyearbyen (LYR) SuperDARN radar used in this thesis. The Longyearbyen radar has its similarities with the first radar.
at Goose Bay, like the 16 beams and its transmitting frequency of 8-20 MHz, as well as its approximate range resolution. However, the two radars use two different types of antennae.

Although the mapping of plasma convection is the main objective of the radar network, there are several other research fields using SuperDARN extensively. These include the study of deca-meter scale irregularities, as we have mentioned in the introduction, as well as the measure of energy influx from MHD waves, polar cap dynamics during substorms and gravity waves, among others (Chisham, 2007 [3]). As we are interested in details around the origin and size of the structures giving high backscattered power, the details around convection velocities and other scientific possibilities are of lesser interest.

3.2 NorSat-1

Norway’s first satellite with scientific objectives, NorSat-1, was launched into a high-inclination, low-Earth orbit from Baikonur, Kazakhstan on July 14th, 2017. It is a small and light satellite, measuring no more than $23 \times 39 \times 44$ cm and weighing about 16 kg. It was built by the University of Toronto, Institute for Aerospace Studies (UTIAS-SFL). Figure 10 shows a schematic of NorSat-1. In addition to the main objective of monitoring maritime traffic using an Automated Identification System (AIS) receiver, NorSat-1 also carries two scientific instruments: a Compact Lightweight Absolute Radiometer (CLARA) to measure solar irradiation and variations in this, and the multi-needle Langmuir
Probe (m-NLP) system intended to measure high resolution electron density irregularities in the ionosphere (Hoang (2018)[10]). This thesis makes use of the m-NLP instrument extensively, and section 3.2.1 explains the system in more detail.

![Figure 10: Schematic of the NorSat-1 satellite with instruments for all three objectives shown. The dimensions are 23×39×44 cm. Image credit: UTIAS-SFL.](image)

NorSat-1 is originally controlled through three rotating discs, enabling the operator to set the attitude of the satellite in any direction. For the CLARA mission, the instrument needs to be pointed towards the Sun, and ideally the m-NLP should be on the front side of the satellite at all times (positive Z-direction in figure 10) to avoid any effects that might arise from the probes being located in the plasma wake of the satellite. Although there has been problems with the attitude control system, everything was working as intended during January of 2018, and any reported issues later in time do not impact the results in this thesis.

### 3.2.1 The multi-Needle Langmuir Probe (m-NLP)

To get accurate measurements from a Langmuir probe we need to understand how a satellite and its probes interact with a plasma. This section seeks to give the basic understanding of the Orbital-Motion-Limited theory in order to describe how the probes in use work.
An object submerged in a plasma will acquire a floating potential due to the collection of charged particles. That is the potential at which ion and electron currents to the object are balanced. This potential will affect the surrounding plasma by attracting and repelling particles depending on the charge. Without a theory including this effect we would be unable to calculate the electron density accurately.

The OML theory deals with collisionless electron trajectories in the vicinity of a small object, in our case a Langmuir probe (see section 3.2.1), submerged in a plasma. It allows us to determine the cross-sections for electron and ion collections from the conservation laws of energy and angular momentum. The theory gives an upper limit to the ion current collected by the probe. It is a good approximation for situations where \( a/\lambda_L \ll 1 \), that is the radius of the probe, \( a \), is much smaller than the Debye length (equation 2) as stated by Ehsan (2011)[6]. This is valid in the situation of NorSat-1 (section 3.2), whose Langmuir probe radius is \( 0.5 \cdot 10^{-3} \) m, with a length of 25 mm (surface area of \( 40 \cdot 10^{-6} \) m\(^2\)) while the Debye length at 600 km altitude is approximately \( 10^{-2} \) m when using an electron density of \( 10^{10} \) m\(^{-3}\) and an electron temperature of 2000 K.

The m-NLP, developed at the University of Oslo (UiO), is with its sampling rate of up to 1 kHz providing an unprecedented high resolution window into deca-meter scale electron density irregularities\(^1\). As described by Jacobsen et al. (2010)[12], conventional Langmuir probes sweep through a range of voltages to obtain the characteristic current vs. voltage curve from which the plasma parameters can be obtained. Although accurate, a probe sweep takes on the order of 1 second which is too long for the resolution we are after. The m-NLP, on the other hand, makes use of four probes biased at different fixed voltage potentials within the electron saturation region, which means the voltage is positive enough for the electron current to dominate.

Perhaps surprisingly, the shape of the probe has significant impact on how the electron density is calculated. While spherical probes are well known and most popular, they depend on the user having knowledge of the electron temperature in order to accurately calculate the density. With a pair of cylindrical probes, however, we are able to calculate the density without knowledge of the electron temperature. This is done by fixing at least two probes at different positive biases, making sure both are well above the threshold for being within the electron saturation region, and subtracting the current-equation of one probe from the other.

\(^1\)Although the m-NLP system has been used at a sampling frequency of more than 5 kHz previously (Jacobsen (2010)[12]), this has been on board rockets with very limited flight time, not satellites.
The following derivation, taken from the OML theory, follows that of Jacobsen et al. (2010)\cite{12}. The equation for the electron current collected by a cylindrical Langmuir probe with positive potential is

\[ I_c = n_e q \sqrt{\frac{k_B T_e}{2\pi m_e}} \frac{2}{\sqrt{\pi}} \sqrt{1 + \frac{qV}{kT_e}} \]  

(27)

where \( n_e \) is the electron density, \( q \) is the charge, \( k_B \) is the Boltzmann constant, \( T_e \) is the electron temperature, \( m_e \) is the electron mass, \( r \) and \( l \) are the radius and length of the cylinder, respectively, and \( V \) is the probe potential. This equation is similar to that of a spherical probe, but the difference has significant consequences. In the spherical probe equation the term for the surface area of the probe is naturally different, and the term \( 1 + \frac{qV}{k_B T_e} \) is not within a square root. The implications of this last difference is evident when squaring equation 27

\[ I_c^2 = \frac{k_B T_e}{2\pi m_e} (n_e q 2\pi r l)^2 \frac{4}{\pi} \left( 1 + \frac{qV}{k_B T_e} \right) \]

\[ = \frac{2k_B T_e}{m_e} (n_e q 2rl)^2 + \frac{2q}{m_e} (n_e q 2rl)^2 V \]  

(28)

With the above equation we have the opportunity to separate density from temperature. In the corresponding calculation for the spherical probe both terms in the last equation depend on the density and the temperature, and the last term also on the voltage. While for the cylindrical probe we see that only the first term depend on the temperature, and only the last on the voltage. As mentioned above, by subtracting the equation for one fixed bias probe from the equation of another, we get the desired separation and can find an expression for the electron density

\[ I_{c2}^2 - I_{c1}^2 = \frac{2k_B T_e}{m_e} (n_e q 2rl)^2 - \frac{2k_B T_e}{m_e} (n_e q 2rl)^2 + \frac{2q}{m_e} (n_e q 2rl)^2 (V_2 - V_1) \]

\[ \Delta (I_c^2) = \frac{2q}{m_e} (n_e q 2rl)^2 \Delta V \]

\[ n_e = \sqrt{\frac{m_e}{2q (2qr)^2}} \frac{\Delta (I_c^2)}{\Delta V} \]  

(29)

We calculate the electron density by using all four probes of the m-NLP and the above equation. Although using only two probes would have been enough to calculate relative differences, using all four gives a more accurate result and introduces a quality check on whether the probe is measuring in the electron
saturation region. This is important as equation [29] is not valid outside of this regime (Jacobsen (2010)[12]). In order to find $\Delta(I_2^c)$ we find the slope of the line created when implementing a linear fit to the squared current versus bias voltage plot. The electron density is proportional to the square root of this slope.

Each cylindrical Langmuir probe on board the satellite is 25 mm long and has a diameter of 0.5 mm. This gives a probe surface area of 39.47 mm$^2$ considering only one of the ends is in direct contact with the surrounding plasma. As described by Hoang et al. (2018), the other end is connected to a bootstrapped section 15 mm in length with a diameter of 2 mm, and this section is biased at the same voltage as the probe itself in order to mitigate edge effects. Furthermore, the probes are placed at the end of relatively long protruding booms of 370 mm length. This is to make sure the probes are in contact with undisturbed plasma, rather than the plasma wake left behind by the satellite as it moves along its orbit. The length of the booms makes certain the floating potential of the satellite itself is not affecting the measurements. Both the probes and the bootstraps are carbon coated.

The electronics on board NorSat-1 saves the measurements every 30 milliseconds, and this process lasts for 10 milliseconds. That is, the resulting data sets come in a "30 on - 10 off" manner, with a data point every 1 millisecond for 30 ms, then a 10 ms gap, repeating throughout. Because of this, it is necessary to interpolate the data, as explained in section 4.1.

3.3 Magnetometers

Magnetometers are widely used in space physics to monitor disturbances in Earth’s magnetic field. As charge carriers move, they create a current, and currents induce magnetic fields, which in the case of plasma particles in the ionosphere are fields that can be detected on the ground as deviations from the background geomagnetic field. The common compass is a form of single axis directional magnetometer using a thin needle to determine the direction of the geomagnetic field. The most common magnetometer in space physics is the fluxgate magnetometer. It detects magnetic field strength along three axes through the use of a highly permeable material with two coils wrapped around it. Driving an alternating current through one of the coils generates a magnetic field with alternating direction in the core material, which again induces a current in the second coil. Without an external magnetic field the input and output of a fluxgate magnetometer will match up. The highly permeable material is more easily aligned with a background field, and within e.g. the geomagnetic field the input and output currents will not match. The difference determines the strength of the external field in each of the three axes. Permeability in electromagnetism is the ability a material has to maintain a magnetic field within itself.

