

Swarm + Innovation: Polar Cap Products

Final Report

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This document presents the results of the Swarm+Innovation: Polar Cap Products (PCP) project. This project was carried out at the Department of Physics, University of Oslo, under ESA Contract No. 4000114121/15/NL/MP in the framework of the STSE (Support To Science Element) Swarm+Innovation Program.

1 Summary

Space weather is the term commonly used to describe the impact of dynamical processes in the near Earth environment on satellite- and ground-based infrastructure. Examples are the severe degradation of air traffic communications and satellite-based navigation systems during high solar activity. Space weather effects are becoming increasingly important in the polar regions, where human activity strongly depends on space-based infrastructure, both for communication and navigation.

Polar cap patches (PCPs) are a phenomenon occurring in the Earth's polar ionosphere, poleward of the auroral oval. By providing favorable conditions for plasma instabilities, the occurrence of PCPs can lead to scintillations of Global Navigation Satellite Systems (GNSS) signals, and result in the degradation of positioning solution accuracy; in severe cases of scintillation the information encoded on the satellite signal is illegible for the ground receiver and a navigation solution cannot be calculated. It is imperative to study the formation and transport of PCPs as well as the plasma instabilities occurring within them if one desires to develop a polar ionospheric space weather forecast system.

In this report we present numerical algorithms that automatically detect PCPs in plasma density data from the Swarm satellites, and provide a PCP Index that can be used to understand the creation and transport of PCPs. We also provide information on growth rates of the most applicable plasma instability (the gradient drift instability) and its error, again calculated from data measured on board the Swarm satellites. Our hope is that these new data products will lead to a deeper understanding of polar ionospheric dynamics in the context of space weather phenomena.

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2 Introduction to magnetosphere-ionosphere coupling at high latitudes

The upper atmosphere of the Sun, the corona, has a temperature of several million degrees Kelvin. As a consequence the corona is not bound by gravity; instead, the Sun not only emits electromagnetic radiation into space but also its upper atmosphere. The particles comprising the corona, mostly electrons, protons, and helium ions, stream away from the Sun and form the solar wind that fills the interplanetary space. Parameters of the solar wind can vary depending on the activity of the Sun. At the distance of the Earth, typical particle densities of the solar wind are $n \in (4 - 15) \text{ cm}^{-3}$, velocities $v \in (350 - 600) \text{ km/s}$, and temperatures of the order of 10^5 K (e.g. [Meyer-Vernet, 2009](#)).

Because the solar wind is to first order a perfectly conducting fluid, the solar magnetic field is embedded within it. Consequently, the interplanetary space is not only filled with particles originating from the Sun's upper atmosphere, but also permeated by the interplanetary magnetic field (IMF). Just as the solar wind is dependent on solar activity, so is the IMF. At Earth, it typically is of the order of $B \sim 6 \text{ nT}$ and it can and does assume any orientation ([Bruno and Carbone, 2005](#)).

The Earth's magnetic field, which can be approximated by a dipole field tilted by ca. 11 degrees with respect to the Earth's rotation axis, forms a shield against the solar wind and the IMF, i.e., under normal circumstances the terrestrial and solar magnetic fields do not mix. Instead, at a distance of approximately 10 Earth radii towards the Sun, the magnetic pressure of the terrestrial magnetic field balances the solar wind dynamic flow pressure, forming a boundary: the magnetopause. The region inside of the magnetopause is called magnetosphere and here the magnetic field of the Earth controls the motion of charged particles (see Figure [2.1](#)).

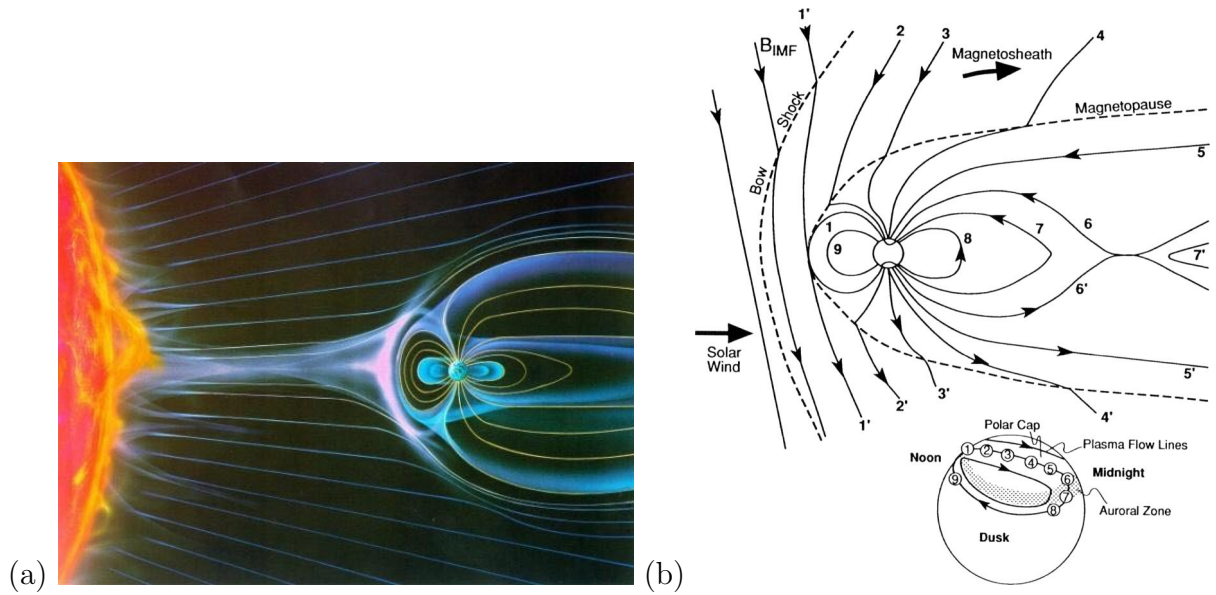


Figure 2.1: (a) Artist's impression of the solar wind interacting with the Earth magnetic field. (Credits: NASA) (b) The Dungey cycle (from [Kivelson and Russell \(1995\)](#))

Under certain circumstances, however, the two magnetic fields can interact in a process called magnetic reconnection. This process occurs when two magnetic fields are anti-parallel; in the Sun-Earth system this is the case when the IMF is oriented southward since the terrestrial magnetic field always points northward. This dynamic interaction between the solar wind and the Earth's magnetic field results in the asymmetric shape of the magnetosphere, in particular the formation of the magnetotail, as shown in Figure 2.1. Under the influence of magnetic reconnection terrestrial magnetic field lines - which are before reconnection called closed magnetic field lines since they connect to Earth on both ends (field line 1 in Figure 2.1) - merge with the IMF (field line 1' in Figure 2.1), forming open magnetic field lines; one end is now connected to the IMF. Once magnetic field lines have been opened on the dayside of the magnetosphere, they are transported with the solar wind flow across the northern and southern polar regions into the magnetotail, where magnetic flux accumulates (field lines 2 to 5 in Figure 2.1). Here again magnetic reconnection can occur, which again disconnects terrestrial (field line 7 in Figure 2.1) from solar magnetic field lines (field line 7' in Figure 2.1), thus closing previously open magnetic field lines. The now closed terrestrial magnetic field lines return to the front of the magnetosphere (field lines 7 to 9 in Figure 2.1) where they can participate in another cycle of reconnection. This cycle is called the Dungey cycle ([Dungey, 1961](#)).

All magnetospheric regions map along magnetic field lines down to the ionosphere, which is the ionized part of the upper atmosphere. It is formed between 100 and 1000 km altitude where solar radiation partly ionizes the neutral gas. The upper atmosphere is thus also in a plasma state and its dynamics are subject to electromagnetic forces. For historical reasons, various layers in the ionosphere have been identified: D (below 80 km), E (90-150 km), and F (150-500 km) layers. There is a significant difference in the dynamics of plasma in different layers which is related in part to the neutral background density: in the E layer the neutral density is high enough to allow for rapid recombination of the ionized gas at nighttime, while in the F layer the corresponding recombination of plasma is less efficient. Thus, the E layer plasma density is significantly depleted during nighttime and its dynamics are subject to collisions with neutrals. This is in contrast to the ionospheric F layer, which can often be considered collisionless, and density structures at higher altitudes can persist for a significant amount of time (*Kelley, 2009*).

The region of the ionosphere which is threaded by open magnetic field lines (those field lines mapping close to the magnetic poles), is called the polar cap. Equatorward of it, extending for a few degrees in latitude, is the so-called auroral oval; here the aurora is formed by precipitating particles from deep inside the magnetosphere that collide with and excite neutrals in the ionosphere (mainly oxygen and nitrogen atoms). The equatorward edge of the polar cap, i.e., the poleward edge of the auroral oval, is the open/closed field line boundary (OCB). The position of OCB varies depending on the geomagnetic activity (*Siscoe and Huang, 1985; Frank and Craven, 1988a; Milan et al., 2003; Clausen et al., 2012*); during increased geomagnetic activity the polar cap contracts, the auroral oval increases in thickness, and OCB moves poleward. On average, the position of OCB is well below 77 degrees of the magnetic latitude (*Feldstein and Starkov, 1967; Milan et al., 2009*).

As magnetic reconnection both on the day- and on the nightside causes plasma motion inside the magnetosphere, the footprints of these field lines move through the ionosphere. This is illustrated in the lower part of Figure 2.1 b) which shows a view of the magnetic field line's track within the northern polar region under the influence of the Dungey cycle.

This movement of plasma called ionospheric convection transports ionospheric plasma from the dayside to the nightside. As the ionospheric plasma is caused by solar illumination, it is easy to understand why the ionospheric plasma densities are about a factor of 10 higher on the dayside compared to the nightside. Consequently, ionospheric convection can be looked upon as a massive conveyor belt that, whenever the Dungey cycle is active,

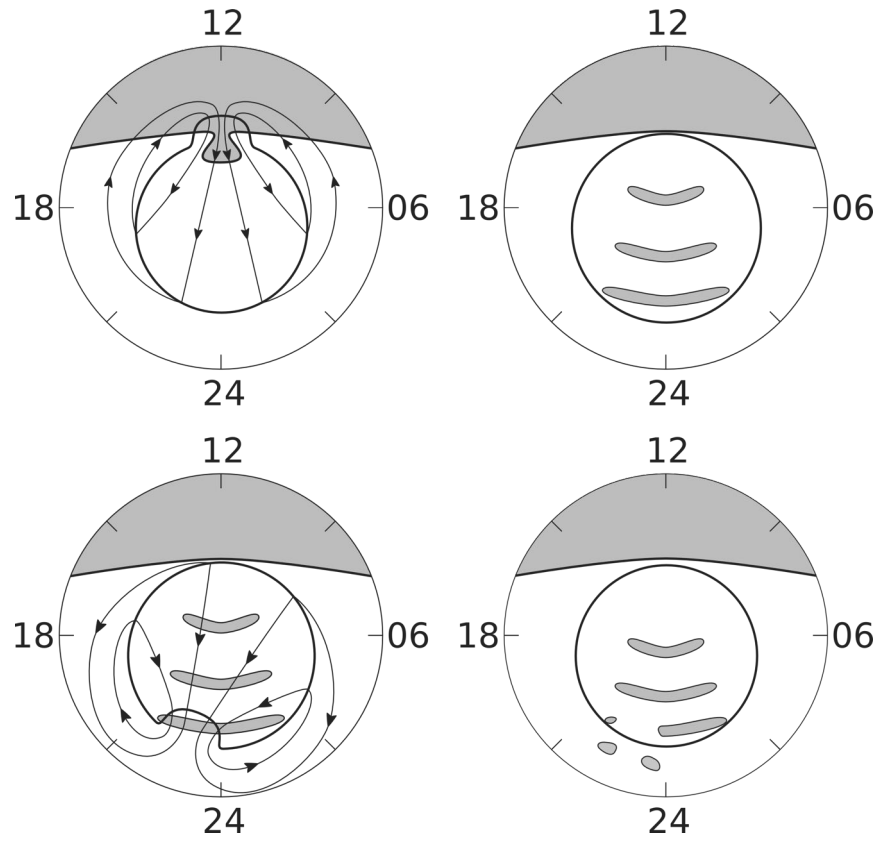


Figure 2.2: Schematic representation of the polar cap patch formation process ([Moen et al., 2015](#)).

transports high density plasma from the dayside over the polar caps into the nightside auroral region (along the tracks of numbers in the lower part of Figure 2.1 b).

As it turns out, the magnetic reconnection occurring on the dayside is not continuous but rather it occurs in bursts, lasting for about 2 minutes and separated by about 8 minutes. This leads to the situation sketched in Figure 2.2 which shows a top down view of the (northern or southern) polar region. The darker gray area represents the high density ionospheric plasma due to higher rates of solar illumination. As dayside reconnection causes bursts of ionospheric convection, chunks of the high-density plasma are placed on the anti-sunward conveyor belt; these are shown as gray blobs inside thick black line, which represents the ionospheric boundary of the polar cap and the auroral region. These islands of high density plasma inside the low density background are called polar cap patches and are, under the influence of subsequent magnetic reconnection bursts, pushed across the polar cap toward the nightside. It is the purpose of this Swarm + Innovation project to automatically detect polar cap patches in plasma density data from the Swarm satellites.

3 Space weather effects at high latitudes

The ionosphere/neutral atmosphere system is particularly complex at high latitudes. This is highlighted in Figure 3.1, which shows schematically the different processes that are at work in this system. At approximately 65 degrees magnetic latitude, the auroral ovals are located (in both hemispheres) which are centered around the magnetic poles (see Figure 3.2(a)), and thus they are asymmetric with respect to the geographic poles. The dynamics inside the polar cap are controlled by large-scale convective motion driven by the magnetosphere. Inside the polar cap the convection is predominantly antisunward over the magnetic poles, while at lower latitudes inside the auroral oval the return flow provides closure of the plasma circulation. The large scale convection motion is monitored for example by the SuperDARN radar network, and an example of such measurements is given in Figure 3.2(b). Because it is driven by the Dungey cycle and hence ultimately by magnetic reconnection, the details of the polar cap convection (e.g. its size and detailed orientation of convection cells) depend on the orientation of the IMF (e.g. *Ruohoniemi and Greenwald, 1996*).

The term space weather describes the impact of spatio-temporal variations of the Earth's near space environment on technological systems (*Bothmer and Daglis, 2007*). As such, space weather is directly related to the activity level of the Sun. For example, solar flares can result in increased radiation (X-rays, particle radiation), which can penetrate satellite subsystems and lead to electronic failures. Flare can also lead to so-called radio blackout storms which disrupt communication systems operating at high-frequencies. This is in particular valid at high latitudes. Large geomagnetic storms caused by Coronal Mass Ejections (CMEs) result in strong ionospheric currents which induce currents in the ground and lead to failure of power grid operations. One of such storms occurred on 29th Oct. 2003 (the Halloween storm), when power grids were destroyed in Sweden and South Africa,

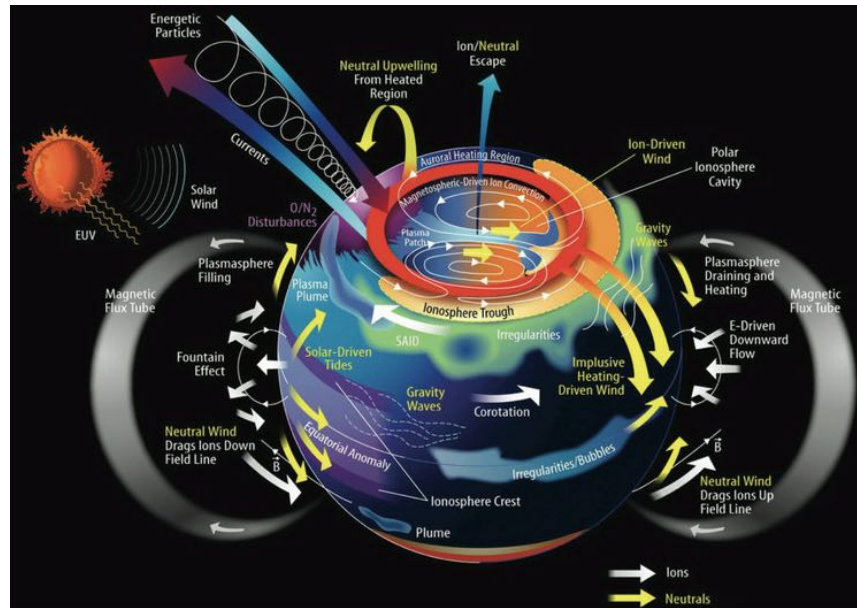


Figure 3.1: Complexity of the Earth's ionosphere-neutral atmosphere system. (Credits: NASA/J. Grobowsky)

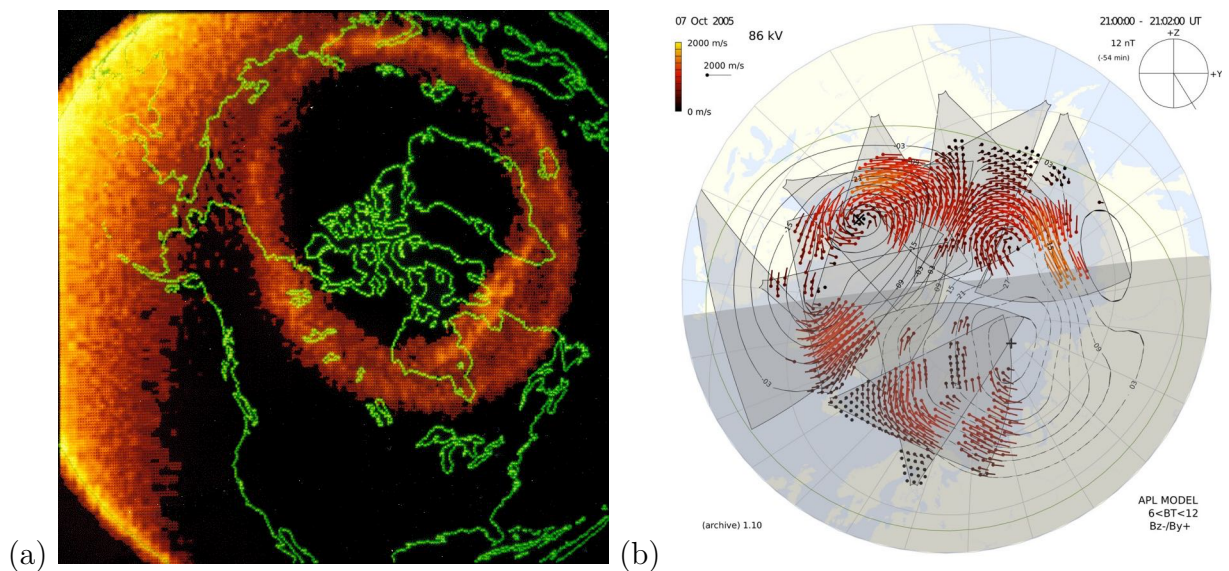


Figure 3.2: (a) Auroral oval above the northern hemisphere as seen by the Dynamic Explorer satellite. (Credits: NASA) (b) Example of the high latitude convection pattern as observed by the SuperDARN radar network. (Credits: SuperDARN)

and extensive satellite problems were reported ([Weaver et al., 2004](#)).