Disturbances in the geomagnetic field measured on the surface of the Earth comes from Hall currents in the ionosphere, described in section 2.8. A current induces a magnetic field around it, with direction dictated by the right hand
rule. For a current in the ionosphere this magnetic field propagates out and hits the surface. A groundbased magnetometer will detect this induced field as deviations in the geomagnetic background field. The larger the measured deviation, the stronger the current.

We are using groundbased magnetometers from the Kjell Henriksen Observatory (KHO) just outside of Longyearbyen, and Ny-Ålesund.

3.4 Sony All-Sky Camera

Among the plethora of instruments located at the KHO just outside of Longyearbyen, Svalbard, is a Sony All-Sky Camera. Essentially, this is a DSLR camera equipped with a full 180 degree fish-eye lens pointing upwards. With the right exposure time we get clear color pictures of the sky above which makes it a great instrument for optical observations of the aurora and its dynamic motions as seen from below. Overcast weather is the All-Sky Cameras greatest enemy. The camera at used at KHO runs with an exposure time of 4 seconds and has a time resolution of 10-30 seconds [24].

We now have the means to detect and measure several connected parts of the dynamic region that is the ionosphere (section 2.7). First of all, SuperDARN measures frozen-in plasma convecting with the magnetic field lines over the poles to the nightside and back to the dayside, by scattering electromagnetic signals off certain plasma structures, as described in section 3.1. The twin-cell pattern in and around the polar cap is closely monitored by the radar network. NorSat-1 is capable of accurately measuring the electron density in the upper ionosphere at 600 km altitude, and can detect structures of the same scale as SuperDARN. By using four fixed bias probes the m-NLP instrument is able to measure the electron density without knowledge of the electron temperature, as described in section 3.2.1. With groundbased magnetometers (section 3.3), we are able to measure deviations in the geomagnetic field, created by Hall currents in the ionosphere. The Hall currents, flowing anti-parallel to the plasma convection, are part of the ionospheric current system alongside the Pedersen and Birkeland currents described in section 2.8. The Birkeland currents, also known as field aligned currents, are the main channel of energy transport between the solar wind and the ionosphere. This energy helps sustain the large scale turbulent structures in the ionospheric plasma, which break up into smaller and smaller scales. At some point, the structures are of the right size for SuperDARN to detect them. As a further measure of the ionospheric conditions we can use All-Sky Cameras to find the amount of aurora present in the sky. More aurora is an indication of an active ionosphere, as it is created by high energy precipitating particles, as described in section 2.9.
4 Observations

By using the above mentioned instruments we can study the ionospheric conditions at any given time, and with the theory described in section 2 we can explain the consequences of the observations. As described closer in section 4.1 we want to find two time periods within a reasonable time frame so that large scale changes (e.g. amount of sunlight per day) in the ionosphere between the two periods are of no concern. One period must present significant backscattered radar signal while the other show minimal backscattered power. We do this in order to conduct a comparison of the two situations. By studying the Fourier transforms of electron density measured by NorSat-1, we should be able to distinguish the two time periods by the intensity of frequencies corresponding to irregularity length scales. In particular, we expect a difference in the intensity of frequencies corresponding to the size of SuperDARN backscatter targets, explained in section 3.1. Ultimately, we should be able to recreate the results of Moen et al. (2002)\cite{17} and Spicher (2013)\cite{28}, and thus further strengthen their hypothesis regarding the origin of ionospheric electron density irregularities.

In this section we take a closer look at the data and point out important observations. We discuss the ionospheric conditions during the two dates one after the other. We will start with locating our instruments and backscatter area on the Earth, and then look at the electron density at the orbit of NorSat-1 (600 km). Next is the behavior of the solar wind in the hours preceding the times of interest, before we end with the groundbased instruments. An overview of data regarding the measured magnetic field on the surface of Earth close to the area of backscatter is given, as well as optical observations of the aurora. We do this in order to be able to point out the differences in ionospheric conditions between the two dates. For a direct comparison of the two dates we will look at differences in section 5.

4.1 Locations and fields of view

In terms of using NorSat-1 and the m-NLP, the first task is to calculate the distance between the satellite and any specific point on the surface of the Earth. This is important as we need to know whether our satellite is within range of the backscatter or not. This is done by accessing data regarding the location of the satellite, which includes geographic latitude, longitude and the time of measure, in addition to the altitude of the satellite. With the geographic latitude and longitude we can make use of the so called Haversine formula to calculate the shortest distance between two points on the Earth’s surface, as follows:

\[
a = \sin^2 \left( \frac{\Delta \phi}{2} \right) + \cos(\phi_1) \cdot \cos(\phi_2) \cdot \sin^2 \left( \frac{\Delta \lambda}{2} \right)
\]

\[
c = 2 \arctan \left( \frac{\sqrt{a}}{\sqrt{1-a}} \right)
\]
\[ d = Rc \]  

where \( \phi \) is latitude, \( \lambda \) is longitude, \( \Delta \) denotes the difference in the trailing parameter and \( R \) is the radius of Earth. The output, \( d \), is the distance between the two points in meters. The formula written like this closely resembles how it is calculated in the script.

With a means to calculate the distance from NorSat-1 to areas of backscatter, we can focus on finding two days to analyze closer. There are a lot of factors that need to line up for an event to be regarded as fit to be used. We need two different periods of time where in one there is almost no backscatter of the SuperDARN signal and in the other there is good backscattered signal. These two periods should occur within a couple of days of each other and during the same hour of the day, to make sure the ionospheric conditions are as similar as possible. Also, NorSat-1 needs to be close to the area with measured backscatter, and within reasonable distance to the same location at approximately the same time each day. Hence, for our event, the two days 23rd and 24th of January 2018 was chosen, at 03:40 and 03:50 UT, respectively. This combination was found manually by going through the amount of backscatter received by the Longyearbyen (LYR) radar each day, comparing those with each other and checking for the distance between NorSat-1 and the backscatter area.

With the two dates found, we move on to obtain data regarding the measured current. The current data from NorSat-1 downloads as Common Data Format (CDF) files, with each individual file containing one hour worth of data. Measurements are taken every millisecond except for the 10 millisecond saving time as mentioned in section 3.2. In order to enable the use of Fourier transforms, which is dependent on uniformly distributed data points, we linearly interpolate the current using a new time grid with 1 millisecond resolution. Since our analysis regards the difference in two calculated densities rather than the total electron density of one specific time interval, we can neglect the discrepancies that might occur by interpolating.

To simplify and speed up the proceeding analysis only the interesting parts of the data are written to .txt-files so that it can easily be accessed also in other scripts. With interesting parts is meant the time period \( \pm 5 \) minutes around the time of NorSat-1 being closest to the backscatter area.

At certain points in the current data we find periods where the data is clearly nonphysical, either dropping quickly towards zero or suddenly jumping to values far above the assumed maximum. Ivarsen et al. (2019) [11] found that the current measured by the Langmuir probes can collapse upon exiting Earth’s shadow into sunlight, before returning to expected values. This effect is, however, much smaller than what is present in the dataset used in this thesis, and the periods of data affected by this behavior must be neglected. Luckily, the anomalies lie outside of the interesting parts of the data sets, in periods where the satellite is located on the dayside of Earth, and they will only affect full-orbit plots of the electron density.
When checking for periods when NorSat-1 was close to an area of Super-DARN backscatter we find that the satellite was within the field of view of the Longyearbyen SuperDARN radar for at least a full 70 seconds on both the 23rd and the 24th of January, just north and west of the Franz Josef Land archipelago in the North Sea.

Figures 11 and 12 show a part of the orbit of NorSat-1 overlaid the field of view of the Longyearbyen SuperDARN radar. The middle annotated point in each plot (03:40:26 and 03:50:26 on the plot for the 23rd and the 24th, respectively) shows the point in the orbit data when NorSat-1 is closest to the middle of the backscatter area. As the orbit data has a 1 minute resolution this is the approximate closest approach. Included in the figures are the range gates with detected backscatter, where different colors correspond to different received power in decibels. In addition, the arrows and crosses on Svalbard correspond to ground based observatories. The purple arrow for the Kjell Henriksen Observatory (KHO) outside Longyearbyen and the lighter magenta arrow for Ny-Ålesund. As mentioned in section 3 we use the magnetometers at KHO and Ny-Ålesund, and the Sony All-Sky Camera at KHO. Both ground based observatories are located on the Svalbard archipelago north of Norway. In relation to our satellite orbit and area of backscatter during our time of interest this is a few hundred kilometers to the south. This is important to remember when we later discuss the data from these observatories.

As we can see in figure 12 NorSat-1 passes the border of the significant backscatter area around 03:50:30, while being within the field of view of the radar from 03:50:10 to 03:51:30. The satellite follows approximately the same orbit on the 23rd of January, staying within the field of view for an equal amount of time. The crossing of the field of view occurs 10 minutes earlier this day.
Figure 11: The orbit of NorSat-1 on the 23rd of January 2018. The filled circles along the orbit correspond to points in the data, with annotated hours around the midpoint. The field of view of the Longyearbyen SuperDARN radar is shown as a dashed line, and the range gates containing backscatter colored according to the received power. Purple (pink) arrow shows location of KHO (Ny-Álesund).

Figure 12: The orbit of NorSat-1 on the 24th of January 2018. The filled circles along the orbit correspond to points in the data, with annotated hours around the midpoint. The field of view of the Longyearbyen SuperDARN radar is shown as a dashed line, and the range gates containing backscatter colored according to the received power. Purple (pink) arrow shows location of KHO (Ny-Álesund).
4.2 Conditions 23rd of January 2018

The Longyearbyen SuperDARN backscatter around 03:40 on the 23rd of January 2018 is as good as non-existent, as seen in figure 11. In this section we shall take a closer look on other data and parameters during this time in an effort to paint a picture of how the ionosphere was behaving in this period of time.

4.2.1 Electron Density

Figure 13 shows the electron density measured by NorSat-1 over 70 seconds during the pass through LYR SuperDARN’s field of view the 23.01.2018. The 0 on the time axis corresponds to the time of closest approach on the 24th of January, 03:50:26 UT, with the data from the 23rd normalized to this. With closest approach is meant the point where the satellite is closest to the geographic center of the backscatter area. The time axis encompasses a total of 70 seconds, that is 490 km along the orbit of the satellite. It is clear that the density fluctuates, between $0.5 \times 10^{10}$ and $3.5 \times 10^{10}$ electrons per cubic meter. However, the average density, shown as a dashed line in the plot, is almost exactly $10^{10} \text{m}^{-3}$ which is a common approximation for the electron density above the F-region.

![Electron Density 23.01.2018](image)

*Figure 13: Electron density as measured by NorSat-1 on the 23.01.2018.*

4.2.2 SuperDARN Frequency and Backscatter

An important factor to discuss is the frequency of the signal sent by SuperDARN in Longyearbyen. This can be changed by the operator, and is usually changed from day to night as the ionospheric conditions change drastically when going from the Earth’s shadow into sunlight. This change in day/night setting is of no
importance to us as we are far enough north to be in the polar night, and thus in Earth’s shadow all day. The emission frequency per beam of the radar at three different times on the 23rd is shown in Figure 15. There are two channels running simultaneously at the Longyearbyen SuperDARN radar. Channel 1, green line in the figure, transmits at approximately 9.8 MHz but fluctuates mildly between 9.8 and 9.9 MHz. Channel 2, blue lines, transmits at approximately 11.6 MHz, fluctuating between 11.6 and 11.7 MHz. The three lines for each channel correspond to 03:38, 03:40 and 03:42 UT. This mild fluctuation in frequency from beam to beam, and over time for specific beams, are not expected to significantly impact the trajectory of the signal. Figure 14 shows examples of modeled ray paths of the Blackstone and Longyearbyen SuperDARN radars, respectively, at the 24th of January 2011 16:00 UT. The grey diverging lines are rays separated by 1° White lines denotes every 5th range gate, and red lines are magnetic field lines. Background colors correspond to electron densities. The Blackstone radar sees its rays bend significantly in the ionosphere, with several of the paths turning back towards the ground. This is not unusual for SuperDARN signals, and groundscatter can often be seen in the data. Evidently, the model of the Longyearbyen signal rays is a lot less disturbed with only slight bending of the ray paths, and no rays turning back to the ground. Although we assume the average electron density in the ionosphere to be the same from year to year in the high latitude polar night, the figures are included purely as an example illustration of SuperDARN ray paths.
Figure 14: Example of modeled SuperDARN ray paths for the Blackstone (top) and Longyearbyen (bottom) radars 24.01.2011 16:00 UT. See text for full explanation. Modeled emission frequency: 10 MHz. Figure credit: VT SuperDARN

Figure 15: Comparison of the SuperDARN signal frequency per beam on the 23rd of January 2018. The three lines per channel are different times close to the NorSat-1 flyby, namely 03:38, 03:40 and 03:42 UT.
4.2.3 The Solar Wind

As described in section 2.5, we get a more dynamic ionosphere following periods of a negative $z$-component in the solar wind magnetic field, $B_z$, which allows for significant magnetic reconnection on the dayside border between the magnetosphere and interplanetary space. We choose to take a closer look at the $B_z$ and the flow speed of the solar wind in the hours leading up to 03:40 on the 23rd. Figure 16 shows how these two parameters behave, courtesy of the OMNI database of Goddard Space Flight Center (GSFC). The plots are time-shifted to show the solar wind at 1 astronomical unit (1AU), that is as it hits the bow shock of Earth. Since the plasma needs time to propagate through the Dungey cycle and end up in the ionosphere on the night side of Earth, we only include a small bit of data after our chosen time interval, but a longer time before. It is usually assumed that the IMF arriving at the bow shock can be translated to measured events in the ionosphere, such as enhanced electrojets and aurora, approximately one hour later. For the IMF $B_z$ in Figure 16 we see how it is negative for a prolonged period of time before turning positive at approximately 02:50. Such a long period of constant negative magnetic field is almost certain to cause disturbances in the ionosphere, and we expect to see aurora around our time of interest at 03:40. IMF data alone is not enough to determine the amount, however, so we look at magnetometer and All-Sky Camera data in addition.

![Figure 16](image)

*Figure 16: Plots of the solar wind $B_z$ and flow speed in the hours before 03:40 on the 23rd of January 2018 at 1AU. Important bits are the negative values of $B_z$ in the upper panel. The flow speed in the lower panel is not extraordinary high. Missing pieces is due to bad data. Courtesy of the OMNI datasets from GFSC’s CDAWeb website.*
4.2.4 Aurora

The presence of aurora is an argument for disturbed conditions above the observer, and thus cameras watching the sky are important instruments in space physics. We will here take a look at auroral events in the period around 03:40 on the 23rd of January 2018.

Figure 17 shows six pictures from the Sony All-Sky Camera located at Kjell Henriksen Observatory (KHO) just outside of Longyearbyen, Svalbard. There are 10 minutes between each picture, starting from the top left. In the pictures geomagnetic north is up, while east is to the left and west to the right. The consistent lights in the north west is Longyearbyen.

The yellow hue present in all 6 pictures are clouds, which makes observations of aurora near impossible. In the top left picture we see aurora in the south, and it is arguably a faint arc visible in the south on the picture taken at 03:40:27. However, based on these pictures alone we can not say anything about the auroral conditions above Svalbard.

Another instrument located at KHO is the Meridian Scanning Photometer (MSP) which would have been helpful to determine the amount of auroral wavelength emission from the upper atmosphere. The MSP consists of a rotating mirror and five photomultiplier tubes. The mirror rotates in such a way that the five channels, tuned to different wavelengths, detect photons along the north-south meridian. Unfortunately, this instrument was offline during our time of interest.

The Kp index, a measure of geomagnetic activity, was fairly low on the morning of the 23rd. The index uses a 0-9 scale, with 9 being the highest. Any Kp above 5 is usually characterized as a geomagnetic storm, and anything above Kp 7 would be a major event, with visible aurora possible even in southern Europe. The Kp index was 2 for the early morning the 23rd [27], which is an arguably typical value. It is important to remember that a low Kp index is preferable when looking for aurora in the arctic, as a high value would decrease the probability of aurora in the north, but increase it further south.
4.2.5 Magnetometers

Figure 18 shows the horizontal component of the magnetometer data from Ny Ålesund (NAL) and Longyearbyen (LYR). The grey area marks the 2 minutes when NorSat-1 is close to and within the field of view of SuperDARN. The horizontal (H) component of the geomagnetic field drops when the electrojets are enhanced, and when we have activity in the ionosphere. From the figure it is clear that the H-component dropped just after 03:00 on the 23rd. The drop is more than 60 nanotesla at Ny Ålesund, and more than 80 nT at Longyearbyen. The drop follows all the characteristic forms of a so called substorm, with its expansion and recovery phases. However, the magnitude is too small for us to characterize this as a significant event. A substorm in itself is a fairly local event, and since the measurements are taken on Svalbard, hundreds of kilometers away from our satellite orbit, we can not with certainty say that this should be picked up by SuperDARN or NorSat-1.
4.3 Conditions 24th of January 2018

In this section we will have a look at the same aspects for the 24th of January as we did for the 23rd in the previous section. This day shows significant backscatter when NorSat-1 passes the field of view of the radar, as shown in Figure 12.

4.3.1 Electron Density

Figure 19 shows the electron density at 600 km as measured by NorSat-1 during 70 seconds in the field of view of the Longyearbyen SuperDARN radar. We see much the same picture as for the density on the 23rd (Figure 13), with the exception of a slightly larger average density. The fluctuations for the 24th are mainly between $1.0 \times 10^{10}$ and $3.5 \times 10^{10}$, with the single drop to $0.5 \times 10^{10}$. These measurements are as expected for the electron density at 600 km altitude.
4.3.2 SuperDARN Frequency and Backscatter

From Figure 20 showing the LYR SuperDARN transmission frequencies for the 24th of January, we see that the second channel was offline for all beams except beam 8 during our time of interest. Beam 8 did, however, transmit at the expected frequency of 11.6 MHz. Consequently we do not have consistent backscatter data for this channel during this time, and we focus mainly on the backscatter measured on channel 1. As for the 23rd, channel 1 fluctuates only slightly between 9.8 and 9.9 MHz, and we can use the same arguments as in section 4.2.2. We thus conclude that we do not expect the signal trajectories to significantly vary during our time of interest.
Figure 20: Comparison of the SuperDARN signal frequency per beam on the 24th of January 2018. The three lines per channel are different times close to the NorSat-1 flyby, namely 03:48, 03:50 and 03:52 UT.