In the context of this project it is reasonable to focus on one particular aspect of space weather related to plasma density structuring inside the ionosphere. Small and medium scale irregularities in the electron density (at scale sizes of hundreds of meters to several kilometers) modify the electromagnetic properties of the ionosphere, which in turn can lead to interference and diffraction of transionospheric electromagnetic waves ([Martin and Aarons, 1977](#); [Fremouw et al., 1977](#); [Rino et al., 1978](#); [Aarons et al., 1981](#); [Kintner et al., 2007](#)). In particular, ionospheric plasma structuring can impact the signal integrity of Global Navigation Satellite Systems (GNSS) such as Galileo, GPS, or GLONASS by introducing fluctuations in the received wave amplitude and phase called scintillations. Thus, the positioning accuracy largely depends on the conditions inside the ionosphere. In severe cases there may even occur loss of lock, and the communication with the GNSS satellite is lost. This aspect of GNSS navigation is becoming of growing importance in the polar regions, the Arctic in particular, where the decrease in the ice cover results in increased human activity like shipping and aviation. Accurate positioning is important not only for navigation but also for search and rescue operations and operational safety in the polar regions.

In 1984 it was found that ionospheric plasma density enhancements inside the polar cap - now called polar cap patches ([Crowley, 1996](#)) - can degrade the signal quality of transionospheric radio waves received on the ground ([Weber et al., 1984](#)). In the following years a substantial amount of research has been conducted to further understand this phenomenon ([Weber et al., 1986](#); [Gondarenko and Guzdar, 2006](#); [Jin et al., 2014](#)).

The general consensus seems to be that as the polar cap patch drifts across the polar cap driven by ionospheric convection ([Buchau et al., 1983](#); [McEwen and Harris, 1996](#); [Moen et al., 2007](#); [Oksavik et al., 2010](#); [Zhang et al., 2015](#)), its trailing edge provides favorable conditions for the growth of the gradient-drift instability (GDI) ([Simon, 1963](#); [Tsunoda, 1988](#)). As this instability breaks up the drifting plasma density gradient associated with the polar cap patch ([Weber et al., 1984](#); [Basu et al., 1990](#); [Gondarenko and Guzdar, 2004a](#)), it creates plasma density structures on a variety of spatial scales ranging from kilometers down to meters ([Gondarenko and Guzdar, 2004b, 2006](#)). These plasma density structures can then, if they are large in amplitude, introduce phase scintillations onto transionospheric radio signals (e.g. [Rino, 1979](#)) and hence polar cap patches are regarded as a space weather threat ([Basu et al., 1988](#); [Basu et al., 2001](#); [Moen et al., 2013](#)).

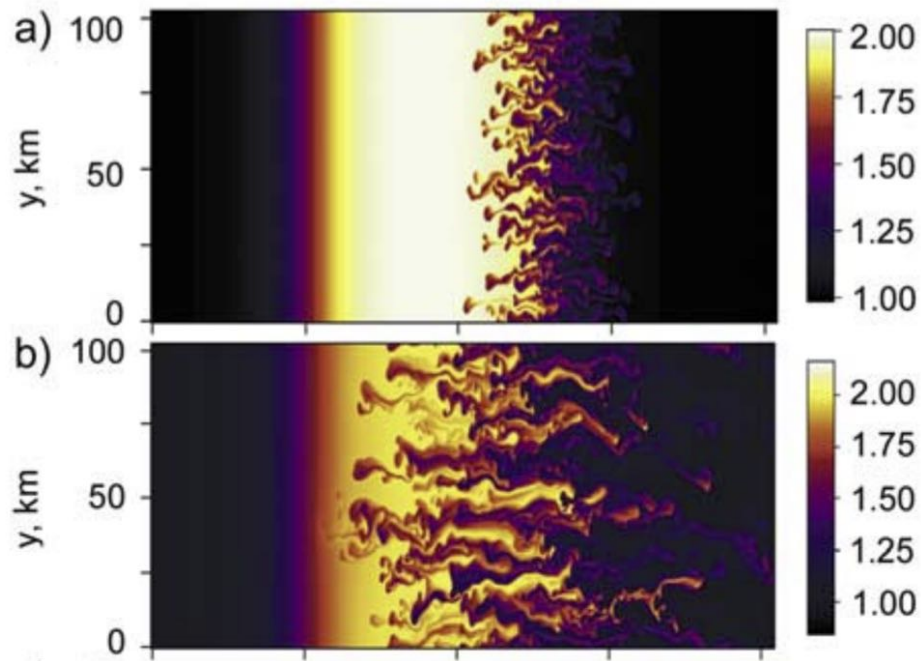


Figure 3.3: Numerical simulation of the temporal evolution of a drifting plasma density enhancement (light region). The upper panel shows the density distribution drifting from right to left. The lower panel shows how, after some time, the trailing edge of the patch is dissolved under the action of the gradient drift instability (*Gondarenko and Guzdar, 2004a*).

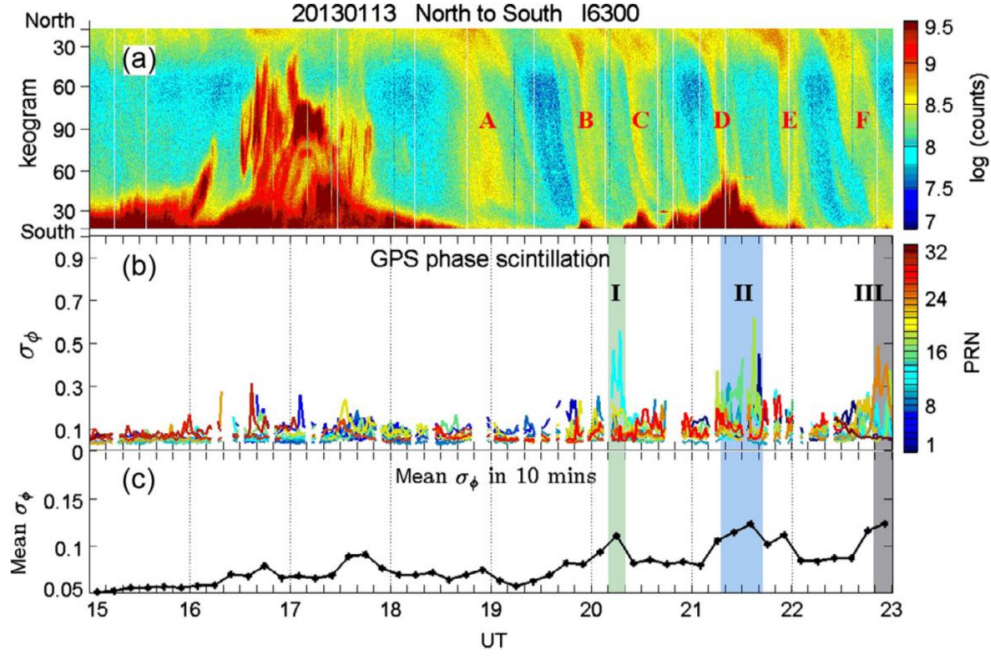


Figure 3.4: Panel (a) shows a keogram of auroral images taken on Svalbard. The lower two panels show instantaneous (panel b) and average (panel c) phase scintillations observed in GPS signals underneath the auroral imager (*Jin et al., 2014*). It can be seen that as polar cap patches (marked with capital letters) connect with the main auroral oval (high intensity brightness on the lower edge of the keogram), the scintillations are strongest.

The development of the GDI in a polar cap patch is illustrated in Figure 3.3 which shows results from a numerical simulation (*Gondarenko and Guzdar, 2004a*). It shows the dynamical evolution of a high plasma density island (light shading) drifting from right to left within a low plasma density background. At the beginning (upper panel) the trailing edge is fairly sharp, although initial structuring is observed. At a later time (lower panel), the structuring due to the GDI has permeated almost the entire patch. This figure illustrates why drifting polar cap patches represent a space weather challenge (*Moen et al., 2013*).

Recently, *Jin et al. (2014)* were able to show the detrimental effect of polar cap patches in conjunction with auroral precipitation on GNSS signals. Figure 3.4 shows in panel (a) a keogram from an auroral imager located on Svalbard. A keogram is constructed from 2D auroral images by extracting a single line of pixels from each image and stacking them beside each other; in a keogram, the horizontal axis represents time and the vertical axis represents location away from the zenith of the all-sky imager. Drifting polar cap patches

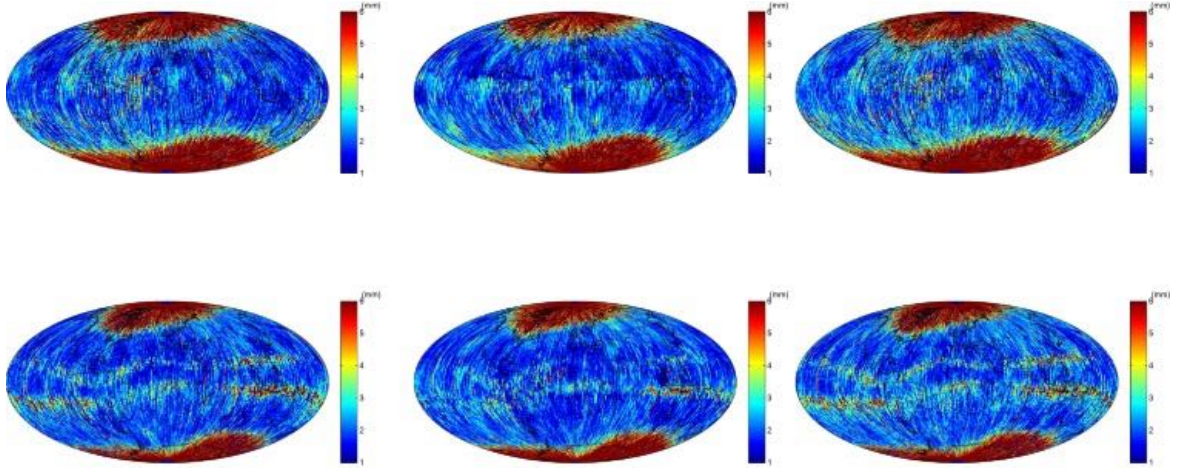


Figure 3.5: Global distribution of the bin-wise RMS error of the residuals from kinematic orbit determination of Swarm A (left column), Swarm B (middle column), Swarm C (right column) for ascending (top row) and descending (bottom row) arcs in the period of days 320–365 of the year 2014 (*Jäggi et al., 2016*).

can be observed by auroral imagers as airglow patches, i.e., regions of faint auroral emissions drifting with the background convection. In a keogram, patches are then represented by inverse integral signs of elevated auroral brightness. The lower panels show instantaneous (2nd panel) and average (bottom panel) phase scintillations as observed on the ground underneath the auroral imager. It can be seen that the scintillations are particularly large when the patches connect with auroral precipitation (high intensity brightness in the lower edge of the keogram colored red). These examples show that it is imperative to study the formation and transport of PCPs as well as the plasma instabilities occurring within them if one desires to develop a polar ionospheric space weather forecast system.

Ionospheric scintillations in the polar regions not only affect the accuracy of satellite positioning services on the ground, they can also impact the determination of terrestrial gravity field models derived from precise satellite orbit measurements. This is illustrated in Figure 3.5 which shows the global distribution of the RMS error in the kinematic precise orbit determination using data from the three satellites of the recent Swarm mission (*Jäggi et al., 2016*). It can be seen that the rms error is particularly high in the northern and southern polar regions. It is suggested that knowledge of the ionospheric plasma structures in these regions can reduce the error of precise orbit determinations.

4 Swarm as a platform for ionospheric study, instrumentation and orbits

The Swarm mission was launched on 22 November 2013 into an almost polar low Earth orbit (LEO) to study the dynamics of the Earth’s magnetic field and its interactions with the Earth system ([Friis-Christensen et al., 2008](#)). It belongs to the series of Earth explorer missions of the European Space Agency (ESA) and consists of three identical satellites. The core instruments of each satellite are the vector and scalar magnetometers to measure the direction and strength of the Earth’s magnetic field. Electrical field instruments, consisting of a thermal ion imager and a Langmuir probe, are used to measure the Earth’s electric field. The non-gravitational accelerations acting on the satellites are measured by onboard accelerometers. For the purpose of orbit determination each satellite is equipped with 8-channel dual-frequency Global Positioning System (GPS) receivers ([Zangerl et al., 2014](#)). Laser retro-reflectors enable an independent validation of the GPS-derived orbits by Satellite Laser Ranging (SLR). Due to this instrumentation one of the secondary objectives of the Swarm mission is dedicated to measure the Earth’s gravity field with the onboard GPS high-low satellite-to-satellite tracking (SST) system.

Figure 4.1 shows a view of one of the Swarm satellites as seen from the front. Centered on the faceplate the thermal ion imagers can be seen; these imagers are capable of directly imaging the thermal ion distributions and allow for the determination of ionospheric electric fields. Underneath the satellite the two Langmuir probes are mounted. They measure the plasma density and electron temperature.

Due to its high inclination orbit, the three Swarm satellites cross through the polar cap region twice per orbit; once through the northern polar cap and once through the southern polar cap. Therefore, the combination of Swarm’s orbit and its instrumentation makes it a uniquely equipped mission to study in great detail the formation and transport of polar cap patches, as well as the influence of plasma structures caused by the gradient drift

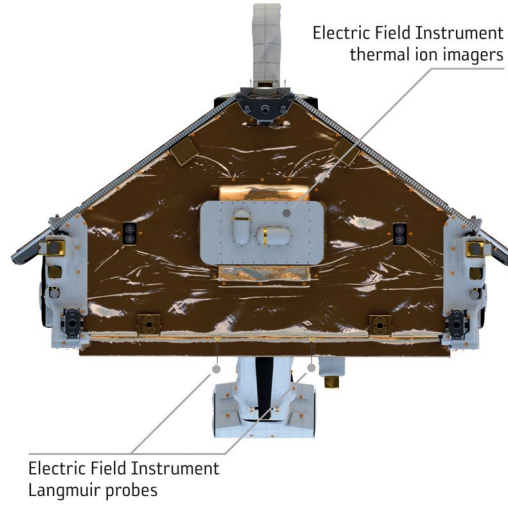


Figure 4.1: Frontal view of one of the Swarm satellites. The two parts of the electric field suite are highlighted. (Credits: ESA)

instability on GNSS signals.

Indeed, there exists a series of papers that have studied the occurrence of polar cap patches using polar orbiting spacecraft. [Coley and Heelis \(1995\)](#) developed an automated algorithm to detect plasma density enhancements inside the polar cap using data from the Dynamics Explorer 2 satellite. They defined these enhancements as regions where the plasma density increased to at least twice the background density; the background density was found through calculating a running mean of the measured plasma densities. For it to be flagged as a polar cap patch, the plasma density enhancement had to rise and fall to twice the background level within a certain spatial scale. [Coley and Heelis \(1995\)](#) found that the occurrence of polar cap patches in the northern hemisphere has a clear preference for the winter months.