4.3.3 The Solar Wind

The OMNI solar wind data for the hours before 03:50 on the 24th of January can be seen in Figure 21. We see a dominantly positive $B_z$ which barely dips below zero just after 02:30. The dip, however small it might be, happens at just the right time to be able to create disturbances in the ionosphere at around 03:50. We do not expect any big activity in the ionosphere from looking at the figure, but the OMNI data alone is not enough to discard the chance, and we again make use of our groundbased instruments.
4.3.4 Aurora

The optical observations through the Sony All-Sky Camera on the 24th of January, shown in Figure 22, suffer from much the same issue as those from the 23rd. However, the cloud cover seems to be thinner this day, and stars are visible. Fewer clouds make it easier to establish the actual amount of aurora and its location. Starting from the top left corner of our six pictures, we see faint aurora across most of the southern sky including at zenith. Around 03:50, the top right picture, this situation has not changed much. There are clouds in the north, and after 04:00 more clouds seem to float in from the west. Despite this we do recognize a faint auroral arc to the south even in the last two pictures. As argued before, with the locations discussed in section 4.1, an arc to the south of KHO is located far away from both NorSat-1 and our region of SuperDARN backscatter. We do not expect this auroral event to largely impact the ionosphere around our satellite.

The MSP at KHO (Figure 23), briefly described in section 4.2.4, was online most of the 24th, and shows much the same situation as the Sony All-Sky Camera, with some aurora in the early hours, and faint green aurora close to 03:50, although the clouds are making it difficult to make proper conclusions.
Figure 22: Sony All Sky Camera pictures for 24th of January 2018. Camera located at KHO outside Longyearbyen. Specks of aurora can be seen before 04:00, mainly in the south, before clouds fill the sky.

Figure 23: Keogram from the Meridian Scanning Photometer located at KHO. Spots of aurora can be seen in the early hours of the 5577 Ångström (557.7 nm) panel, though clouds makes it blurry.
4.3.5 Magnetometers

Figure 24 shows magnetometer data during the 24th of January 2018 from Ny Ålesund and Longyearbyen. The grey area marks the time interval when NorSat-1 is within the field of view of the LYR SuperDARN radar. As is clear from the figure, the geomagnetic field was a lot less disturbed between 03:00 and 04:00 on the 24th than it was during the same time interval on the 23rd (Figure 18). Notice how the oscillations starting around 04:00 never exceed a magnitude of 30 and 40 nT for the NAL and LYR magnetometers, respectively. Showing very little fluctuation in the time before and around the flyby, the H-component implies a quiet and undisturbed ionosphere over Svalbard this day.

Figure 24: Magnetometer data from Longyearbyen 24th of January 2018.
5 Discussion

In this section we will discuss the implications of the observations done in the previous section, and compare the results from each day. We start with revisiting the arguments that the polar ionosphere were quiet and similar the two days of interest. From there we go through the differences we find in the Welch method FFT plots, associating the differences with structures in the ionospheric plasma.

5.1 Ionospheric conditions

As we have already discussed in section 4, the ionosphere above Svalbard on the 23rd and 24th of January 2018 seem to be fairly undisturbed and, most importantly, similar during the two time intervals studied in this thesis. There were faint aurora both days as shown in Figures 17 and 22 with the most prominent arcs in the south when observed from KHO outside Longyearbyen. The magnetometers detected small deviations in the background geomagnetic field, as described in sections 4.2.5 and 4.3.5, but these are not big enough for us to count as significant. The largest difference in ionospheric conditions, apart from the obvious backscatter, is in the average electron density. Figure 25 shows the comparison of electron density during 70 seconds on the 23rd and the 24th of January. The 0-point on the time axis correspond to the time at which NorSat-1 was closest to the backscatter area on the 24th, that is 03:50:26. The density from the 23rd is time shifted to this. Both densities are within the expected value at 600 km, fluctuating between \(0.5 \times 10^{10}\) to \(3.5 \times 10^{10}\) m\(^{-3}\). The average density sees a difference of \(0.88 \times 10^{10}\) m\(^{-3}\), larger on the 24th as compared to the 23rd. As explained in section 2.1, the refractive index of ionospheric plasma depend on the electron density. Because of this it is reasonable to expect the ray paths of the SuperDARN signal to be different on the two days. However, as the bottom part of the modeled ray tracing in Figure 14 shows, a change in electron density from \(10^{10}\) m\(^{-3}\) to \(10^{11}\) m\(^{-3}\) does not significantly change the path of the signal. We thus argue that the SuperDARN signal follows approximately the same trajectories on the 23rd and 24th of January 2018.
5.2 Differences in FFT-plots

In this section we shall study the Welch method FFT plots and the difference between them. This will give us an indication on what type of structures are present in the ionosphere during the two days, and whether there are certain structures more common on the 24th than the 23rd that could explain the observed difference in backscattered power. First, however, we must address two issues we have so far avoided, namely plasma moving in relation to our satellite and the altitude difference between SuperDARN backscatter and NorSat-1. When dealing with the ionosphere, and especially the polar cap, it is safe to assume the plasma within is moving. As explained in section 2.6, plasma is convecting over the poles towards the nightside and back in the direction of the dayside at lower latitudes. What NorSat-1 is actually measuring is the relative velocity between the satellite and the surrounding plasma. We therefore take a look at SuperDARN velocity plots to determine the velocity of the plasma at our time of interest. Figure 26 shows 6 plots of the field of view velocity as measured by the LYR SuperDARN radar 24th of January 2018. Together with Figure 12 showing the orbit of the satellite, we can discuss the impact of the plasma velocity on our measurements. A plasma velocity of 800 m/s parallel to the orbit of NorSat-1 would change the relative velocity as seen by the satellite by approximately 11%. Based on Figure 12 we argue that the angle between the plasma velocity and the satellite velocity is somewhere between 45° (east side of FOV) and 90° (west side). An angle of 90° would mean the relative velocity would be the same as the satellite velocity. The worst case scenario is a 45° angle with the anti-parallel trajectory of the satellite, in which case the relative velocity would change by 565 m/s, corresponding to about 8%. This
would change the spatial scales we are able to see, as the relative velocity would be 7,545 km/s. An increase in relative velocity like this would make the detected structures seem larger than what they are. However, the difference is small, only a few meters at 200 Hz, and it would only significantly impact sharp enhanced frequencies in the lower ranges below 200 Hz. We thus argue that the effects of relative velocities can be neglected.

![SuperDARN velocity plots](image)

Figure 26: SuperDARN velocity plots for 6 minutes around closest approach on the 24th of January 2018, showing a clear velocity shear. Credit: VT SuperDARN.

The second issue to consider is the difference in altitude between the SuperDARN backscatter targets and the orbit of NorSat-1. SuperDARN is expected to measure irregularities in the F-region, approximately 300-400 km altitude. NorSat-1 is orbiting at 600 km, and this difference of a few hundred kilometers must be addressed. The main difference between the two altitudes would be the measured electron density. Figure 5 shows the electron density profile of the ionosphere. In general, the electron density decreases with altitude above the F-region. As mentioned earlier, however, the total density is of limited interested to us as we are studying differences. Through the assumption of near-infinite conductivity, a key assumption in ideal MHD (section 2.3 and 2.4), we expect the plasma and the structures therein to be glued to the magnetic field lines, and having little to no resistance when moving along them. With the field lines themselves being almost vertical at high latitudes, we argue that any feature originating at SuperDARN target altitudes quickly propagates along the field lines to the orbit of NorSat-1.
Taking a look at the Welch Method FFT-plots in Figures 27-29 we find some clear differences between the two dates. The figures show the Welch method applied to the same data with different bin sizes and number of overlapped points. This is to show that the differences evident in the plots are not a consequence of the choice of bin size. There are some artifacts which pop out, however. There are clear spikes between 75 and 110 Hz, where both the orange and blue lines jump. The fact that the same sharp frequencies are boosted on both days indicates that this is an issue arising from the platform, meaning the satellite itself.

Figure 27: Comparison of FFT of electron density on 23rd and 24th of January 2018. Frequencies above 333.33Hz is removed for clarity. Welch’s method is applied, here with a bin size of 0.5 seconds (500 points) and 0.25 second overlap.
Figure 28: Comparison of FFT of electron density on 23rd and 24th of January 2018. Frequencies above 333.33Hz is removed for clarity. Welch’s method is applied, here with a bin size of 1.0 second (1000 points) and 0.5 second overlap.

Figure 29: Comparison of FFT of electron density on 23rd and 24th of January 2018. Frequencies above 333.33Hz is removed for clarity. Welch’s method is applied, here with a bin size of 2.0 seconds (2000 points) and 1.0 second overlap.

The orange line, corresponding to 24.01.2018, seem to be of a generally higher magnitude than the blue line of 23.01.2018. This is especially clear in Figure 27 using a bin size of 0.5 seconds (500 data points) and an overlap of 0.25 seconds.
We can confirm this by plotting the percentage difference between the two lines for every frequency. For consistency, this is done for the three different bin sizes and overlaps already used. Figures 30-32 show this percentage difference, calculated through the following formula

\[
\frac{V_{24i} - V_{23i}}{V_{24i} + V_{23i}} \times 100
\]  

where the subtext 23i/24i denotes the i’th data point for the 23rd and 24th respectively, and V is the value at this point. In the plots, a positive difference means the power density on the 24th is higher than on the 23rd. It is clear that the difference fluctuates a lot. Notice, however, how the average difference, shown by a solid red line in the figures, is positive in all three plots. This proves that the power spectrum of the electron density measured the 24th of January 2018 is generally of higher magnitude than that of the 23rd of January.

This can be seen in combination with the energy cascade described in section 2.10 and Figure 8. If we have more small scale structures for SuperDARN to scatter off of, there must also be a larger number of bigger structures. This is because the smaller structures feeds on the energy of the larger ones. Thus we have found evidence to support that the turbulent energy cascade must be present for SuperDARN to measure backscatter. This is in accordance with the results of Moen et al. (2002)[17], (2012)[16], Oksavik et al. (2012)[18] and Spicher (2013)[28]. As previously mentioned, Moen et al. (2002)[17] proposed that the deca-meter scale irregularities might be originating from the cascade down of unstable intermediate-scale gradients in the plasma. This result was further investigated after the ICI-2 sounding rocket campaign, where the m-NLP was used to measure deca-meter scale irregularities in the cusp region. Moen et al. (2012)[16], Oksavik et al. (2012)[18] and Spicher (2013)[28] found evidence for the gradient drift instability being the main source of irregularity production.

The previously mentioned SuperDARN velocity plots, Figure 26, show a prominent velocity shear. The plasma flow in the eastern parts of the field of view is negative, and thus flowing away from the radar, while the western part is positive, flowing towards the radar. The velocities are measured at ± 800 m/s. At some points the two different flows are in adjacent range gates, which makes the velocity gradient significant. Since the Kelvin-Helmholtz instability regards flows over an obstacle, or two flows with different velocities in contact with each other, we should expect the KHI to play a role in the production of the detected irregularities in the 24th of January 2018.
Figure 30: Percentage difference in FFTs the 23rd and the 24th of January 2018. A positive percentage corresponds to the 24th being of higher value than the 23rd. Grey dashed line is at zero difference. 24th being generally higher is evident from the straight red line representing the average value of the difference.

Figure 31: Percentage difference in FFTs the 23rd and the 24th of January 2018. A positive percentage corresponds to the 24th being of higher value than the 23rd. Grey dashed line is at zero difference. 24th being generally higher is evident from the straight red line representing the average value of the difference.
The plots comparing FFT’s gives us the amount of difference per frequency. Since the original data is electron density measurements made by NorSat-1 traveling at close to $7 \text{ km/s}$ we can associate each frequency with a spatial scale through the following formula.

$$D = \frac{v_{NS-1}}{f_{FFT}}$$

with $D$ being the width of an irregularity, $v_{NS-1}$ being the velocity of NorSat-1 and $f_{FFT}$ being the observed frequency at which we have a difference.

For NorSat-1, a detected frequency of 1 Hz would then correspond to a structure with a width of 7 km, while the largest detectable frequency is 500 Hz, corresponding to a distance of 14 meters. This is the decameter scale we have discussed previously, and is the scale at which SuperDARN is most sensitive to backscatter.

The lowpass filter onboard NorSat-1 has its threshold set at 333 Hz. Above this, we still get measurements, but those are naturally a lot lower in amplitude than those below. Since we are only looking at the difference between the two days, we are not concerned with the total amplitude of our FFT plots, and the lowpass filter does not raise a large problem for the analysis.

Figures 33-35 give the FFT plot of the lowpass filter regime above 333 Hz. As is already evident from the percentage difference in Figures 30-32, the orange line for 24th of January has a generally larger amplitude than the blue line for the 23rd. This further strengthens the case of instabilities being the main source of decameter scale irregularities in the ionosphere. As with Figures 27-29, the
figures regarding the lowpass filter range show evidence of energy cascading down through smaller and smaller density structures.

Figure 33: Comparison of FFT of the electron density for both days in the lowpass filter regime above 333 Hz. Welch’s method applied with 2 second bin size and 1 second overlap.

Figure 34: Comparison of FFT of the electron density for both days in the lowpass filter regime above 333 Hz. Welch’s method applied with 2 second bin size and 1 second overlap.
Figure 35: Comparison of FFT of the electron density for both days in the lowpass filter regime above 333 Hz. Welch's method applied with 2 second bin size and 1 second overlap.
Conclusion and Outlook

Through the analysis done in this thesis we have found that there are several different sized irregularities present at 600 km altitude during SuperDARN backscatter which are not as common during periods of low backscatter. The high frequency sample rate of NorSat-1 have made it possible for us to detect irregularities down to decameter scales, and through this we have created detailed Welch method FFT plots to study the density structures in the ionosphere.

We have found that there are significant differences in the amount of irregularities at all the scales we can measure, from 7 km to 14 meters. Most interesting are the high-frequency, low-wavelength cases we have found, which correspond better to the SuperDARN emission frequencies, giving decameter scale wavelengths.

The Longyearbyen SuperDARN radar transmitted with a channel 1 frequency of approximately 9.8 MHz during the two time intervals we have studied. As mentioned previously, this correspond to a target wavelength of 15.3 meters, which is just within what NorSat-1 is able to measure. The second channel transmitted with a frequency of 11.6 MHz, corresponding to a wavelength of 25.9 meters, and a target wavelength of just below 13 meters. This is too small for NorSat-1 to measure, as the shortest wavelength detectable is 14 meters for the satellite. The second channel of SuperDARN was not used in the study, though this is based on the fact that all but one beam was offline during time of interest the 24th of January.

The study has given more evidence to the theory proposed by Moen et al. (2002) and further investigated by e.g. Oksavik et al. (2012) and Spicher (2013), regarding the gradient drift instability as the main source of decameter scale ionospheric irregularities. The evidence is in the form of an energy cascade (section 2.10) present in and around the area of backscatter. With this being clearly more prominent during high intensity backscatter, we can conclude that it is a key process in the production of deca-meter scale irregularities in the ionosphere.

We also argue that the KHI could play a role in the production of the detected irregularities. This is because we see a clear velocity shear in the SuperDARN velocity plots.

This thesis has presented the first study using SuperDARN radar data and high resolution electron density data from NorSat-1. It compares two connected cases of in-situ measurements of HF backscatter targets during high and low backscattered power in the polar cap.

Further research using more radars and a high number of pairs of days, with the conditions previously discussed, is necessary to give a statistical analysis of the scales at which we find irregularities in the ionosphere. This will increase our understanding of ionospheric deca-meter scale irregularities. Similar studies in other ionospheric regions is also encouraged. Hopefully this thesis can work as a motivational starting point for further research on this topic.
7 Bibliography

References


8 Appendix

In the following we include the scripts used to analyze the data used in the thesis and to produce the plots throughout.

Listing 1: Calculate haversine formula

```python
# Find distance from the NorSat-1 satellite to a specific SuperDARN range gate.

# Setup of NorSat orbit data:
alt: CDF.FLOAT [1, 1440]
epoch: CDF.EPOCH [1, 1440]
glat: CDF.FLOAT [1, 1440]
glon: CDF.FLOAT [1, 1440]
iri.nd: CDF.FLOAT [1, 1440]
iri.te: CDF.FLOAT [1, 1440]
iri.ti: CDF.FLOAT [1, 1440]
sza: CDF.FLOAT [1, 1440]
vx: CDF.FLOAT [1, 1440]
vy: CDF.FLOAT [1, 1440]
vz: CDF.FLOAT [1, 1440]

# Make sure the number of days in month are correct

for i in month:
    # Open every file containing orbit-data from Jan-May
    cdf = pycdf.CDF('norsat_orbit/NorSat-1-orbit-2018{}{}'.format(i, j))
    ns_lat = np.asarray(cdf['glat'])
    ns_long = np.asarray(cdf['glon'])
    time = np.asarray(cdf['epoch'])
    nd = np.asarray(cdf['iri.nd'])
```
def haversine(sd_lat, sd_long, ns_lat, ns_long):
    # Implement the Haversine formula to find distances between two points on sphere
    # sd: SuperDARN, ns: NorSat-1
    Re = 6371e3  # Earth's radius in m
    sd_lat = np.radians(sd_lat)  # radians
    ns_lat = np.radians(ns_lat)
    d_phi = (ns_lat - sd_lat)  # change in latitude
    d_lam = np.radians((ns_long - sd_long))  # change in longitude
    a = np.sin(d_phi/2)*np.sin(d_phi/2) + np.cos(sd_lat)*np.cos(ns_lat)*np.sin(d_lam/2)*np.sin(d_lam/2)
    c = 2*math.atan2(np.sqrt(a), np.sqrt(1-a))
    d = Re*c  # distance between two points in meters
    return d/1000  # want km

distance = []
location = []
limit = 500  # km
for i in range(len(ns_lat)):
    for j in range(len(ns_lat[i])):
        dist = haversine(84.83, 61.43, ns_lat[i][j], ns_long[i][j])  # sd-coords corresponding to manually put range gate
        if dist <= limit:  # if NorSat-1 within dist km of backscatter
            print "NorSat-1 within {:.2f} km of SuperDARN backscatter location: {}".format(dist)
            print time[i][j], '---', ' ({})'.format(dist), 'km away'
            distance.append(np.floor(dist))
            location.append([ns_lat[i][j], ns_long[i][j]])
        print "Two Points:", ns_lat[i][j], ns_long[i][j], " and ", ns_lat[i-1][j-1], ns_long[i-1][j-1], "\n"  # print two points along orbit