Later, [Noja et al. \(2013\)](#) used total electron content (TEC) measurements from the GPS receiver on board the CHAMP satellite. Again, they used a similar algorithm as that developed by [Coley and Heelis \(1995\)](#) to identify polar cap patches. They presented global distributions of polar cap occurrence which show that they have a preference for certain geographical regions; these regions coincide with regions of large RMS error in precise orbit determinations derived from Swarm ([van den IJssel et al., 2016](#)) which strengthens our hypothesis that the two are related; it also highlights the possibility that better orbit determination could possibly be achieved if knowledge about local plasma density structures

is included in the orbit calculations.

5 Introduction to Polar Cap Products (PCP)

Motivated by the combination of fortuitous orbit and instrumentation of the Swarm satellites and the space weather threat that polar cap patches pose on GNSS signals, the Polar Cap Products project was developed within the framework of the of the STSE (Support To Science Element) Swarm+Innovation Program. It aims to be an extension of previous studies on polar cap patches presented above by including measurements of the ionospheric electric fields; the combination of these fields with plasma density measurements allows not only the automatic detection of polar cap patches, but also the calculation of growth rates of the gradient drift instability, which quantifies the rate at which plasma structuring occurs.

In fact, the feasibility of studying the formation and space weather impact of polar cap patches using data from the Swarm mission has already been documented in two papers that were written during the CaNoRock STEP PhD school at Andøya, Norway, in 2014. Within the first study ([Goodwin et al., 2015](#)) which focused on the formation of polar cap patches on the dayside and their association with large ionospheric flow channels, it was also shown that a series of polar cap patches as schematically drawn in Figure 2.2 is routinely observed in the plasma density data provided by the Langmuir probes on board Swarm. The second study ([Spicher et al., 2015](#)) presented calculations of the linear GDI growth rate associated with polar cap patches; it should be noted, though, that the necessary plasma velocities for these calculations were in this case not taken from the thermal ion imagers.

As part of this this project two new data products were developed from existing Swarm data products:

1. The polar cap patch index which identifies a Swarm measurement as part of a polar cap patch or not; and

2. The gradient drift instability growth rate and its error along the edges of polar cap patches.

The underlying scientific hypothesis is that the kilometer-scale density gradients along polar cap patches, which can be adequately resolved by Swarm measurements, provide a proxy for meter-scale plasma density structures. The amount of meter-scale structuring is determined by the gradient drift instability growth rate along the kilometer-scale plasma density gradients. Strong evidence supporting this hypothesis has been provided by sub-meter resolution plasma density and ion drift measurements on board sounding rockets ([Moen *et al.*, 2013](#); [Spicher *et al.*, 2014, 2015](#)). Meter-scale plasma density structures are important in a space weather context because they affect the signal quality of transionospheric electromagnetic waves at a wide range of frequencies, from HF signals used in aircraft communication to L band signals used for Global Navigation Satellite Systems. Validation of the scientific hypothesis is done in this project by comparing in situ measurements of plasma density gradients and gradient drift instability growth rate by Swarm with ground-based observations of signal scintillations from the GNSS receivers.

6 Approach, instrumentation, and challenges

In the past, a few attempts to automatically detect PCPs with in situ satellite data have been published. [Coley and Heelis \(1995\)](#) used time series of the plasma density from the retarding potential analyzer on board the DE 2 satellite (altitude between 300 and 1000 km). For an accurate detection algorithm to consistently work they identified four questions that are also highly relevant to this project:

- How is the edge of a PCP determined?
- What is the minimum plasma density enhancement defining a PCP?
- How is the background plasma density level determined?
- What are the minimum and maximum horizontal scale-sizes that define a PCP?

[Coley and Heelis \(1995\)](#) use a median filter technique to estimate the background and also filter out signatures at smaller scale-sizes which can be considered as noise in this context. They go on to define the edge of a PCP as a 40% plasma density increase above the background over a spatial scale of 140 km; in their work this is a necessary requirement for the plasma density enhancement to be identified as a PCP. Last but not least, they require the plasma density enhancement to be at least a factor of two larger than the background, which is consistent with the PCP definition provided by [Crowley \(1996\)](#). With this definition, [Coley and Heelis \(1995\)](#) and later [Coley and Heelis \(1998\)](#) are able to identify PCPs in in situ satellite data.

The PCP detection technique based on CHAMP (altitude about 400 km) TEC data described by [Noja et al. \(2013\)](#) is slightly different: they simply require that a positive slope in plasma density is followed by a negative slope, without putting any constraints

on the steepness of the slopes. Once two matching slopes are found, the background plasma density is found by linearly interpolating between the plasma density values at the beginning of the positive and the end of the negative slope. If the maximum TEC value between the slopes exceeds a certain threshold, the plasma density enhancement is identified as a polar cap patch.

Both of these techniques have disadvantages. By placing a steepness requirement on the slopes, [Coley and Heelis \(1995\)](#) fail to detect PCPs with shallow edges. This, however, is likely to occur on the trailing edge of the PCP which is acted upon extensively by the GDI. By not placing any constraints on the slopes, [Noja et al. \(2013\)](#) are likely to identify steps in plasma density as PCPs. Furthermore, they do not adhere to the generally accepted definition of a PCP as a twofold plasma density increase. In this project, we combine aspects from these two studies in a way which we find superior.

After the polar cap patches have been identified, we calculate the spatial plasma density gradient needed to find the linear growth rate of the gradient drift instability. This is simply achieved by least-squares fitting a linear model to plasma density measurements within a moving window. From the background plasma density, the spatial plasma density gradient, and the ion drift speed the GDI growth rate can be estimated. In a final step, the direction of the patch motion (i.e., the ion velocity) is compared to the satellite motion (which dictates the direction of the plasma density gradient) in order to find the leading and trailing edge of the patch.

The program logic of the software which produces both the polar cap patch index and the GDI growth rates is indicated in the flow chart shown in Figure 6.1. After the data from the Swarm electric field instrument (EFI) - which includes data from both the Langmuir probe and the thermal ion imager - has been read and the magnetic coordinates of the spacecraft has been computed, the data is passed to the functions `swarm_pcp_find_patches`, `swarm_pcp_calc_ngrad`, `swarm_pcp_calc_gdi`, and `swarm_pcp_write_cdf`. These functions find the polar cap patches in the plasma density measurements and calculate the GDI growth rate on the trailing edge of each patch. The results are written into a common data format (CDF) file; this file is then read and its contents are used to produce plots for the website. The parts indicated by a monospace font can be downloaded from the project [webpage](#).

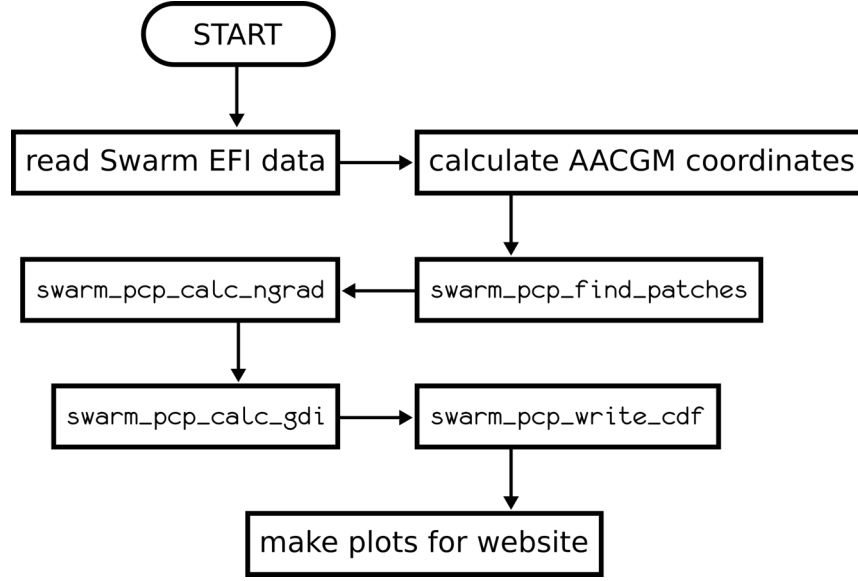


Figure 6.1: Flowchart of the overarching program used within the PCP project.

6.1 Initial approach

The work on the Polar Cap Patch Detection Algorithm (PCPDA) was first attempted with the use of wavelet transform. First the Swarm data was handled to determine the Sun's direction for the pass as well as relate geographical coordinates to magnetic ones. The polar cap was chosen to be above magnetic latitudes (MLAT) of 70 degrees. This is slightly less than the average position of the open/closed magnetic field line boundary (OCB) being 77 degrees, but has been chosen for testing purposes. Note that OCB might be also calculated dynamically, by taking into account electron temperature data combined with the density data. However, while this method will give clear results for the winter hemisphere, it might be uncertain for the summer hemisphere due to increased plasma density in the polar cap. Therefore, for the initial phase of the project and testing purposes we chose to use 70 degrees boundary. An example of different boundaries applied to a set of data from Swarm A is shown in Figure 6.2.

Having extracted the data for further analysis, which is being located above 70 degrees MLAT, we used a wavelet transform to determine different structures and patches within the given region. This proved to be successful in identifying various density enhancements within the polar cap, where the mapping of density enhancement was carried out in the wavelet domain and then translated back to the original signal. An example of the results

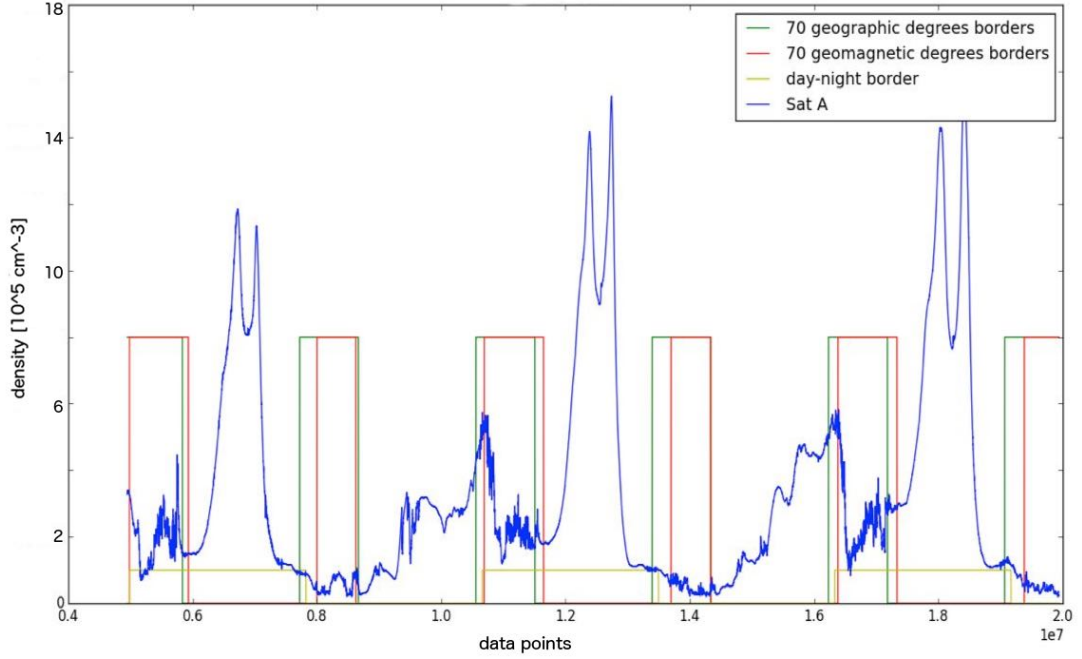


Figure 6.2: An example of applying of different boundaries to Swarm data. Only data within red squares (within 70 degrees MLAT) are considered in further data analysis.

is shown in Figure 6.3, where the wavelet transform of the data and the corresponding part of the time series with overdrawn plasma enhancement indicators are given.

However, while this approach can provide information on different scales and strengths of the density enhancements, it turned out that it was not optimal for the purpose of this study. The wavelet approach can provide the location of the density enhancement but it is not straightforward to then determine whether this enhancement qualifies as a PCP. One remaining question was the background density that needs to be determined with other methods. Moreover, the wavelet approach might not be clear for potential users, who are not familiar with details of the wavelet transform, and may also be computationally expensive. Therefore, it was decided to look for a more straightforward approach which could also account for, and improve previous attempts of the patch detection.

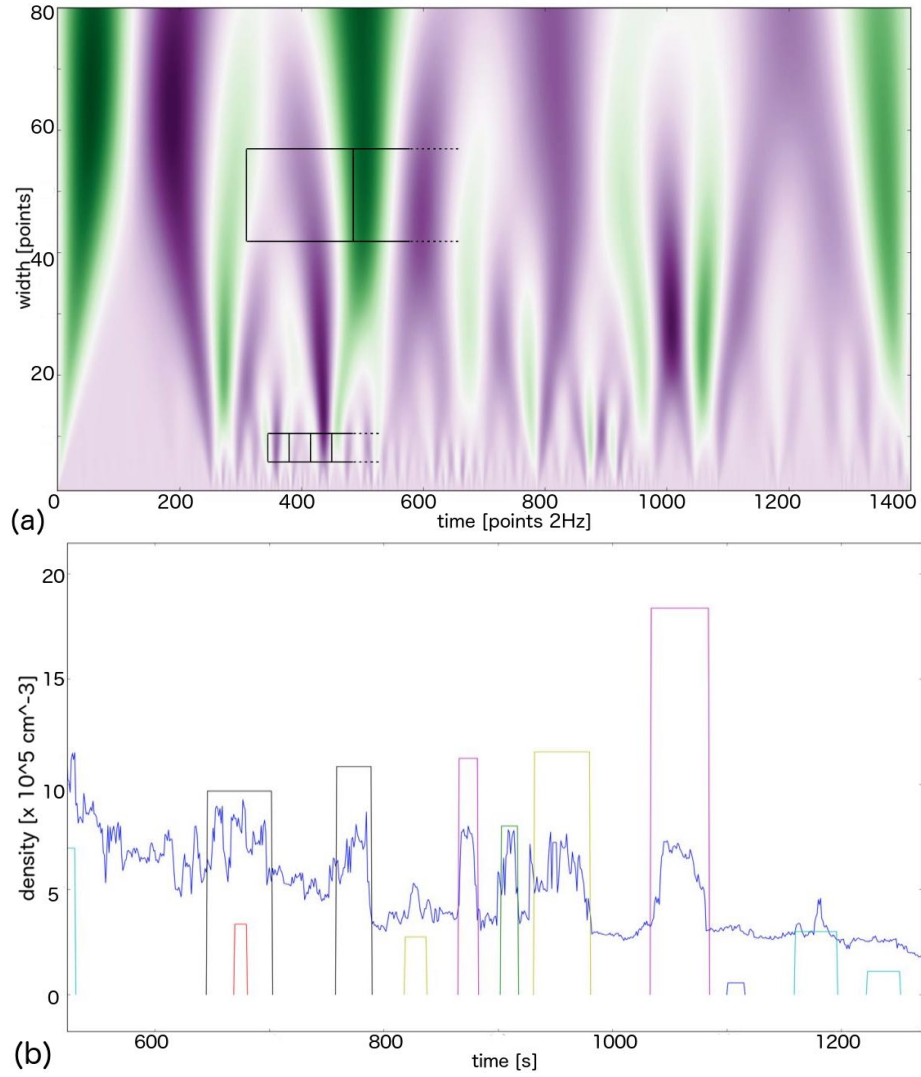


Figure 6.3: (a) An example of wavelet transform of the Swarm data with squares denoting different scales of the density enhancement. (b) The Swarm data with plasma density enhancements indicated in the figure. The heights of squares are related to the strength of enhancement (i.e., height $\times$ width).

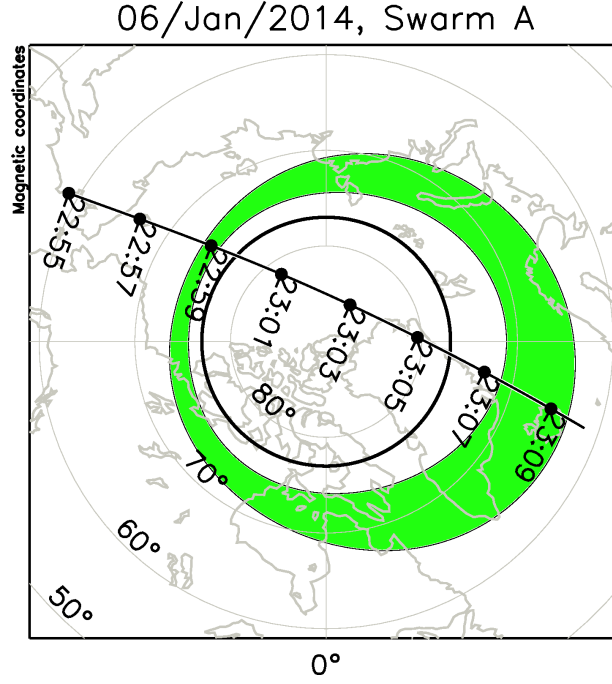


Figure 6.4: Plasma density data measured by the Swarm A satellite during a pass of the northern polar region on 06 January 2014.

6.2 Polar Cap Patch Detection Algorithm

The Polar Cap Patch Detection Algorithm as presented in this section is now being used to calculate the Polar Cap Patch Index (PCP Index).

The objective of this work package is to attach to each Swarm measurement of the plasma density a flag which identifies the measurement as part of a polar cap patch (PCP) or not. As outlined above, a PCP is defined as a plasma density increase above the background of at least a factor of two. It usually extends several hundreds of kilometers in latitude and several thousands of kilometers in longitude.

In Figure 6.4 an example pass of the Swarm A satellite through the northern polar region is shown in magnetic altitude adjusted corrected geomagnetic (AACGM) coordinates ([Baker et al., 1989](#)); the pass occurred on 06 January 2014, roughly in the noon-midnight plane. The green region indicates the statistical position of the auroral oval ([Feldstein and Starkov, 1967](#)) for the prevailing geomagnetic activity (Kp value of 1) during the pass.

Since PCPs occur by definition only inside the polar cap, i.e., on open magnetic field lines poleward of the open/closed field line boundary (OCB), we first need to find polar

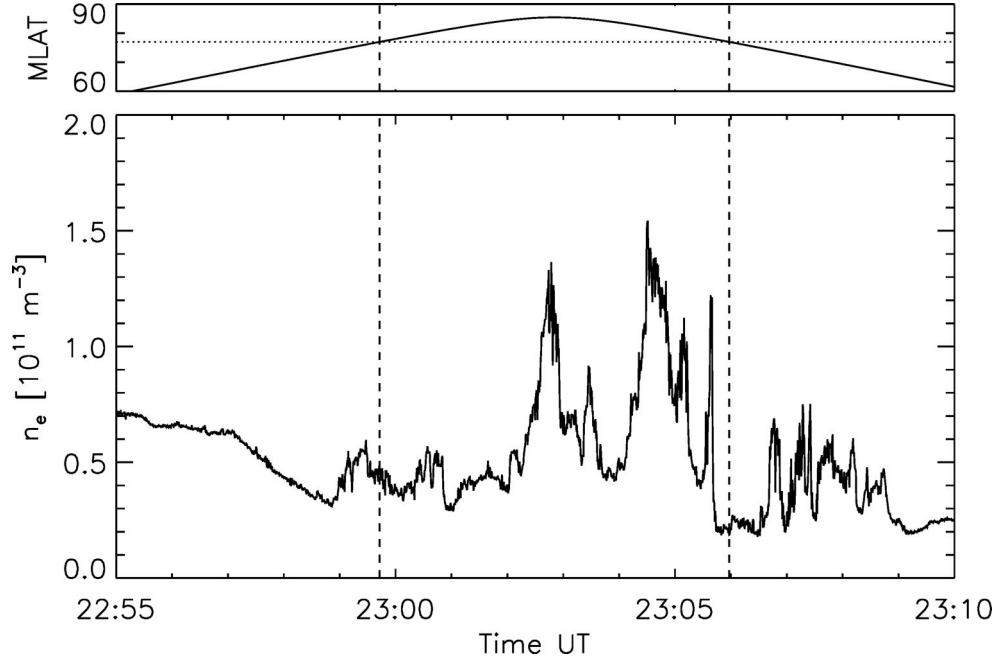


Figure 6.5: Plasma density data measured by the Swarm A satellite during a pass of the northern polar region on 06 January 2014.

cap boundary. Identifying the OCB is notoriously difficult although many attempts have been made ([Craven and Frank, 1987](#); [Frank and Craven, 1988b](#); [Lassen and Danielsen, 1989](#); [Elphinstone et al., 1990](#); [Mishin, 1990](#); [Newell et al., 1996](#); [Germany et al., 1997](#); [Brittnacher et al., 1999](#); [Milan et al., 2003](#); [Wing et al., 2010](#); [Ohtani et al., 2010](#); [Clausen et al., 2013](#)). For simplicity's sake we assume that the OCB is located somewhere below 77 degrees magnetic latitude, and therefore only consider plasma density measurements above that latitude. 77 degrees magnetic latitude is indicated by a black thick line in Figure 6.4; it shows that the statistical oval even for such a low Kp value is equatorward. For larger Kp values the oval will grow in size, showing that our estimate of the OCB located at 77 degrees magnetic latitude is conservative.

Figure 6.5 shows the plasma density measured during this pass. In the top panel the magnetic latitude of the satellite is shown, followed by the plasma density measured by the Langmuir probe. The vertical dashed lines give the times when the satellite crossed 77 degrees magnetic latitude, i.e., the magnetic latitude above which the algorithm considers density enhancements as patches. As the satellite approached the northern magnetic pole, it encountered a drop in plasma density (around 22:57 UT) associated with the equatorward edge of the high-latitude convection; the higher-density plasma equatorward of this edge

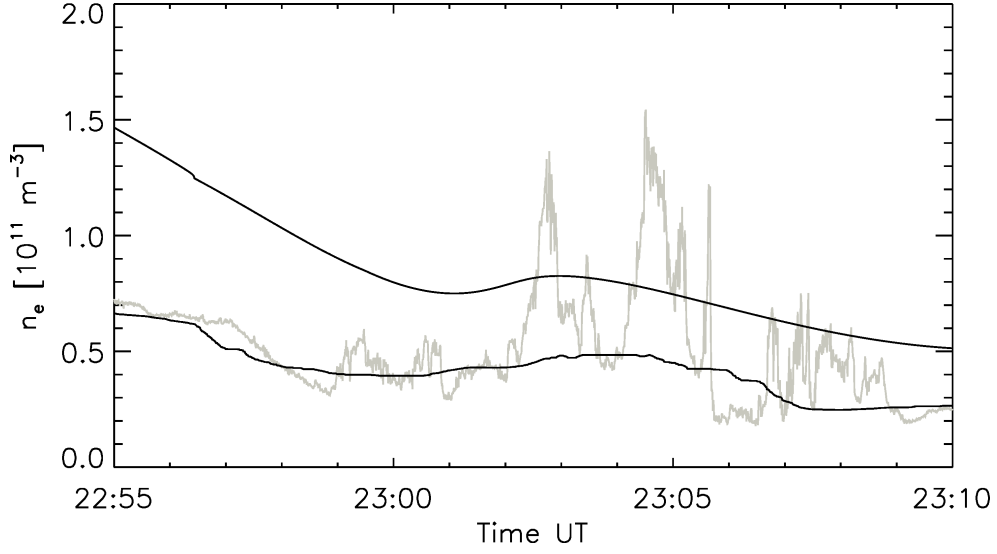


Figure 6.6: Plasma density data of the same pass as in Fig. 6.5 is shown in gray; the lower black line represents the background b calculated as the 35th percentile in a moving window with a length of 551 points; the upper black line shows the plasma density as predicted by the IRI-2012 model.

is the source of PCPs. Inside the polar cap it subsequently measured a couple of large plasma density enhancements before exiting into the auroral oval on the nightside around 23:07 UT.

6.2.1 The background b

Crucial to this task is the correct identification of the background plasma density inside the polar cap. First, the International Reference Ionosphere was used to provide information about the plasma background; however, it was quickly realized that this model did not provide data accurate enough within the polar regions.

Instead, a percentile filtering technique is now used to identify the background plasma density, similar to the previous work by [Coley and Heelis \(1995\)](#). In a window of 551 data points, the 35th percentile of the plasma density measurements is calculated for the standard 2 Hz plasma density data available from the Langmuir probes; that value is then defined as the background plasma density and the window is advanced one data point before the next background calculation. The length of the window corresponds to a distance of about 2000 km (or 20 degrees of latitude) traveled by the satellite along its track. Typically, the plasma density inside the polar cap is smaller than that of the

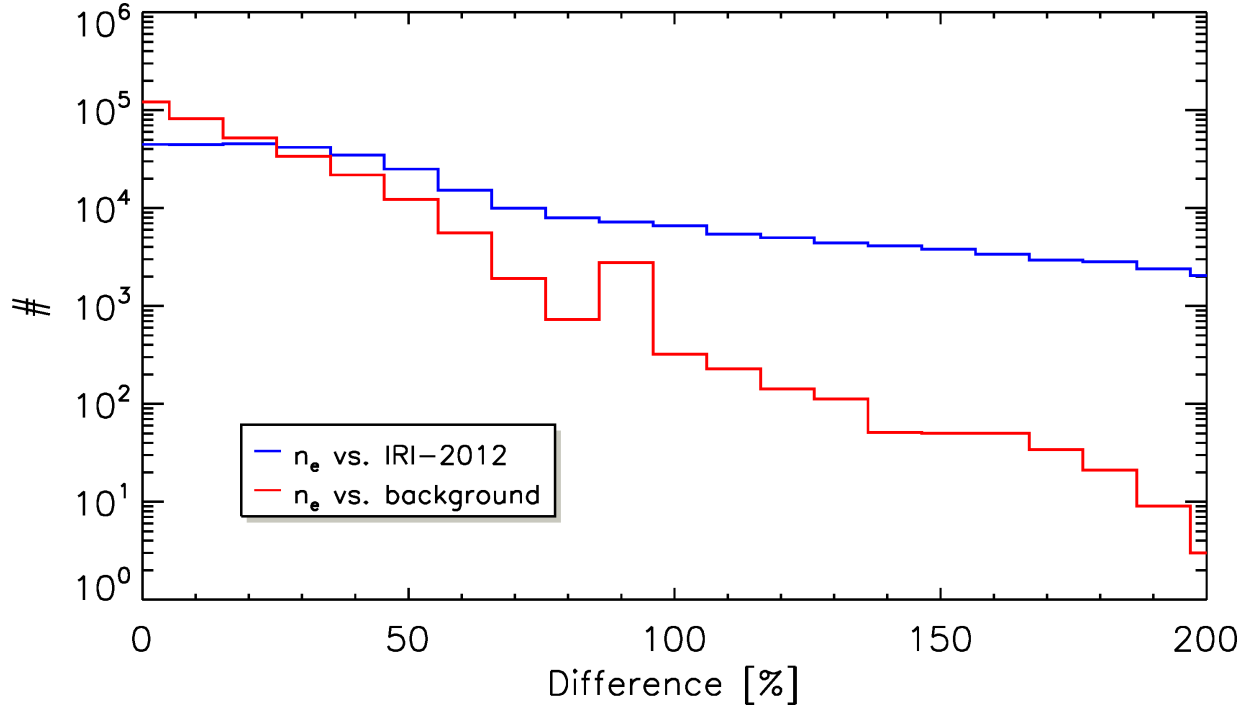


Figure 6.7: Histograms of the relative difference between the actual plasma density and the IRI prediction (blue curve) and the background b (red curve).

auroral region and only enhanced through polar cap patches. To not let individual strong density increases like polar cap patches affect the determination of the background, the 35th percentile was chosen to represent the background. In combination, the percentile filtering eliminates all plasma density structures with scale size larger than 2000 km; the largest extent of PCPs is typically 1000 km. For the same pass as shown in Fig. 6.5 the calculated background b is shown as the solid black lower curve in Figure 6.6. It shows that the percentile filtering correctly estimates the background plasma density inside the polar cap.

In Fig. 6.6 we also show the plasma density as predicted by the IRI-2012 model as the upper black curve. For this polar cap pass, the IRI is overestimating the plasma density by about a factor of two. We have also statistically compared the actual observed density with the IRI predicted plasma density and the background b as described above. This analysis shows (see Figure 6.7) that the relative difference between b and the unfiltered plasma density is significantly lower than the relative difference to the IRI, thereby confirming that the method chosen here to identify the background plasma density is superior.

To further check the quality of the determined background, we in Figure 6.8 show in the

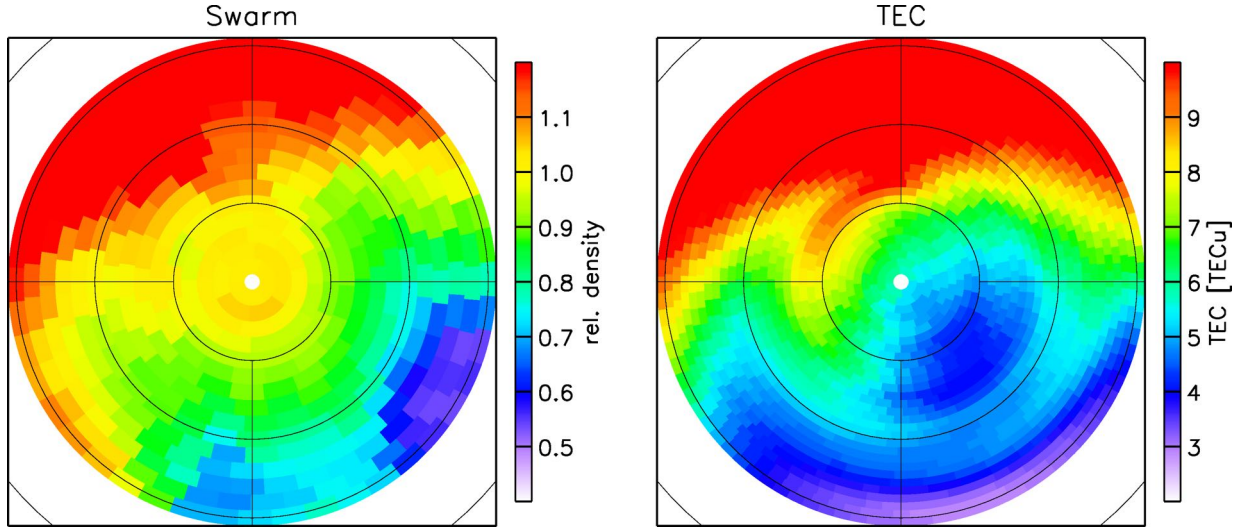


Figure 6.8: The left panel shows the spatial distribution of the average relative plasma density across the northern polar region between Dec 2013 and Jul 2014. The data is presented in a MLAT/MLT coordinate system with 12 MLT located toward the top. The right panel shows the total electron content derived from GPS measurements for a similar time period.

left panel the average relative plasma density on an equal area grid across the northern polar region in a MLAT/MLT coordinate system (*Baker et al., 1989*); 12 MLT is located to the top. For each satellite and day between Dec 2013 and Jul 2014 the plasma density measurements above 60 degrees MLAT were scaled by the daily average of the plasma density in that region. These relative plasma density measurements were then gridded and the median in each grid cell was calculated and plotted. The scaling of the values relative to the daily averages was performed to mitigate seasonal variations of the plasma density; as the satellites precess through local time, the plasma density measurements fill only certain spatial bins, thus introducing a seasonal bias to the bins.

As expected, the plasma density is larger on the dayside than on the nightside. The dayside high density plasma reservoir can also be seen to be tilted toward the dusk sectors.

On the right of Figure 6.8 we show as a proxy for ionospheric plasma densities the average distribution of the total electron content (TEC). These averages are based on GPS measurements made by an array of ground-based receivers covering large parts of the northern hemisphere continent (*Rideout and Coster, 2006*). The qualitative agreement between the TEC and the background determined from Swarm plasma density observations is reasonable, indicating that our background determination procedure is adequate.

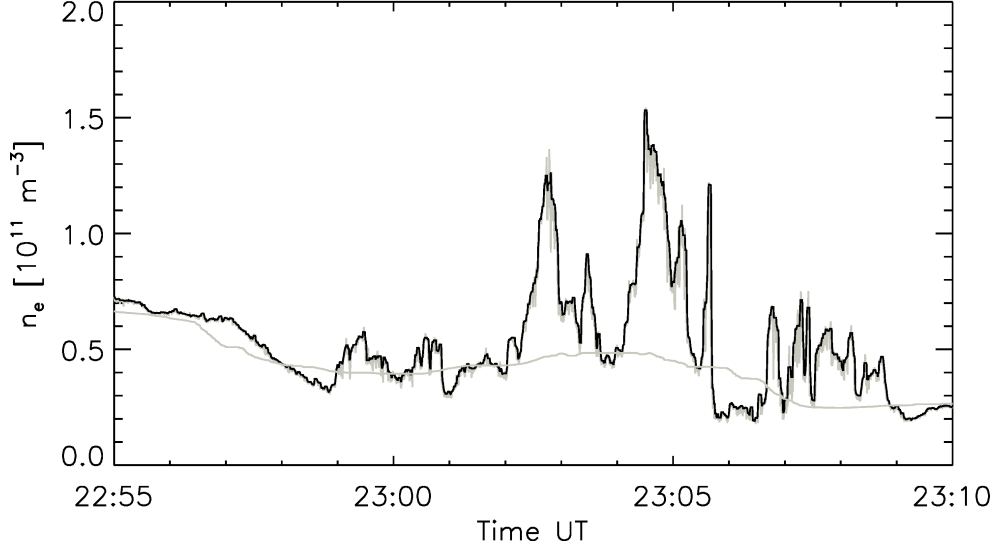


Figure 6.9: Original and background plasma density data of the same pass as in Fig. 6.5 are shown in gray; the black line represents the foreground f calculated as the median in a 7-point moving window.