Listing 2: Extract Orbit data. Corresponding script exists for the current data.
import numpy as np
from spacepy import pycdf
import datetime as dt

date = 20180124

cdf = pycdf.CDF('norsat_orbit/NorSat−1−orbit−{}-cdf'.format(date))

lons = np.asarray(cdf['glon'][0])
lats = np.asarray(cdf['glat'][0])
time = np.asarray(cdf['epoch'][0])

print("Lon: {}, Lat: {} at {}", format(lons[229], lats[229], time[229]))
print("Lon: {}, Lat: {} at {}", format(lons[230], lats[230], time[230]))
print("Lon: {}, Lat: {} at {}", format(lons[231], lats[231], time[231]))

midpoint = 230

f = open("orbit_arrays/orbit_{}.", format(date), 'w+')
for i in range(-5, 6):
    f.write("{:5f} {:5f} {}\n".format(lons[midpoint+i], lats[midpoint+i], time[midpoint+i]))
f.close()
# CHOOSE CORRECT DATE
offset = 35000  # =35 seconds of data
date = 240118
knee = 1750  # index of border between linfit lines. Found
            visually in FFT log-plot
#[2400000-60000:2400000+60000] interesting part 230118
#[3000000-60000:3000000+60000] interesting part 240118

variables = ["c1", "c2", "c3", "c4", "b1", "b2", "b3", "b4"]
data = []
for element in variables:
f = open("{0}.70s/time.txt".format(date, element), "r")
array = np.asarray([float(i) for i in f])
data.append(array)
f.close()
currents = [data[0], data[1], data[2], data[3]]
bias = [data[4], data[5], data[6], data[7]]
interpc1, interpc2, interpc3, interpc4 = currents[1], currents[2], currents[3]
interpb1, interpb2, interpb3, interpb4 = bias[0], bias[1], bias[2], bias[3]
#extract time
ftime = open("{0}.70s/time.txt".format(date), "r")
time_ms = [str.strip(i) for i in ftime]
time.close()

def check_ms(list):
    yes = []
    for txt in list:
        try:
            yes.append(dt.datetime.strptime(txt, "%Y-%m-%d %H:%M:%S.%f"))
        except ValueError:
            yes.append(dt.datetime.strptime(txt, "%Y-%m-%d %H:%M:%S"))
    return yes
newTime = np.asarray(check_ms(time_ms))

#find slope of I^2 − V curve
slope = []
for i in range(len(currents[0])):
c1, c2, c3, c4 = currents[0][i], currents[1][i], currents[2][i], currents[3][i]
b1, b2, b3, b4 = bias[0][i], bias[1][i], bias[2][i], bias[3][i]
slope_four, intercept_four, r_value_four, p_value_four,
std_err_four = stats.linregress([b1, b2, b3, b4], [c1 **2, c2**2, c3**2, c4**2])
slope.append(slope_four)

#calculate electron density from currents
me = 9.11e-31  # electron mass, kg
e = 1.6e-19   # electron charge, C


```python
K = e**((3/2.)/np.pi * np.sqrt(2./me))  # constant
A = 39.47e-6  # probe surface area, m^2
ne_four = 1./(K*A)*np.sqrt(slope)  # constant

plt.figure()
plt.title("Density, {}".format(date))
plt.plot(newTime, ne_four, label="4 probes")

""

densityFile = open("{}70s/calculated_density_4probes.txt".format(date), "w+")
for i in range(len(ne_four)):
    densityFile.write("{}\n".format(ne_four[i]))
densityFile.close()
""

avgNe_four = np.sum(ne_four)/float(len(ne_four))
rmdAvg_four = ne_four - avgNe_four

plt.figure("Electron Density {}".format(date), figsize=(16,9))
plt.plot(newTime, ne_four)
# plt.plot(newTime[startIndex:endIndex], fitNE)
plt.title("Calculated Electron Density (probes 2&4) {}".format(date))
plt.xlabel("Time")
plt.ylabel(r"Density, $\frac{1}{m^3}$")

# Fast Fourier Transform
import scipy.fftpack
T = 1.0/1000.0  # sample spacing (1kHz)
N = len(ne_four)  # no. of sample points
yf = scipy.fftpack.fft(rmdAvg_four)  # Fourier of density with average removed
xf = np.linspace(0.1, 1.0/(2.0*T), N//2)  # Frequencies for x-axis

# Filter Index and Knee
from bisect import bisect
filterIndex = bisect(xf, 333.33)  # find index of low-pass filter kick-in
print("Filter Index: {}".format(filterIndex))
print("Knee Frequency: {} Hz".format(xf[knee]))

#

yf = yf[1:filterIndex]  # omit 0th index due to spike in data
xf = xf[1:filterIndex]
yLog = np.log10(yf)  # take log of data before linfit
xfLog = np.log10(xf)
yfLog = yfLog[:N//2]  # first half of logarithmic y-axis (real)
slope1, intercept1, r_value1, p_value1, std_err1 = stats.linregress(xfLog[:knee], yfLog[:knee])  # linfit
slope2, intercept2, r_value2, p_value2, std_err2 = stats.linregress(xfLog[knee:], yfLog[knee:])  # linfit
```

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Write data to files

xfFile = open("{}\_70s/xf\_4probes.\_txt".\_format(date) , "w+"")
yfFile = open("{}\_70s/yf\_4probes.\_txt".\_format(date) , "w+"")
xfLogFile = open("{}\_70s/xfLog\_4probes.\_txt".\_format(date) , "w+"")
yfLogFile = open("{}\_70s/yfLog\_4probes.\_txt".\_format(date) , "w+"")

for index in range(len(xf)):
    xfFile.\_write("{}\n".\_format(xf[index]))
for index in range(len(xfLog)):
    xfLogFile.\_write("{}\n".\_format(xfLog[index]))
for index in range(len(yf)):
    yfFile.\_write("{}\n".\_format(np.\_real(yf[index])))
for index in range(len(yfLog)):
    yfLogFile.\_write("{}\n".\_format(np.\_real(yfLog[index])))
xFile.\_close()
xLogFile.\_close()
yFile.\_close()
yLogFile.\_close()

line1 = 10***(np.\_real(intercept1) + np.\_real(slope1)*xfLog[:\_knee])
line2 = 10***(np.\_real(intercept2) + np.\_real(slope2)*xfLog[:\_knee])
for index in range(len(line1)):
    line1File.\_write("{}\n".\_format(line1[index]))
for index in range(len(line2)):
    line2File.\_write("{}\n".\_format(line2[index]))
line1File.\_close()
line2File.\_close()

#Plot

fontTitle = {'family' : 'normal',
            'weight' : 'bold',
            'size' : 22}
fontAxis = {'family' : 'normal',
            'size' : 20}
plt.\_rc('font', **fontAxis)

plt.\_figure("FFT\_{}\_knee {:.2f}\ Hz.\_png".\_format(date, xf[knee]),
             figsize=(16,9))
plt.\_title("FFT of Electron Density {}\. Knee: {:.1f} Hz".\_format(date, xf[knee]), fontTitle)
plt.\_xlabel("Frequency")
plt.\_ylabel("Amplitude")
plt.\_plot(xf, np.\_abs(yf[:N\_2]),
    line1, color="r")
plt.\_plot(xf[knee:], line2, color="y")
plt.\_legend(["FFT", "Slope: {:.3}"]\_format(np.\_real(slope1), "Slope: {:.3}"\_format(np.\_real(slope2)))]

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# plt.savefig("../Plot Bilder/FFT_ne_{:.2f}Hz_{:.2f}s.png", format(date, xf[knee], int(float(offset)/1000)))
plt.show()
elapsedTime = klokke.time() - startTime
print("Time taken: {:.2f} seconds".format(elapsedTime))

def nan_helper(y):
    """ Helper to handle indices and logical indices of NaNs."
    Input:
    - y, 1d numpy array with possible NaNs
    Output:
    - nans, logical indices of NaNs
    - index, a function, with signature indices= index(logical_indices),
      to convert logical indices of NaNs to 'equivalent' indices
    Example:
    >>> # linear interpolation of NaNs
    >>> nans, x= nan_helper(y)
    >>> y[nans]= np.interp(x(nans), x(~nans), y(~nans))
    """
    return np.isnan(y), lambda z: z.nonzero()[0]

Listing 4: Plot figures

""" Plotting multiple dates of NorSat-1 manipulated data in same plot
Author: Henrik Bjoner Lie
"""

import numpy as np
from spacepy import pycdf
import math
import scipy.signal
from bisect import bisect
import datetime as dt
import pandas as pd
import matplotlib.pyplot as plt
import matplotlib.dates as mdates
from matplotlib.ticker import FormatStrFormatter
import re
import time as klokke
import sys

def check_ms(list):
    """ Append every point in time-list, including whole seconds
    """
timeList = []
for txt in list:
    try:
        timeList.append(dt.datetime.strptime(txt, "%Y-%m-%d
%H:%M:%S.%f"))
    except ValueError:
        timeList.append(dt.datetime.strptime(txt, "%Y-%m-%d
%H:%M:%S"))
return timeList

# constants for Welch
nperseg = 500
noverlap = None
dates = ["230118", "240118"]
offset = 35000  #ms, = 70 s total
knee = 1750

# Extract data

master = []  # m[0][0] = time of date1, m[0][1] = data of date 1, m[1][0] = time of date2, m[1][1] = data of date 2 asf.
fourier = []  # add fourier components
linfit = []  # add linfit components
welch = []  # add Welch method components

for date in dates:
    variables = ["c2", "c4", "b2", "b4", "$calculated\_density\_4\_probes"]  # variables to plot
data = []  # data goes here
for element in variables:  # do this for every variable
    f = open("{}\_70s/{}.txt".format(date, element), "r")  # read in specific file
    array = np.asarray([float(i) for i in f])  # save every line in file, turn to np.array
    data.append(array)  # send to main data-list
f.close()

ftime = open("{}\_70s/time.txt".format(date), "r")  # retrieve time
time_ms = [str.strip(i) for i in ftime]  # strip because of datetime
ftime.close()

newTime = np.asarray(check_ms(time_ms))  # include every point and turn to np.array
wrap = [newTime, data]  # data: array([c2, c4, b2, b4, density])
master.append(wrap)  # master includes everything

xfFile = open("{}\_70s/xf.txt".format(date), "r")
xfLogFile = open("{}\_70s/xfLog.txt".format(date), "r")
yfFile = open("{}\_70s/yf.txt".format(date), "r")
yfLogFile = open("{}\_70s/yfLog.txt".format(date), "r")
line1File = open("{}\_70s/linfit1\_knee{}.txt".format(date, knee), "r")
line2File = open("{}\_70s/linfit2\_knee{}.txt".format(date, knee), "r")

xf = [float(i) for i in xfFile]
xfLog = [float(j) for j in xfLogFile]
yf = [float(k) for k in yfFile]
yfLog = [float(l) for l in yfLogFile]
splitLine1 = np.asarray([j.split() for j in line1File])
splitLine2 = np.asarray([h.split() for h in line2File])
line1 = [float(splitLine1[m]) for m in range(len(splitLine1))]