6.2.2 The foreground f

To obtain the foreground plasma density f , the original 2 Hz plasma density data provided by the Langmuir probe on board the Swarm satellites are also percentile filtered; patches are typically several hundreds of kilometers wide, such that a percentile filter of width 7 is chosen to eliminate structures smaller than about 25 km. Within this window the 50th percentile (median) is designated to be the value of the foreground plasma density f . For the Swarm A pass across the southern polar region shown in Fig. 6.5, the foreground f is shown in Figure 6.9; also shown (in gray) are the measured plasma density and the background b .

6.2.3 The ratio inc

From the foreground f and the background b plasma density the increase inc is calculated:

$$inc = \frac{f}{b}. \quad (6.1)$$

In Figure 6.10 inc is shown in the bottom panel, alongside the original plasma density measurements (in gray) and the background b and foreground f (both in black) in the

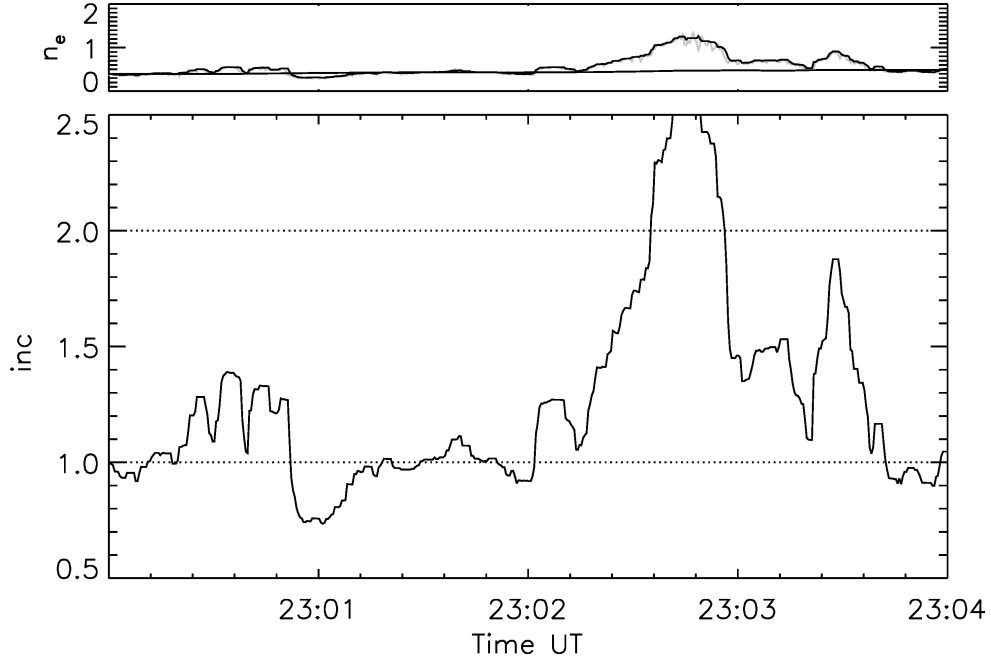


Figure 6.10: For the same pass as in Fig. 6.5 the original, background, and foreground plasma density data is shown in the upper panel. The lower panel shows the increase in plasma density inc .

upper panel. It can be seen that the plasma density enhancement is indeed more than a factor of 2 larger than the background and hence should be flagged as a PCP. Outside of the plasma density enhancement the ratio inc is very close to one, indicating that the value of b is a good representation of the actual background value.

6.2.4 The PCP detection algorithm

Once the plasma density ratio inc is determined from the background b and the foreground f , all values of inc are examined and the algorithm proceeds as indicated by the flowchart in Figure 6.11.

First, it is checked whether the measurement was performed above 77 degree magnetic latitude or below -77 degree magnetic latitude; if so, it is assumed that the measurement was made inside the polar cap (poleward of the open/closed field line boundary) and it is examined whether the inc value is above 2. If yes, and it is the first value that exceeds the threshold, a polar cap patch is started by setting the variable `pstarted` to 1. Furthermore, a counter for the length of the polar cap patch `plen` is initialized. Under the condition that subsequent inc values also exceed the threshold (and that still `pstarted` = 1), this

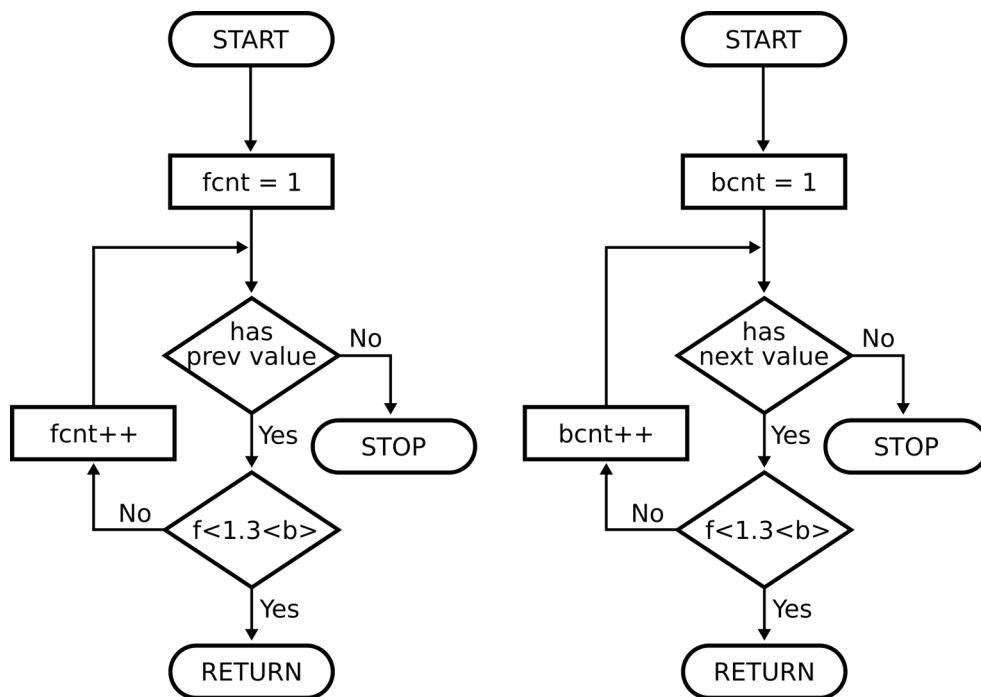


Figure 6.12: Flowcharts of those parts of the PCP detection program that identify the edges. The left chart finds the left edge, and the chart on the right finds the right edge. Both charts are placed in Fig. 6.11 at "find edges".

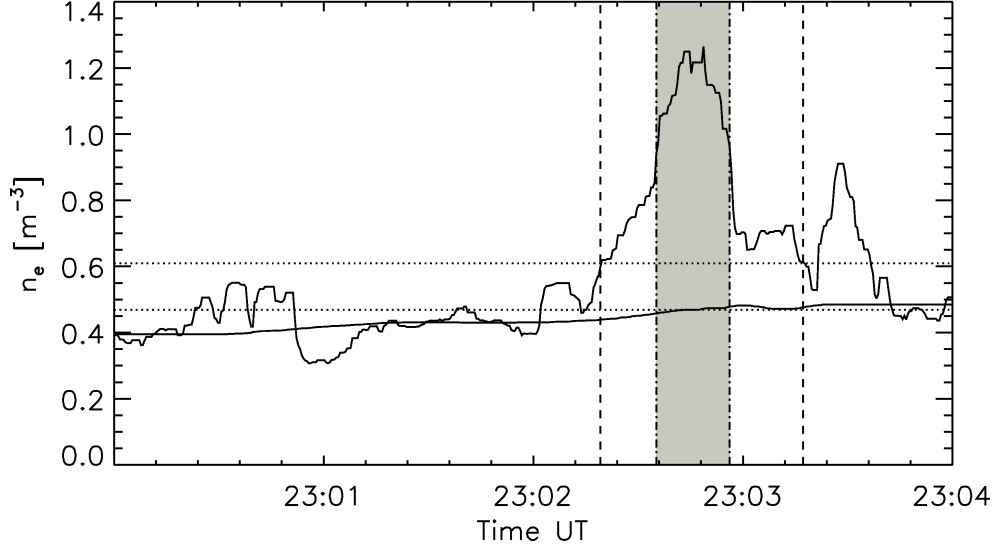


Figure 6.13: Plasma density data of the same pass as in Fig. 6.5. The PP identified by the detection algorithm is highlighted in gray; the beginning and end of the edges are marked by vertical dashed lines. Horizontal dotted lines mark the average background plasma density inside the PP and its 30% threshold.

counter is incremented until *inc* drops below a value of 2. This region of the plasma density observations, where the foreground is at least twice as large as the background, constitutes what will be called the "patch proper" or PP. Once the PP is identified, the average (mean) background plasma density within the PP, $\langle b \rangle$, is calculated.

Starting at the beginning of the PP, previous foreground density values are checked whether they drop below $1.3\langle b \rangle$, i.e., below 1.3 times the average background density within the PP. The first value that does (i.e., *fcnt* points before the start of the PP) is marked as the beginning of the left edge of the patch. The same procedure is repeated for values following the last value of the PP, identifying the first point *bcnt* points away from the end of the PP where the foreground plasma density drops below $1.3\langle b \rangle$. This point marks the end of the right edge of the patch. A flowchart for this part of the algorithm is provided in Figure 6.12.

If the entire length of the patch from the beginning of the left edge through the PP to the end of the right edge, i.e., $\text{bcnt} + \text{plen} + \text{fcnt}$, is longer than the minimum patch length (set to 15 data points or, at 2 Hz, correspondent to about 50 km), then the location

of the patch is saved.

It is important that, during the edge detection process, the foreground plasma density values are compared to the average background value of the PP $\langle b \rangle$, and not to the background b . If the foreground is simply asked to drop to within 30% of the background, steep cliffs will erroneously be identified as PCPs.

Of course, sometimes the foreground does not return below $1.3\langle b \rangle$. In fact, if f does not drop below $1.3\langle b \rangle$ poleward of ± 77 degree magnetic latitude, a plasma density enhancement is not identified as a PCP.

The criteria for a plasma density enhancement to be identified as a PCP can be summarized as follows:

- The plasma density background is defined as the 35th percentile within a moving 551-point window of the plasma density measurements.
- The plasma density foreground is defined as the 50th percentile within a moving 7-point window of the plasma density measurements.
- The plasma density enhancement must be at least a factor of 2 larger than the background.
- On both sides of the region where the plasma density increase is at least twice the background values (the patch proper, PP), there has to be a region where the plasma density decreases to values of the order of the background density during the PP.
- The entire length of the patch, PP including edges, must be larger than 50 km.

The result for the pass on 06 January 2014 is shown in Figure 6.13. The gray area highlights the PP, i.e., the region where inc exceeds the threshold value of 2. The vertical dashed lines give the beginning and end of the left and right edge of the patch, characterized by the fact that the foreground f drops below 1.3 times the average background value during the PP; $\langle b \rangle$ and the 30% threshold value are marked by horizontal dotted lines.

Although the edges are identified using the above procedure, we are not yet able to determine which edge is the leading and which is the trailing edge. Therefore, the polar cap patch index is set to the value 4 throughout the patch proper, and to 1 throughout the two edges. Once the relative direction between the ion drift and the spacecraft velocity (i.e., the direction of the spatial plasma density gradient) is known, the trailing and leading

edge of each patch can be correctly identified and the associated polar cap patch index values are adjusted (a value of 2 for the leading edge and a value of 3 for the trailing edge). In those cases where no ion velocity data are available, the polar cap patch index will remain at a value of 4 throughout the patch proper and a value of 1 throughout the two edges.

6.3 Gradient drift instability growth rate

After the polar cap patch detection algorithm has been applied to the plasma density data, the spatial plasma density gradient κ along the track of the satellites is calculated. Finally, we include Swarm measurements of the ion drift velocity to identify the leading and the trailing edge of each PCP to then, only on its trailing edge, calculate the linear growth rate of the gradient drift instability given by ([Tsunoda, 1988](#)):

$$\gamma = \frac{v_0}{L}, \quad (6.2)$$

where v_0 is the ion drift speed in the direction of the spatial plasma density gradient κ (i.e., along the satellite track), and L is the plasma density gradient length. The gradient length is given by:

$$L = b\kappa^{-1} = b \left(\frac{dn}{dx} \right)^{-1}, \quad (6.3)$$

where b represents the background plasma density, and κ is the horizontal plasma density gradient.

6.3.1 The plasma density gradient $\kappa = dn/dx$

The density gradient on the trailing edge of a polar cap patch is a crucial parameter for the GDI growth rate γ . Here it is determined as the slope of a linear fit through the density data over a moving window of length 27 data points, corresponding to a spatial scale of about 100 km.

The edges of the PCP found by the polar cap patch detection algorithm are typically of the order of 200 km. A linear regression over 100 km will therefore smooth out the density data, but will for most PCPs be shorter than the edge. Figure [6.14](#) shows an example of the gradient calculation; the upper panel shows a PCP identified in the plasma density measurements by the PCPDA on 15 May 2014 by Swarm A; the corresponding gradient

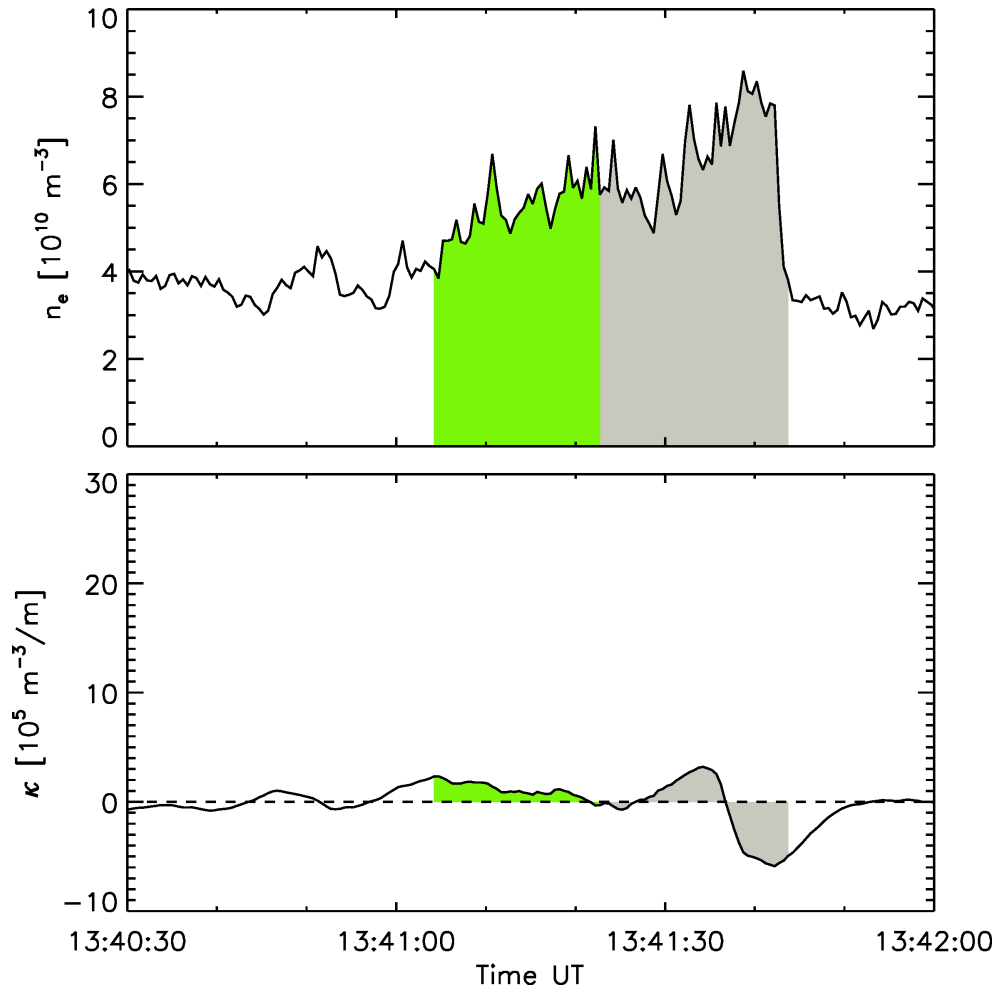


Figure 6.14: Plasma density (top panel) and plasma gradient (bottom panel) for a PCP detected on 15 May 2014 by Swarm A. The green area indicates the trailing edge, the gray area indicates the rest of the PCP. The edges were identified using ion velocity data.

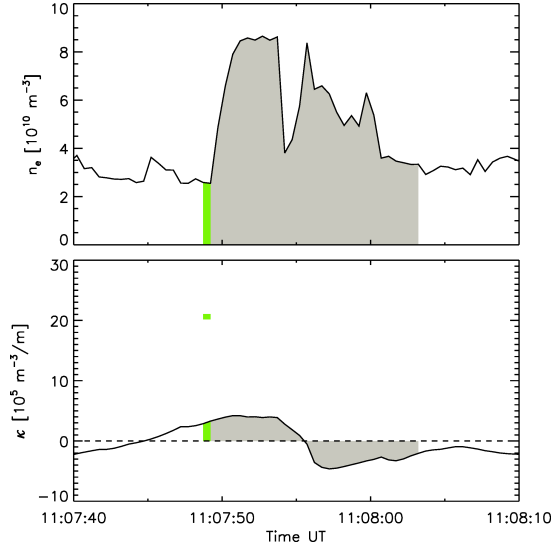


Figure 6.15: Plasma density (top panel) and plasma gradient (bottom panel) for a PCP detected on 17 May 2014 by Swarm A. Using ion velocity data the leading and trailing edge of the PCP could be identified: the green area indicates the trailing edge, the gray area indicates the rest of the patch. The green line in the lower panel is the mean plasma density gradient across the entire trailing edge.

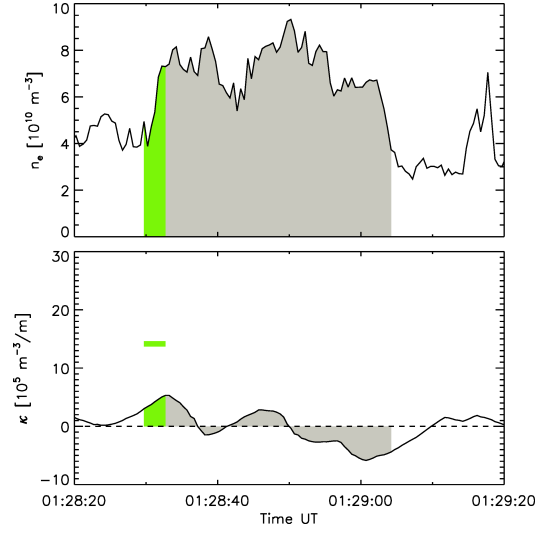


Figure 6.16: Plasma density (top panel) and plasma gradient (bottom panel) for a PCP detected on 18 December 2013 by Swarm A. Using ion velocity data the leading and trailing edge of the PCP could be identified: the green area indicates the trailing edge, the gray area indicates the rest of the patch. The green line in the lower panel is the mean plasma density gradient across the entire trailing edge.

is shown in the lower panel. Ion velocity data was available for this interval such that the trailing and leading edge of the PCP could be identified; in Fig. 6.14 the trailing edge is shaded green while the rest of the PCP is shaded gray.

While the edges of a PCP detected by the PCPDA are strictly identified according to the conditions given above, they not always match the expectations of a knowledgeable human observer. This is illustrated in Figure 6.15. The upper panel shows the plasma density, with one edge marked in green, and the corresponding density gradient is shown the bottom panel. As seen from the figure, a significant increase of the density occurs outside the edge marked in green, within the patch proper. For such strong density increase, it sometimes might be difficult to determine the gradients on the edges, and for this reason we have chosen to calculate the gradients in the entire patch and provide them in the data files. Therefore, users can choose to include the edge borders found by the Polar Cap Products, or define their own edges. Another advantage of including gradients for the whole patch,

is that there are often several areas in the patch with a positive gradient outside the edge, which can correspond to patches that have already been structured. This can be seen in Figure 6.16, where there is a positive gradient in the middle of the patch. By including these data, the plasma instability growth rate and the nature of polar cap patch can be studied not only at the edge of the patch, but also in the patch proper.

Data files also contain values for the average gradient in the trailing edge. This value is defined as the slope of a linear fit to the density in the trailing edge. The average gradient is thus not affected by the scale length of 100 km, but is based on the actual length of the edge. The advantage of this method is that the gradients for edges shorter than the length of 100 km will not be reduced, and will be properly represented. As seen in Figure 6.15, the trailing edge (in green) is relatively short which leads to underestimated gradient presented in the lower panel, while the mean gradient of the trailing edge (shown as a green line in the lower panel) properly reflects the gradient. This effect is also seen in Figure 6.16.

When the ion drift velocity data is not available, only the plasma gradients are saved to the output data file and the value of the PCP flag is set to 1. It is still possible to obtain some information about the patch, as the gradients themselves can give an indication of the nature of the patch. Steep gradients indicate fast erosion, while irregular patches with smaller gradients might already have been affected and structured by the instability. The patches can therefore to a certain extent be examined even without the velocity data.

6.3.2 The ion velocity v_0

The ion velocity data is available as a part of the Thermal Ion Imager, TII derived parameters. However, an anomaly affecting TII has not allowed for a continuous data production after the initial stage of the mission. While this problem is being under evaluation and there are perspectives of obtaining reliable data, the ion velocity is currently only available for selected periods.

To find the gradient drift instability growth rate, only the ion velocities over the polar caps are needed. Most of the time, one polar cap is more exposed to the sun than the other, and the photoionization rate varies over the two poles. This leads to differences in ion densities in the polar caps, which again can affect the ion velocity measurements, since lower plasma densities will result in lower quality ion velocity measurements. This

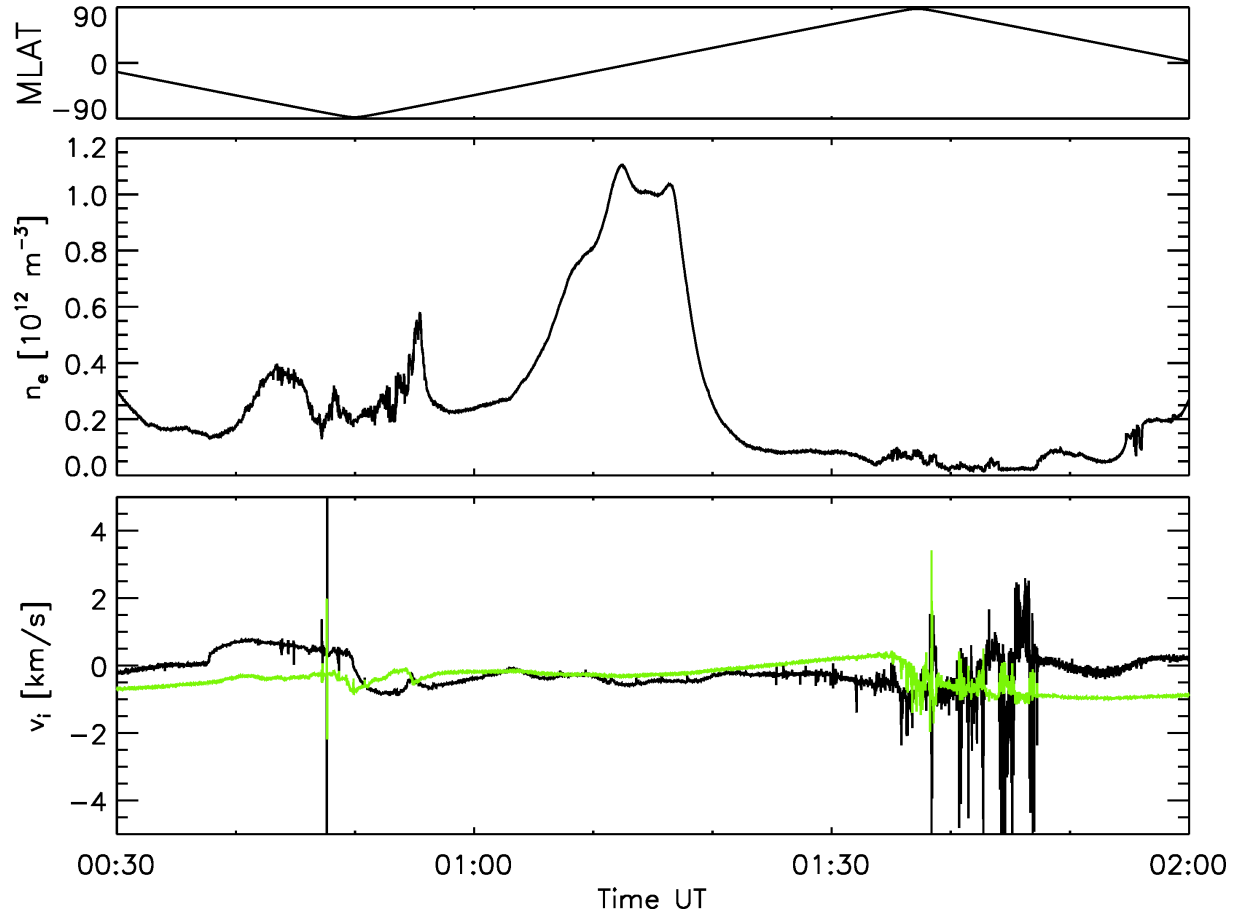


Figure 6.17: Plasma density (middle panel), and ion drift velocity (bottom panel) measured with Swarm A on 13 December 2013. The top panel presents geographic latitude of the satellite: +90 corresponds to the North Pole (which is in the shadow), while -90 refers to the South Pole which is illuminated in December. The velocity is decomposed into northward (black line) and eastward (green line) components.

is shown in Figure 6.17, where the top panel with the latitude indicates the location of Swarm A with respect to the geographic poles, while other panels show the corresponding velocity data. As seen in the middle panel, the south pole (corresponding to the latitude of -90) has higher density than the north pole (latitude $+90$). This has a significant impact on the ion velocities, shown in the bottom panel. It is evident that velocities taken over the north polar cap are noisier (between time 01:30 and 01:47), and these data need to be interpreted with care.

To investigate the velocities further, in Figure 6.18 a zoom-in for the data over the poles is shown for the satellite pass presented in Figure 6.17. Statistically, the plasma convection in the polar caps results in an anti-sunward ionospheric flow. The northward velocity component is therefore expected to change the sign as the satellite passes the pole. This can indeed be observed in the first velocity plot in Figure 6.18, where the black line (northward component) indicates a velocity change from about 500 m/s to -500 m/s. This clear change of sign occurs in the southern hemisphere which was exposed to the sun. The data for the northern polar cap, which was in the shadow, is characterised by a higher noise level, and a clear sign change of the northward velocity component cannot be observed. Users of the PCP data products should be aware of the high noise levels for ion velocities derived from TII measurements in the winter hemisphere.

The ion velocity will be used in conjunction with the plasma density gradients in order to calculate the GDI growth rate. Since the plasma density gradients are determined as the slope of a moving 27-point window, we choose to filter the ion velocity data over the same window length. The filtering is performed as the 50th percentile in a window of 27 data points.

In the dataset produced by the PCP algorithm, also the filtered velocity data is included. Filtered velocities are available for the entire patch, so as in the case of the gradients, the user may choose to use them accordingly. The average of the filtered velocities are included for the trailing edges.

6.3.3 Trailing and leading edge

Identifying leading and trailing edges of the polar cap patches is important because plasma density gradients which are parallel to the background ion drift are susceptible to the plasma instability, whereas gradients that are anti-parallel to the ion drift are expected to

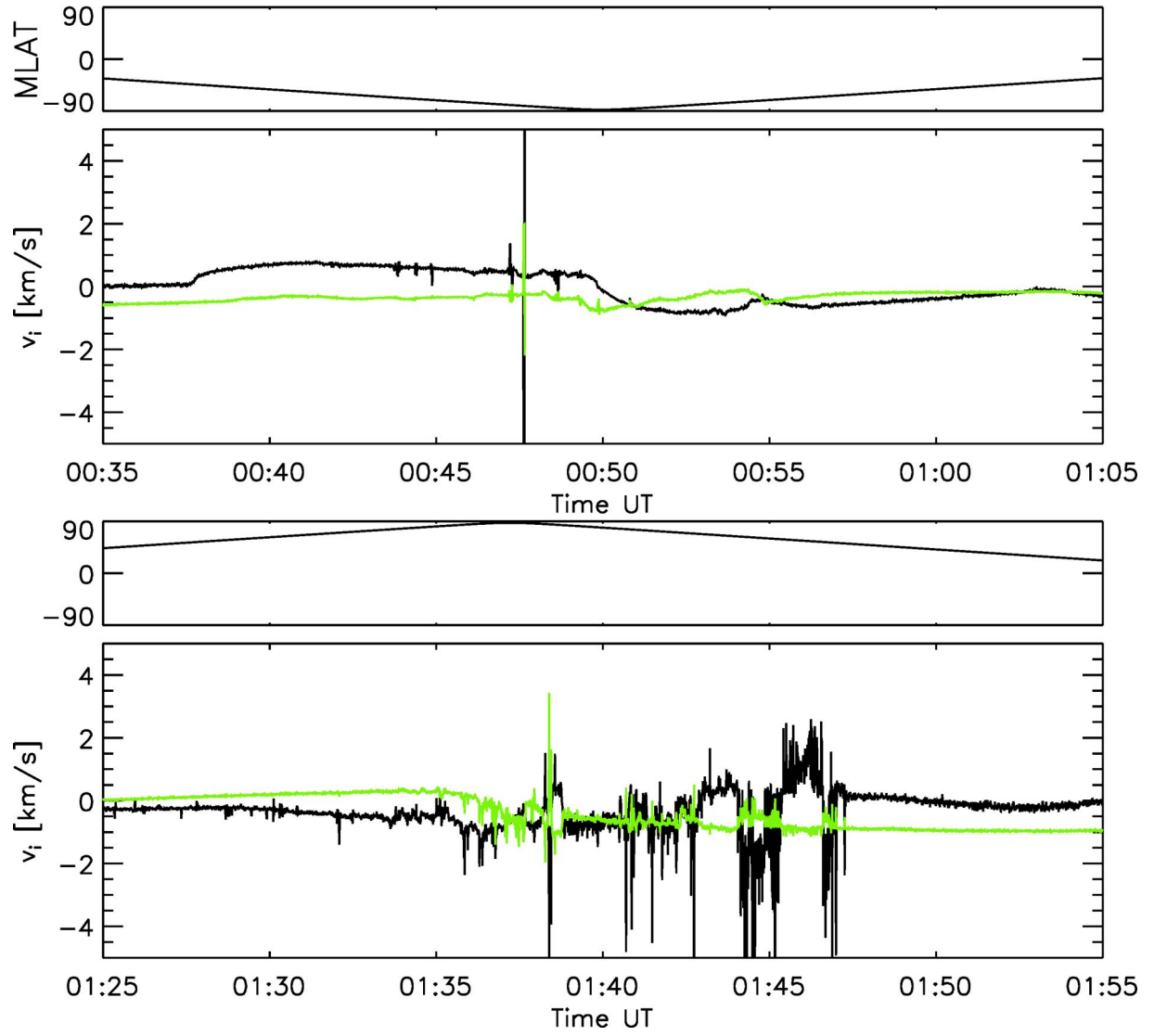


Figure 6.18: Velocity data over the two poles for the satellite pass presented in Figure 6.17. The southern hemisphere is presented in the two upper panels, while the northern hemisphere is in the two lower panels.

be stable. The leading edge of a patch is defined as the boundary of the polar cap patch where the plasma density gradient is anti-parallel to the ion drift, whereas at the trailing edge the two vectors are parallel.

The polar cap index produces four timestamps per patch, indicating the beginning of the edge, beginning of patch proper, end of patch proper, and end of the edge. To determine if the trailing edge is the first or the second edge in an observed patch, the northern and eastern component of the ion drift velocity $\vec{v}_{ion}$ and the space craft velocity $\vec{v}_{sat}$ are used. If the angle α between the two velocity vectors is between 0 and 90 degrees, the satellite reaches the trailing edge first, and if the angle is between 90 and 180, the first encountered edge is the leading edge, while the second encountered edge reached is the trailing edge. The angle α between the two velocity vectors is found with:

$$\cos(\alpha) = \frac{\vec{v}_{sat} \cdot \vec{v}_{ion}}{|\vec{v}_{sat}| |\vec{v}_{ion}|} \quad (6.4)$$

The two situations are illustrated in Figure 6.19, where α_1 represents a parallel component of the two velocity vectors, and α_2 indicates the anti-parallel component. Note that in case of large noise in ion velocities, especially over the winter hemisphere, this method might give conflicting results. The angle α is calculated for every individual polar cap patch (from the start of the first until the end of the second edge) and used to determine if the first or second edge reached by the satellite is the trailing edge. Note that this will likely be opposite over the two hemispheres.

The project homepage contains plots of the angle between spacecraft velocity and ion drift velocity, and two examples are presented in Figure 6.20. The ion drift speed is in black, and the gray line indicates the angle. Here, "+||" indicates parallel velocities, and "-||" are anti-parallel velocities. The upper panel shows a polar pass with a steady velocity and parallel velocities for the whole polar pass. The lower panel however, showing an adjacent polar pass, has a highly fluctuating ion drift speed and hence also rapidly changing angle. In this case, with the daily mean we can avoid the ambiguity in determining the ion flow.

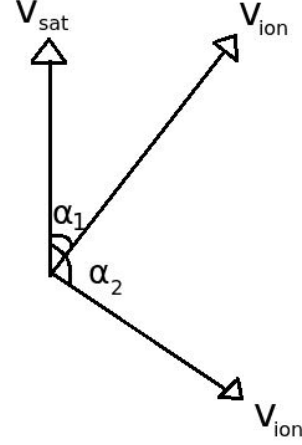


Figure 6.19: Schematics of parallel (α_1), and antiparallel (α_2) movement of the plasma v_{ion} with respect to the satellite v_{sat} .