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```python
line2 = [float(splitline2[n]) for n in range(len(splitLine2))]

fourier.append([xf[1:], xfLog[1:], yf[1:]])  # remove first element because of its low value
linfit.append([line1[1:], line2[1:]])

# close files
xfFile.close()
xLogFile.close()
yfFile.close()
yLogFile.close()
line1File.close()
line2File.close()

# calculate and remove average density
density = data[4]
avgDensity = sum(density)/float(len(density))
remAvgDensity = density - avgDensity

# Implement Welch method
welchFreq, welchPxx = scipy.signal.welch(remAvgDensity, fs=1000.0, window="hamming", nperseg=nperseg, noverlap=noverlap)  # returns array([sample freq, power spectrum])
lowpassWelchIndex = bisect(welchFreq, 333.33)
lpWelchFreq = welchFreq[:lowpassWelchIndex]  # lowpassWelchIndex
lpWelchPxx = welchPxx[:lowpassWelchIndex]
welch.append([lpWelchFreq, lpWelchPxx])

print("Length Pxx: {} original and {} with lowpass removed".format(len(welchPxx), len(lpWelchPxx)))

dateOne = master[0]
dateTwo = master[1]

# timePoints = np.asarray(range(len(dateOne[0][len(dateOne[0])//2-int(=offset):len(dateOne[0])//2+int(=offset)])))  # normalize time

timePoints = np.asarray(range(-35000, 35000, 1))
density1 = dateOne[1][4][len(dateOne[1][4])//2-int(=offset):len(dateOne[1][4])//2+int(=offset)]  # extract +/- offset around midpoint
density2 = dateTwo[1][4][len(dateTwo[1][4])//2-int(=offset):len(dateTwo[1][4])//2+int(=offset)]
N = len(dateOne[1][4])
fourier = np.asarray(fourier)
linfit = np.asarray(linfit)

averageDen1 = np.sum(density1)/len(density1)
averageDen2 = np.sum(density2)/len(density2)

# PLOTTING

fontTitle = {'family': 'normal',
             'weight': 'bold',
             'size': 22}
```

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```python
fontAxis = {'family': 'normal', 'size': 20}
plt.rc('font', **fontAxis) #add to all text elements in plots

plt.figure("Density Comparison", figsize=(16,9))
plt.title("Electron Density 24.01.2018", fontTitle)

plt.plot(timePoints/1000.0, density1, color="royalblue", label="23.01.2018")
plt.plot(timePoints/1000.0, density2, color="orange", label="24.01.2018")

plt.axhline(y=averageDen1, color="royalblue", linestyle="--", label="Avg={:.2e}".format(averageDen1))
plt.axhline(y=averageDen2, color="orange", linestyle="--", label="Avg={:.2e}".format(averageDen2))

plt.axvline(x=5.15, color='grey', linestyle="--", alpha=0.5)
plt.axvline(x=5.362, color='grey', linestyle="--", alpha=0.5)

plt.xlabel("Time, seconds")
plt.ylabel(r"Density, $\frac{1}{m^3}$")
plt.legend()

plt.savefig('..\Plot Bilder\final\ne23.png'.format(dates[0], dates[1], int(2*float(offset)/1000)))

if nooverlap == None:
    nooverlap = nperseg/2.0

fig = plt.figure("Welch", figsize=(16,9))
ax = fig.add_subplot(111)
plt.title("Welch's Method Comparison | Binsize: {} | Overlap: {}")'.format(nperseg, noverlap), fontTitle)
plt.xlabel("Frequency, Hz")
plt.ylabel("Power")
plt.plot(welch[0][0], welch[0][1], color="royalblue", label="23.01.2018") #23.01.2018
plt.plot(welch[1][0], welch[1][1], color="orange", label="24.01.2018") #24.01.2018
plt.xscale("log")
plt.yscale("log")
ax.xaxis.set_major_formatter(FormatStrFormatter("%.0f")
plt.legend(loc="lower left")
plt.savefig('..\Plot Bilder\final\welch_comparison\{}\{}\{}comparison_lowpass.png'.format(nperseg, noverlap))

#calculate the percentage difference between the two FFTs. If 24th >23rd: positive number.
avg = [(welch[1][1][i] + welch[0][1][i])/2.0 for i in range(len(welch[0][0]))]
diff = [(welch[1][1][j] - welch[0][1][j])/avg[j] for j in range(len(welch[0][0]))]
diffen = np.asarray(diff)*100.0

plt.figure("Difference in Welch FFT", figsize=(16,9))
plt.plot(welch[0][0], diffen, label="Difference", color="royalblue")
plt.axhline(y=np.mean(diffen), color="r", alpha=0.4, label="Average diff.")
plt.axhline(y=0.0, linestyle="--", color="grey", alpha=0.5)
plt.xlabel("Frequency, Hz")
```

Listing 5: Plot OMNI data

```python
# Listing 5: Plot OMNI data

# Plot OMNI Solar Wind data.

Author: Henrik Bjoner Lie

```
### Listing 6: Create Basemap figure with overlaid SuperDARN FOV

```python
if v[i] >= 9999.99:
    v[i] = np.nan

fontTitle = {'family': 'normal',
             'weight': 'bold',
             'size': 22}

fontAxis = {'family': 'normal',
             'size': 20}

plt.rc('font', **fontAxis)

fig = plt.figure(fig.title, figsize=(16,9))
plt.suptitle(title)

ax1 = fig.add_subplot(211)
ax1.set_ylabel(r'$B_z$, nT')
plt.setp(ax1.get_xticklabels(), visible=False)
ax1.plot(time, bz, label=r'$B_z$', color='orange')
ax1.axhline(y=0.0, color='r', alpha=0.4, linestyle='--')
ax1.axvspan(time[230], time[232], color='grey', alpha=0.5)
plt.gca().xaxis.set_major_locator(mdates.HourLocator())
ax1.legend()

ax2 = fig.add_subplot(212)
ax2.plot(time, v, label='Velocity', color='g')
ax2.set_xlabel(r'Velocity, km/s')
ax2.set_xlabel(r'Time')
ax2.axvspan(time[230], time[232], color='grey', alpha=0.5)
plt.gca().xaxis.set_major_formatter(mdates.DateFormatter('%H:%M'))
ax2.legend()
plt.savefig('..//Plot Bilder/final/' + saveTitle)
plt.show()
```

Basemap and SuperDARN FOV plot for 23.01.2018.

Author: Henrik Bjoner Lie
```python
lats = np.array([float(data[j][1]) for j in range(len(data))])
dateOrbit = np.array([data[j][2] for j in range(len(data))])
hourOrbit = np.array([data[j][3] for j in range(len(data))])

# Stereographic projection
map = Basemap(width=9000000, height=6000000,
               resolution='l', projection='stere',
               lat_0=20, lon_0=lon[5] + 4.00, lon_0=lon[5])

# SUPERDARN FOV
file = pd.read_csv("./SD_GeoData/20180123_0330-0400_Longyearbyen_00.dat", sep="\s+", header=None, names=list(range(0, 70)), comment="#")

sdlat1, sdlon1, sdlat2, sdlon2, sdlat3, sdlon3, sdlat4, sdlon4 = file[0][0:1137], file[1][0:1137], file[2][0:1137], file[3][0:1137], file[4][0:1137], file[5][0:1137], file[6][0:1137], file[7][0:1137]

count = 0
beamIndex = []
for i in sdlat1:
    count += 1
    if i == "Beam":
        beamIndex.append(count-1)

# MAXRANGE
beam1lat = np.array(sdlat1[beamIndex[0]+1:beamIndex[0]+70])
beam1lon = np.array(sdlon1[beamIndex[0]+1:beamIndex[0]+70])
beam1lat = np.append(beam1lat, sdlat4[beamIndex[0]+70])
beam1lon = np.append(beam1lon, sdlon4[beamIndex[0]+70])

def maxRangeLat():
    for j in range(len(beam1lat)+70):
        maxRangeLat.append(sdlat4[beamIndex[j]+70])

maxRangeLon():
    for j in range(len(beam1lon)+70):
        maxRangeLon.append(sdlon4[beamIndex[j]+70])

# MINRANGE
beam16lat = np.array(sdlat2[beamIndex[-1]+1:beamIndex[-1]+70])
beam16lon = np.array(sdlon2[beamIndex[-1]+1:beamIndex[-1]+70])
beam16lat = np.append(beam16lat, sdlat3[beamIndex[-1]+70])
beam16lon = np.append(beam16lon, sdlon3[beamIndex[-1]+70])

minRangeLat[:] = []
```

for j in range(len(beamIndex)):
    minRangeLat.append(sdlat1[beamIndex[j]+1])
    minRangeLon.append(sdlon1[beamIndex[j]+1])
    minRangeLat.append(sdlat2[beamIndex[j-1]+1])
    minRangeLon.append(sdlon2[beamIndex[j-1]+1])
minRangeLat = np.asarray(minRangeLat)
minRangeLon = np.asarray(minRangeLon)

# = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = =
# COLOR PROJECT
# GRID

colorlat1 = file[0:1137]
dataBeam1 = np.asarray(colorlat1.loc[2:71])
dataBeam2 = np.asarray(colorlat1.loc[73:142])
dataBeam3 = np.asarray(colorlat1.loc[144:213])
dataBeam4 = np.asarray(colorlat1.loc[215:284])
dataBeam5 = np.asarray(colorlat1.loc[286:355])
dataBeam6 = np.asarray(colorlat1.loc[357:426])
dataBeam7 = np.asarray(colorlat1.loc[428:497])
dataBeam8 = np.asarray(colorlat1.loc[499:568])
dataBeam9 = np.asarray(colorlat1.loc[570:639])
dataBeam10 = np.asarray(colorlat1.loc[641:710])
dataBeam11 = np.asarray(colorlat1.loc[712:781])
dataBeam12 = np.asarray(colorlat1.loc[783:852])
dataBeam13 = np.asarray(colorlat1.loc[854:923])
dataBeam14 = np.asarray(colorlat1.loc[925:994])
dataBeam15 = np.asarray(colorlat1.loc[996:1065])
dataBeam16 = np.asarray(colorlat1.loc[1067:1142])

coodsBeam1, coordsBeam2, coodsBeam3, coodsBeam4, coodsBeam5,
    coodsBeam6, coodsBeam7, coodsBeam8 = [], [], [], [], [], [], [], []
coodsBeam9, coordsBeam10, coodsBeam11, coodsBeam12,
    coodsBeam13, coodsBeam14, coodsBeam15, coodsBeam16 = [], [], [], [], [], [], [], []

for hello in dataBeam1:
    hello = hello[0:8]
    coodsBeam1.append(hello)
for hello in dataBeam2:
    hello = hello[0:8]
    coodsBeam2.append(hello)
for hello in dataBeam3:
    hello = hello[0:8]
    coodsBeam3.append(hello)
for hello in dataBeam4:
    hello = hello[0:8]
    coodsBeam4.append(hello)
for hello in dataBeam5:
    hello = hello[0:8]
    coodsBeam5.append(hello)
for hello in dataBeam6:
    hello = hello[0:8]
    coodsBeam6.append(hello)
for hello in dataBeam7:
    hello = hello[0:8]
coordsBeam7.append(hello)
for hello in dataBeam8:
    hello = hello[0:8]
    coordsBeam8.append(hello)
for hello in dataBeam9:
    hello = hello[0:8]
    coordsBeam9.append(hello)
for hello in dataBeam10:
    hello = hello[0:8]
    coordsBeam10.append(hello)
for hello in dataBeam11:
    hello = hello[0:8]
    coordsBeam11.append(hello)
for hello in dataBeam12:
    hello = hello[0:8]
    coordsBeam12.append(hello)
for hello in dataBeam13:
    hello = hello[0:8]
    coordsBeam13.append(hello)
for hello in dataBeam14:
    hello = hello[0:8]
    coordsBeam14.append(hello)
for hello in dataBeam15:
    hello = hello[0:8]
    coordsBeam15.append(hello)
for hello in dataBeam16:
    hello = hello[0:8]
    coordsBeam16.append(hello)

def draw_screen_poly(lats, lons, map, facecolor=None):
x, y = map(lons, lats)
xy = zip(x, y)
poly = Polygon(list(xy), edgcolor=facecolor, facecolor=facecolor, alpha=1.0)
plt.gca().add_patch(poly)

# COLOBAR
startIndex = 1468 #1402 #1468 #1534
dateFOV = data0340.loc[startIndex][0:2]
ranges = []
for i in range(powerStart, endIndex, 2):
    ranges.append(np.asarray(data0340.loc[i]))
extractFrequency = []
for i in range(powerStart-1, endIndex, 2):
    extractFrequency.append(np.asarray(data0340.loc[i]))
freq = [extractFrequency[i][3] for i in range(len(extractFrequency))]
frequencies = [str(yes[0:5]) for yes in freq]

freqFile = open("SD_frequencies_230118.txt", "a")
for elem in frequencies:
    freqFile.write(elem + " ")
freqFile.write("\n")
freqFile.close()

freqFile = open("SD_frequencies_230118.txt", "r")
lines = []
for line in freqFile:
    lines.append(line.split())
flyter = [np.float32(j) for j in lines]

beams = range(1, 17)

plt.figure(figsize=(16,9))
plt.plot(beams, flyter[0], color="green", label="Channel 1")
plt.plot(beams, flyter[1], color="green")
plt.plot(beams, flyter[2], color="green")
plt.plot(beams, flyter[3], color="royalblue", label="Channel 2")
plt.plot(beams, flyter[4], color="royalblue")
plt.plot(beams, flyter[5], color="royalblue")
plt.xticks(beams)
plt.ylim(9.5, 12.0)
plt.xlabel("Beam no.")
plt.ylabel("Frequency, MHz")
plt.title("SuperDARN Signal Frequency 23.01.2018", fontTitle)
plt.legend()
# plt.savefig("./Plot_Bilder/final/SD_FreqCompare_230118.png")
plt.show()

beam1, beam2, beam3, beam4, beam5, beam6, beam7, beam8, beam9, beam10, beam11, beam12, beam13, beam14, beam15, beam16 =
    ranges[0], ranges[1], ranges[2], ranges[3], ranges[4],
    ranges[5], ranges[6], ranges[7], ranges[8], ranges[9],
    ranges[10], ranges[11], ranges[12], ranges[13], ranges[14],
    ranges[15]
grid = [beam1, beam2, beam3, beam4, beam5, beam6, beam7, beam8, beam9, beam10, beam11, beam12, beam13, beam14, beam15, beam16]

interest = []
interestValue = []
beamNo = 0
for beam in grid:
    rangeNo = 0
    for value in beam:
        value = np.float32(value)
        if value < 9999:
            interest.append([rangeNo, beamNo])
            interestValue.append(value)
            print("Value {} in range {} beam {}", format(value, rangeNo, beamNo))
            rangeNo += 1
        beamNo += 1

# = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = =
# PLOTTING
fig, ax = plt.subplots(figsize=(16,9))
# plot map
map.drawcoastlines(linewidth=0.25)
map.drawmeridians(np.arange(0, 360, 20), labels=[0, 0, 0, 1])
```python
map. drawparallels(np.arange(-90, 90, 10), labels=[1, 1, 1, 0])
map. fillcontinents(color="grey", alpha=0.2)
map. drawcountries()

# plot orbit
x, y = map(lons, lats)
map. plot(x, y, "o", color="b", label="NS-1 Orbit")
plt.annotate("{}").format(hourOrbit[5]), xy=(map(lons[5], lats[5]))
plt.annotate("{}").format(hourOrbit[3]), xy=(map(lons[3], lats[3]))
plt.annotate("{}").format(hourOrbit[7]), xy=(map(lons[7], lats[7]))
plt. suptitle("NorSat-1 orbit at 23.01.2018 {}--{}").format(hourOrbit[0][:-3], hourOrbit[1][:-3]), fontsize=22, fontweight="bold")
plt. title("Channel 1")

# plot SD FOV
sdx1, sdy1 = map(beam1lon, beam1lat)
map. plot(sdx1, sdy1, "--", color="k")
maxRangeX, maxRangeY = map(maxRangeLon, maxRangeLat)
map. plot(maxRangeX, maxRangeY, "--", color="k")
beam16x, beam16y = map(beam16lon, beam16lat)
map. plot(beam16x, beam16y, "--", color="k", label="LYR SuperDARN FOV {}".format(dateFOV[1][0:5]))
minRangeX, minRangeY = map(minRangeLon, minRangeLat)
map. plot(minRangeX, minRangeY, "--", color="k")

# add KHO, 78.148 N, 16.043 E, and NAL, 78.92500N 11.92222E
x, y = map(16.043, 78.148)
i, j = map(11.922, 78.925)
map. plot(x, y, "x", color="purple")
plt.annotate("KHO", xy=(x, y), xytext=(0.35, 0.35), textcoords="axes fraction", arrowprops=dict(facecolor="purple", edgecolor="k", width=0.1))
map. plot(i, j, "x", color="magenta")
plt.annotate("NAL", xy=(i, j), xytext=(0.35, 0.45), textcoords="axes fraction", arrowprops=dict(facecolor="magenta", edgecolor="k", width=0.1))

# plot grid
gridlock = [coordsBeam1, coordsBeam2, coordsBeam3, coordsBeam4, coordsBeam5, coordsBeam6, coordsBeam7, coordsBeam8, coordsBeam9, coordsBeam10, coordsBeam11, coordsBeam12, coordsBeam13, coordsBeam14, coordsBeam15, coordsBeam16]

strahl = 0
for nalgene in gridlock:
gateNo = 0
for gate in range(len(nalgene)):
    if [gateNo, strahl] in interest:
        index = interest.index([gateNo, strahl])
        power = interestValue[index]
        if power < 2.00:
            facecolor = "k"
        else power > 2.00 and power < 5.00:
            facecolor = "royalblue"
```

```python
if power > 5.00 and power < 10.00:
    facecolor = "g"
if power > 10.00 and power < 16.00:
    facecolor = "y"
if power > 16.00 and power < 20.00:
    facecolor = "orange"
if power > 20.00:
    facecolor = "r"

lats = np.asarray([nalgene[gate][0], nalgene[gate][2], nalgene[gate][4], nalgene[gate][6]])
lons = np.asarray([nalgene[gate][1], nalgene[gate][3], nalgene[gate][5], nalgene[gate][7]])
draw_screen_poly(lats, lons, map, facecolor)
gateNo += 1
strahl += 1
plt.legend(loc="lower left")
plt.savefig("./Plot_Bilder/70s/NSOrbit_{0}_SDFOV_{1}_Channel1_noColorbar.png".format(dateOrbit[0], dateFOV[1][0:9]))
plt.show()
file.close()
```