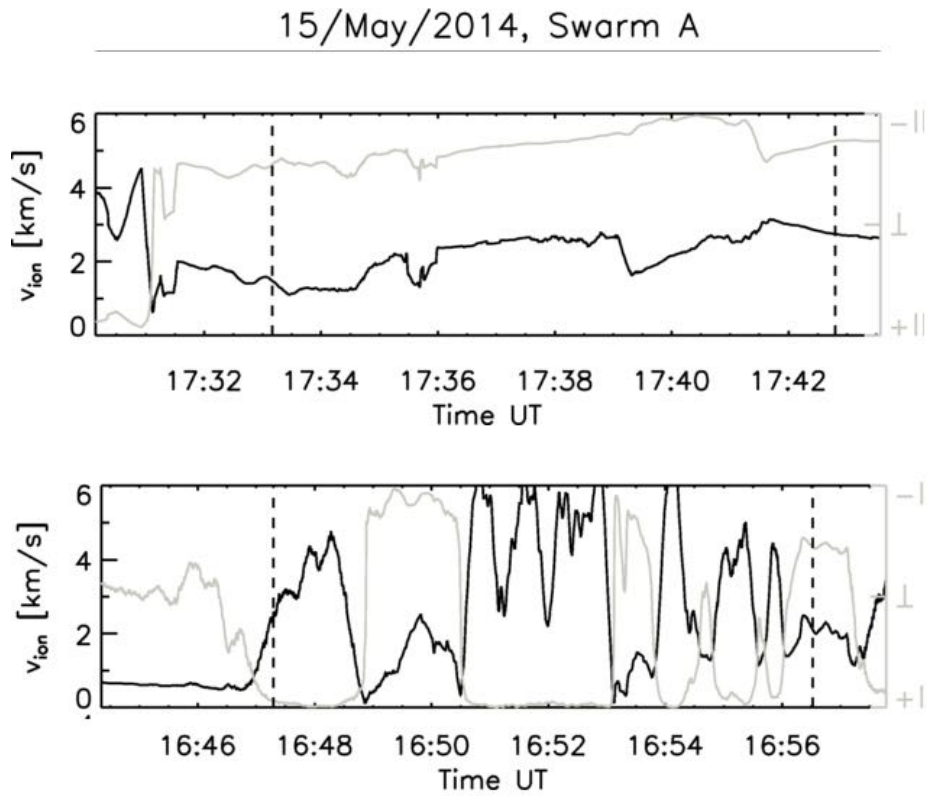


Figure 6.20: Ion drift speeds v_{ion} shown in black, and angle between spacecraft velocity and ion drift velocity in gray. Here, "+||" indicates parallel velocities, and "-||" are anti-parallel velocities. The panels show two adjacent polar passes, with different velocity characteristics.

Finally, the filtered velocity, the density gradient, and the background density are used to calculate the growth rate of the gradient drift instability. Due to the ragged nature of the patches, there are areas of negative gradient on the trailing edge of the patch, which causes the instability rate to be negative. Since the underlying condition for the gradient drift instability is not fulfilled in this case, all negative growth rates of the instability are set to zero. As with the gradients and velocities, the growth of the gradient drift instability is available for the entire patches, together with an average value for the trailing edge. Figure 6.21 shows the density, the gradient, the ion speed and in the bottom panel the gradient drift instability growth rate, calculated for the entire patch and the average values for the trailing edge.

6.4 Error calculation

The GDI growth rate γ is calculated

$$\gamma = \frac{v_0 \kappa}{b}, \quad (6.5)$$

where v_0 is the ion velocity in the direction of the plasma density gradient κ , and b is the background plasma density.

To estimate the error of the GDI growth rate $\Delta\gamma$ from the error estimates of the three dependent variables Δv_0 , Δb , and $\Delta\kappa$, simple Gaussian error propagation can be used:

$$\Delta\gamma = \sqrt{\left(\frac{\kappa}{b}\Delta v_0\right)^2 + \left(-\frac{v_0\kappa}{b^2}\Delta b\right)^2 + \left(\frac{v_0}{b}\Delta\kappa\right)^2}. \quad (6.6)$$

The relative error in the plasma density measurements is estimated as 10% (*S. Buchert*, private communications); therefore, Δb is assumed to be $0.1b$. With this error estimate of the plasma densities, the error of the gradient $\Delta\kappa$ can be determined as the 1-sigma uncertainty in the linear slope parameter during the fitting process (*Press et al.*, 2002, sect. 15.2). Finally, the velocity error Δv_0 is estimated as 50 m/s. With these values, the error in the GDI growth rate can be estimated, both for the entire edge and for the individual points within the edge.

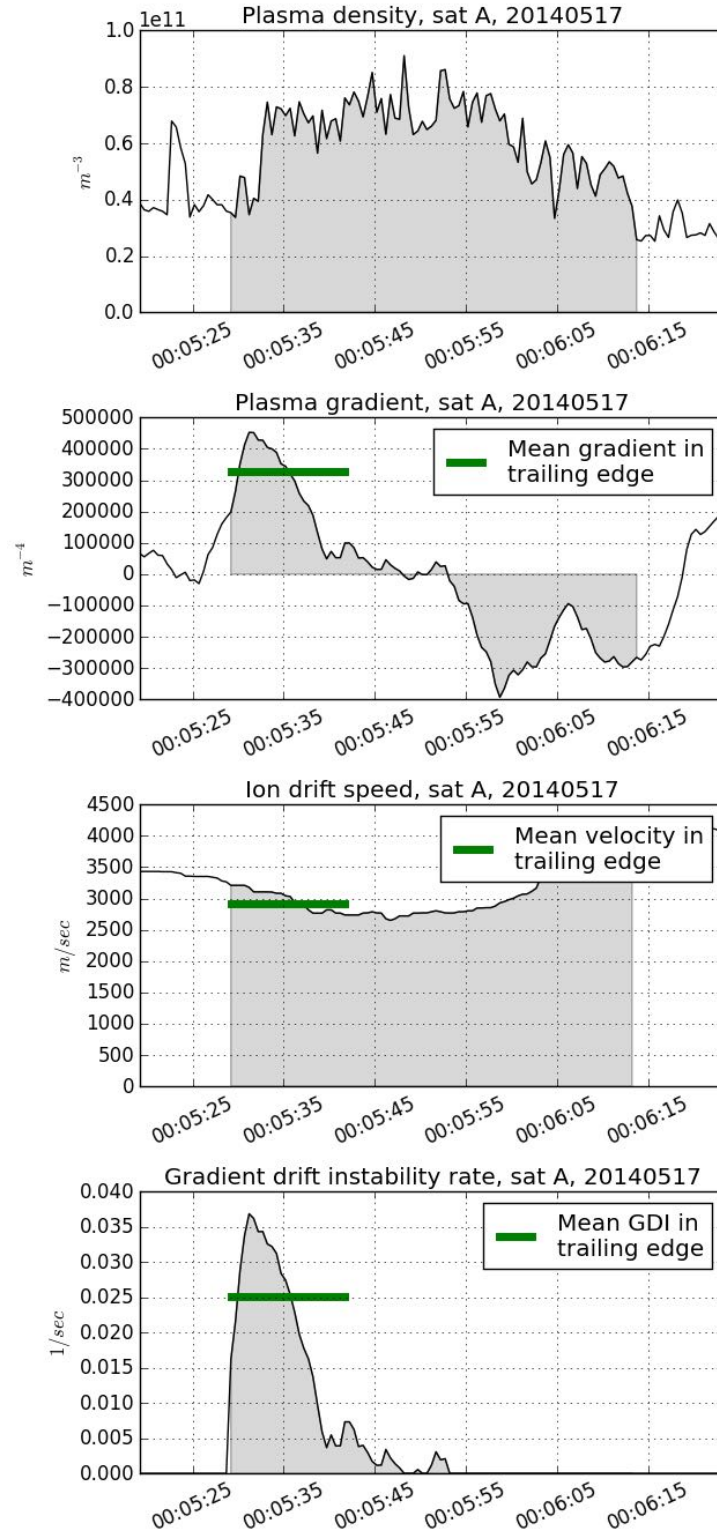


Figure 6.21: From top to bottom: plasma density, plasma gradient, ion drift speed, and gradient drift instability rate for a polar cap patch detected with Swarm A on 17 May 2014. The polar cap patch is marked with gray, while the mean values are indicated with green lines.

7 PCP index: description of the product, validation

As outlined earlier, the objective of the PCP index is to identify and flag plasma density measurements made by the Langmuir probe on board the Swarm satellites which are part of a polar cap patch. The results of the algorithms described in previous chapters are written, along with some of the original input data, into common data format (CDF) files. These files contain header information (global attributes in CDF language) as summarized in Table 7.1.

Furthermore, the CDF files contain global data descriptors as shown in Table 7.2 and the actual time series data as summarized in Table 7.3. In particular, the PCP index has five possible values; its meaning is summarized in the Table 7.4.

Thus, the PCP flag constitutes an extended PCP Index. The PCP Index should provide the information on whether the measurement is taken inside PCP or not. The extended PCP Index with the flags given in Table 7.4 provides further information whether the measurement is on the leading or trailing edge, or within the patch proper. It should be noted that the PCP flag is 4 through the patch proper, and is set to 1 on both edges when no ion drift data is available. This is motivated by the fact that without plasma velocity data a accurate determination of the trailing and leading edge of the path cannot be achieved.

To validate our results, we first compare the occurrence rates of polar cap patches with previously published results. Figure 7.1 shows the number of patches detected by the automated procedure in plasma density data from Swarm A and B as monthly totals since the beginning of the Swarm mission in November 2013; we do not show Swarm C as it resides in essentially the same orbit as Swarm A and hence its patch detection results are almost identical.

The histograms show a clear seasonal dependence: patches are dominant in the winter

Table 7.1: Global attributes of the PCP CDF files.

Name	Value
gDesc	This file contains the polar cap patch flag and the linear gradient drift instability growth rate derived from Swarm Langmuir probe and Thermal Ion Imager data. These data products were developed as part of the Swarm + Innovation: Polar Cap Products project. Please visit http://www.mn.uio.no/fysikk/english/research/projects/swarm/ for more information.
gFunding	PCP (Polar Cap Products) is a project funded by the European Space Agency (Contract No. 4000114121/15/NL/MP) in the framework of the STSE (Support To Science Element) Swarm + Innovation Program.
gWebsite	http://www.mn.uio.no/fysikk/english/research/projects/swarm/
gContact	If you have any questions, please contact Lasse Clausen (lasse.clausen@fys.uio.no) or Wojciech Miloch (w.j.miloch@fys.uio.no).

Table 7.2: Global data attributes of the PCP CDF files.

Name	Value
PMININC	Minimum relative increase of the foreground above the background to qualify as a patch. This value is typically 2.
PMAXDIFF	Percent density increase that marks the beginning and end of the patch edges. This value is typically 30.
PMINLEN	Minimum number of points during which the relative increase has to be higher than PINCMIN. This value is typically 15.
PMINLEN	Minimum geomagnetic latitude below which we expect no patches. This value is typically 77.
PGRADLEN	Length (in data points) over which the density gradients for the GDI growth rate are calculated. This value is typically 27.
backfilterlen	Length of the percentile filter used for the calculation of the background density, in data points. This value is typically 551.
backfilterperc	Percentile to be used for the calculation of the background density (0-100). This value is typically 35.
forefilterlen	Length of the percentile filter used for the calculation of the foreground density, in data points. This value is typically 7.
forefilterperc	Percentile to be used for the calculation of the foreground density (0-100). This value is typically 50.

Table 7.3: Data variables in the PCP CDF files.

Name	Value
epoch	CDF epoch of the measurement, i.e., number of milliseconds since 01.01.0000 00:00.
glats	Geographic latitude of the satellite in degrees.
glons	Geographic longitude of the satellite in degrees.
alts	Geocentric altitude of the satellite in km.
ndens	Plasma density, directly copied from the Langmuir probe files (in cm^{-3}).
te	Electron temperature, directly copied from the Langmuir probe files (in K).
background	Background density, as calculated from ndens using a percentile filter of backfilterlen length and backfilterperc as the percentile.
foreground	Foreground density, as calculated from ndens using a percentile filter of forefilterlen length and forefilterperc as the percentile.
pcp_flag	The polar cap patch flag: 0 if the plasma density measurement occurred OUTSIDE a polar cap patch. 1 if the plasma density measurement occurred in one of the edges of a polar cap patch - however, no ion drift data was available to determine whether this was the leading or trailing edge. 2 if the plasma density measurement occurred at the LEADING edge of a polar cap patch. 3 if the plasma density measurement occurred at the TRAILING edge of a polar cap patch. 4 if the plasma density measurement occurred INSIDE a polar cap patch proper.

Table 7.4: Meaning of the polar cap patch flag.

Flag Value	Meaning
0	The measurement is not part of a PCP.
1	The measurement is part of one of the edges of a PCP - no ion drift data is available.
2	The measurement is part of the leading edge of a PCP.
3	The measurement is part of the trailing edge of a PCP.
4	The measurement is part of the patch proper.

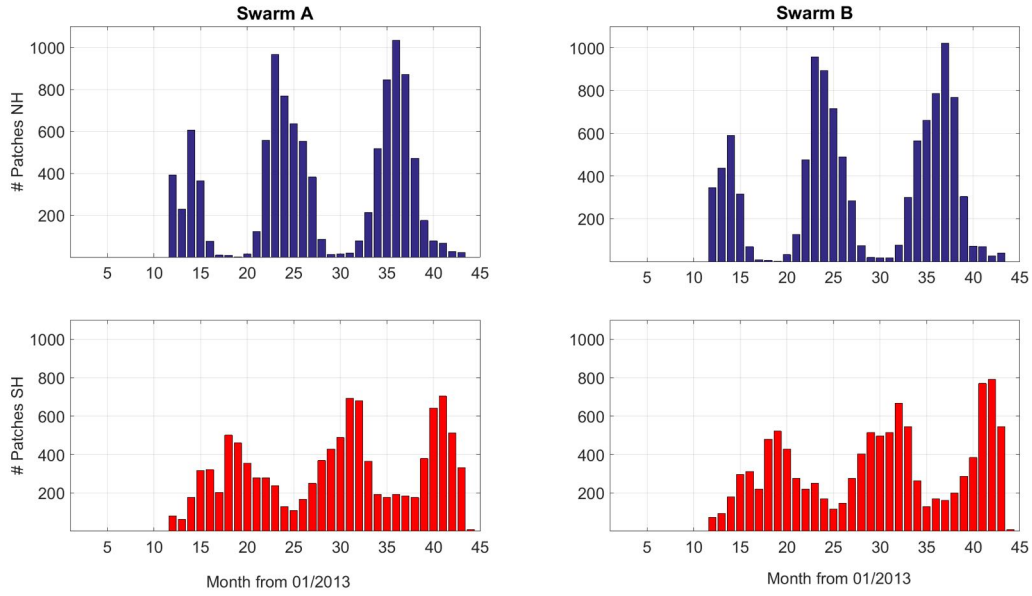


Figure 7.1: Histogram of the monthly polar cap patch occurrence in the norther (blue) and southern (red) hemisphere. The left column shows the results for Swarm A, the right column shows the results for Swarm B.

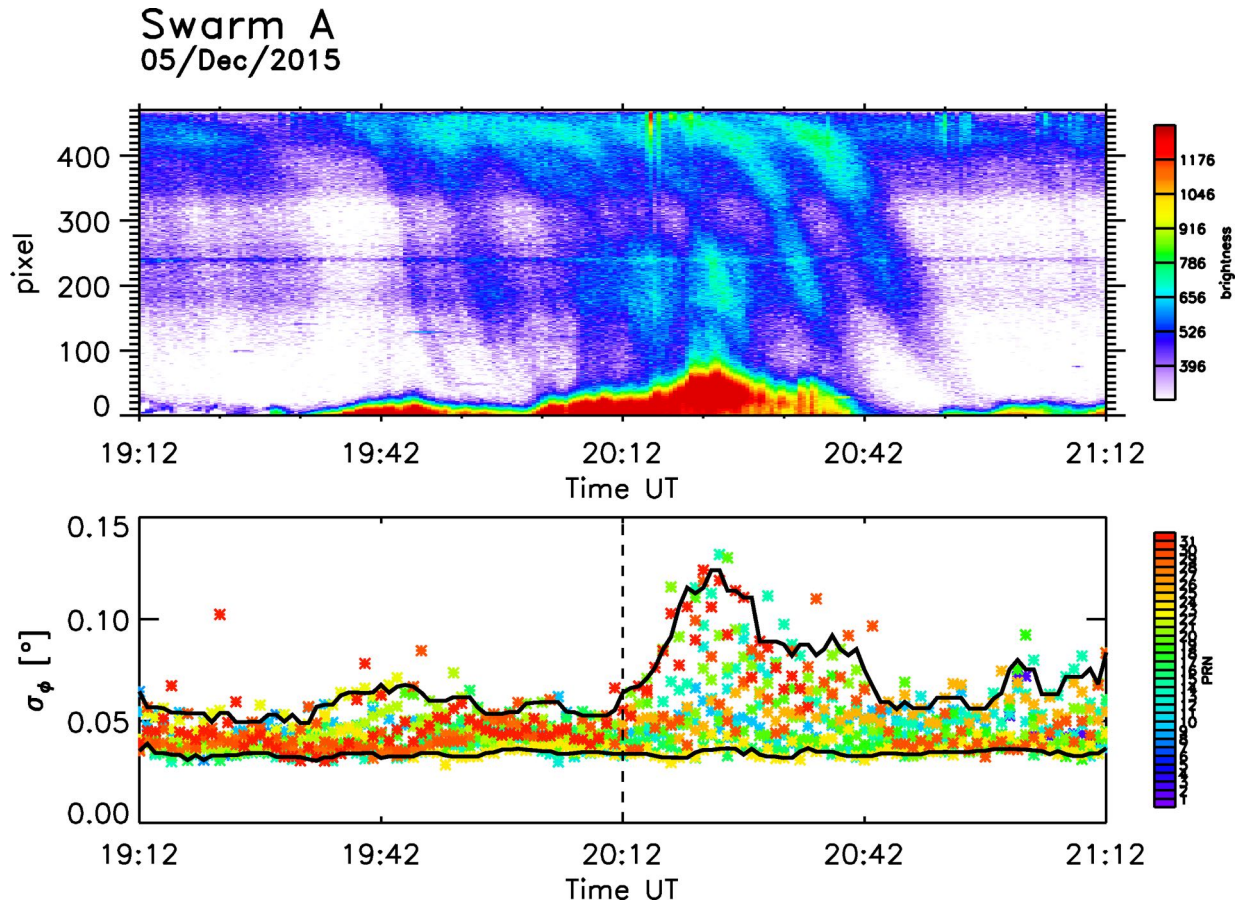


Figure 7.2: The upper panel shows a keogram of the all-sky imager data from Ny Alesund on 05 December 2015; it shows polar cap patches moving into the main auroral oval. The lower panel shows GPS phase scintillation levels recorded near the all-sky imager, indicating that the GPS signal quality decreases as patches appear between the GPS satellites and the receiver on the ground.

hemisphere. This pattern has been published before (*Coley and Heelis, 1995*) and has been attributed to the lower background plasma densities in the winter hemisphere, i.e., not sun lit, polar cap; against this background a twofold density increase is easier accomplished. It should be noted, though, that *Noja et al. (2013)* reported elevated patch occurrence in both the northern and southern hemisphere during northern hemisphere winter. This is in contrast to our findings.

As mentioned before, polar cap patches are also routinely observed with high-sensitivity all-sky imagers in the form of airglow patches (*Weber et al., 1984; Hosokawa et al., 2006, 2009a,b, 2011; Jin et al., 2014*). In Figure 7.2 we present a conjunction between the all-sky imager at Ny Alesund on Svalbard and Swarm A. The upper panel shows a keogram of the

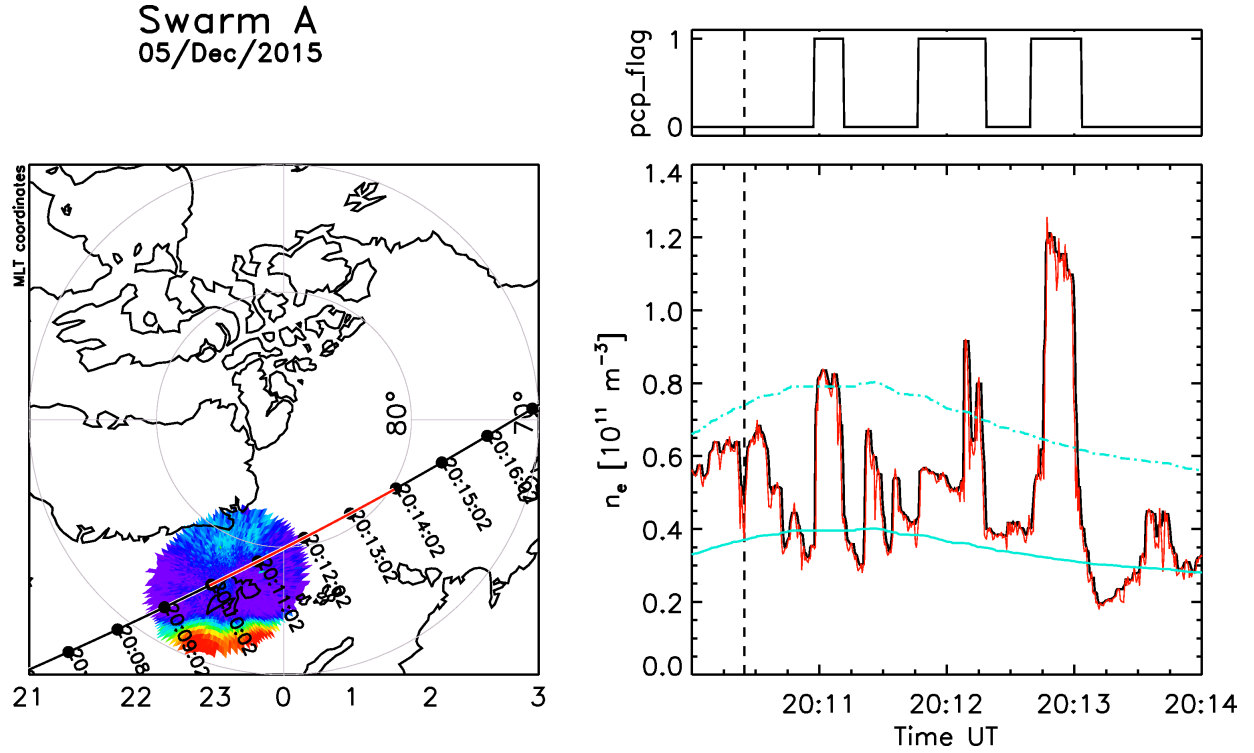


Figure 7.3: On the left the track of the Swarm A satellite across the field-of-view of the all-sky imager at Ny Alesund is shown. The red trace marks the location of the satellite corresponding to the plasma density measurements shown in the right panel. Polar cap patches are also observed on the plasma density data and flagged by the automatic detection algorithm.

auroral emissions at 630.0 nm; it shows a series of patches entering the main auroral oval located on the equatorward side of the all-sky imager’s field-of-view. The lower panel shows the GPS phase scintillations observed on the ground near Ny Alesund; these measurements clearly show an increase in phase scintillations as the polar cap patches connect with the main auroral oval (*Jin et al., 2014*).

In Figure 7.3 we show the corresponding Swarm A plasma density measurements. The left panel shows the satellite’s track across the imager’s field-of-view. One of the polar cap patches which was seen in the keogram data from Ny Alesund to drift toward the auroral boundary is also shown on the map. The red trace marks the time for which the plasma density measurements from Swarm A are shown in the right panels. They confirm that, indeed, Swarm A also encountered a series of patches during that time, and they were flagged accordingly by the automatic detection algorithm.

The example above is one of many. Of course, from such examples we cannot conclude

that every patch that is flagged in the Swarm plasma density measurements is also observed by a ground-based auroral imager, or vice versa. However, we have also compared the amount of patches observed by Swarm (regardless of the satellite's position) during periods when the imager on Svalbard observed patches and compared that to the number of patches observed by Swarm whenever the all-sky imager did not see patches. We find that during times the auroral camera observes patches, the number of patches observed by Swarm is significantly higher than during the other times. This indicates that our polar cap patch detection algorithm is consistently flagging plasma density enhancements which qualify as polar cap patches.

8 GDI growth rates: description of the product, validation

The second part of the PCP project is concerned with calculating the density gradients, velocities, and linear growth rates of gradient drift instability (GDI). It adds data variables to the CDF files described in the previous section. These are summarized in Table 8.1.

The validation of the GDI growth rate was originally intended to be conducted through comparing it with ground-based scintillation observations of GNSS signals during conjunctions, similar to the way the polar cap patch detection algorithm can be validated through ground-based observations. However, the quality of the ion velocity data currently available, which are essential for final product calculations, imply that the GDI growth rate presented at this stage should be considered with care. At this stage, therefore, we present tentative results which indicate that our original scientific hypothesis is correct.

Instead of comparing GDI growth rates with GNSS phase scintillations on the ground, we present in Figure 8.1 a comparison of the plasma density RMS vs GNSS phase scintillations as measured by σ_ϕ . Only periods during which the Swarm satellites were conjunct to the ground receiver are included. It shows that there appears to be a causal relationship between the two. This relationship can be explained by assuming that the RMS on the spatial scales that Swarm can resolve can be used as a proxy for the plasma density structures at smaller scales that would eventually cause phase scintillations.

Further evidence for this scenario is provided by Figure 8.2 which shows histograms of σ_ϕ for period when Swarm observed patches (green) and for times when no patches were observed (blue). Although the difference between the two statistics does not seem to be statistically significant, there appears to be a preference for higher phase scintillations during periods of polar cap patches.

In summary, the current state of the ion drift data does not allow a confident determination of trailing vs leading edge or of the GDI growth rate. The numerical code to perform

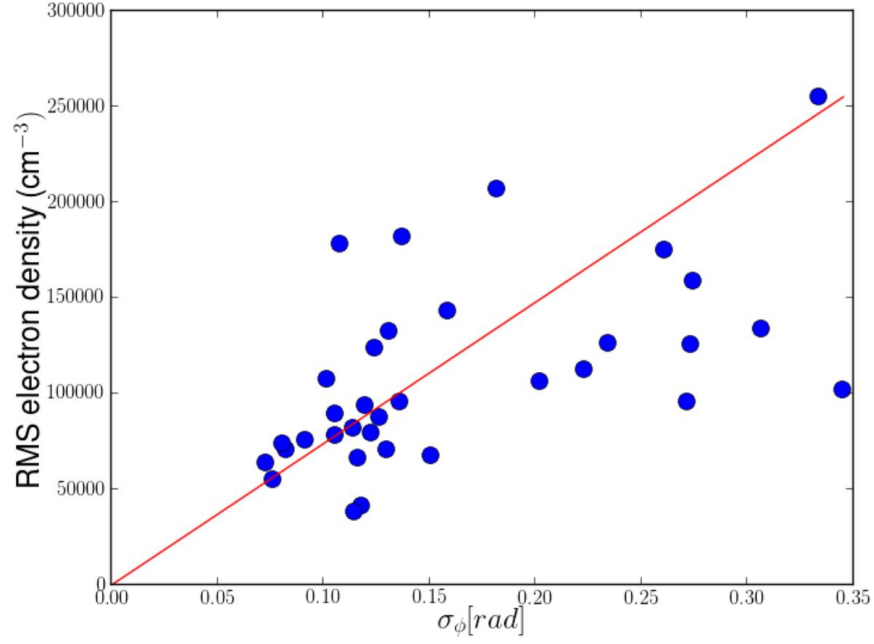


Figure 8.1: Comparison of the plasma density RMS measured during conjunctions with the GPS receiver located at Ny Alesund and the GPS phase scintillation index σ_ϕ measured on the ground.

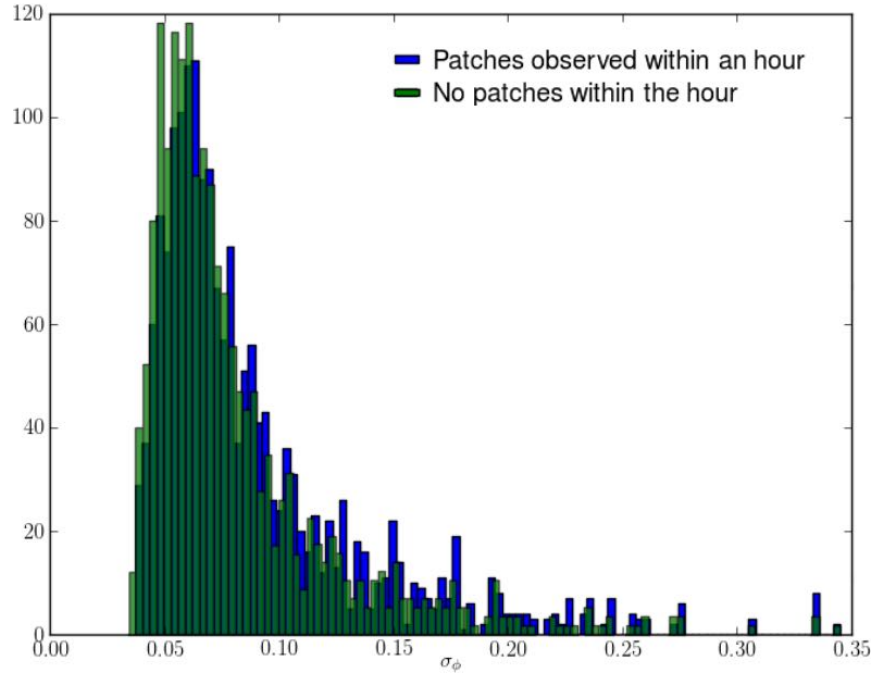


Figure 8.2: Histogram of σ_ϕ measured by a GPS receiver near Ny Alesund on the ground during period that Swarm observed patches (blue) vs periods when no patches were observed (green).

the calculations, however, is in place such that should better data arrive in the future, these data products can be provided automatically as well. Once such data is available, further validation of the GDI growth rate product will be performed.

Table 8.1: Additional data variables in the PCP CDF files.

Flag Value	Meaning
ndens_gradient	Running electron density gradient calculated via linear regression over PGRADLEN data points. In units of m^{-3}/m .
ndens_edge_gradient	Linear electron density gradient calculated over the edges of a patch. In units of m^{-3}/m . This variable is non-zero only on the edges of polar cap patches.
ion_velocity	Absolute ion velocity from the Thermal Ion Imager averaged over PGRADLEN data points. In units of m/s .
ion_edge_velocity	Absolute ion velocity from the Thermal Ion Imager averaged over the edges of a patch. In units of m/s . This variable is non-zero only on the edges of polar cap patches.
gdi_growth_rate	Growth rate of the Gradient Drift Instability. In units of $1/\text{s}$. This variable is non-zero only within polar cap patches.
gdi_edge_growth_rate	Growth rate of the Gradient Drift Instability calculated from <code>ndens_edge_gradient</code> and <code>ion_edge_velocity</code> . In units of $1/\text{s}$. This variable is non-zero only on the edges of polar cap patches.
error_gdi_growth_rate	Error estimate of the GDI growth rate, from Gaussian error propagation. In units of $1/\text{s}$.
error_gdi_- edge_growth_rate	Error estimate of the GDI growth rate, from Gaussian error propagation. In units of $1/\text{s}$.

9 Dissemination, ongoing work, and scientific outlook

All results presented in the report are available through the website (see Figure 9.1). In particular, interested users can browse overview plots of the polar cap patches detected during each Swarm pass through the polar cap or for the entire day. Furthermore, the computer code used to detect polar cap patches and calculate the GDI growth rate is available there.

The products developed through this project and presented in this report have strong potential for being used in space weather and ionospheric research. They form the first step in establishing the space weather forecast service at high geomagnetic latitudes, in the polar cap. Swarm can as the first mission, pave the path for future forecasting and nowcasting service in the polar cap with the use of more satellites in near polar orbits on the routine basis. However, for this to happen, statistical studies for polar cap patches combined with the ground based GNSS receivers should be carried out in order to build a prototype model. These studies include seasonal occurrences of patches, their morphology, and distribution of gradients in the context of geomagnetic activity. This is the ongoing work at the University of Oslo. Furthermore, the dissemination in form of scientific papers and presentation of the product and results at geophysical and topical conferences are planned in order to popularize the product among potential users.

The market for the space weather services has been increasing during the last years, as more ground services rely on the GNSS signals. In particular in the polar regions, with increasing human activity, offshore operations, air and marine traffic, the detailed space weather prediction model needs to be developed, and we expect that the current Polar Cap Products will be an important element in it.

Thus, Swarm Polar Cap Products will play an important role in contributing towards both understanding the physical processes in the high latitude ionosphere as well as for

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In this project we develop Polar Cap Products (PCP) based on the in-situ data from the *Swarm* satellites. PCP will provide essential information on polar cap patches, which are an important element of the space weather in the polar regions. The project is supported by the European Space Agency, through STSE Swarm+ Innovation.




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[Detailed list of participants](#)

Involved research groups

- 4DSpace - Strategic Research Initiative
- Plasma and space physics

Figure 9.1: Screenshot of the project website at <http://www.mn.uio.no/fysikk/english/research/projects/swarm/>

space weather monitoring in the polar regions with spaceborne missions in future.

Apart for studies focusing on the impact on GNSS signals received on the ground, future work will also focus on the impact of plasma density structures on GPS positioning of the Swarm spacecraft themselves. As outlined earlier, there seems to be a connection between large RMS errors in the precise orbit determination and the occurrence of plasma density structures inside the polar cap. This effect can be attributed to space weather effects as well as the relative orbits of Swarm and GPS. A detailed study is planned to quantify what is the relative importance of those effects. This can be carried out by, for example, taking into account seasonal differences in the polar cap patch distribution. This research line will also be continued in the future.

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