Grand Challenge Initiative – Cusp: rockets to explore solar wind-driven dynamics of the top side polar atmosphere

J Moen[1, 2], A Spicher[1], DE Rowland[3], C Kletzing[4], J LaBelle[5]

1 Department of Physics, University of Oslo, Oslo, Norway
2 University Centre in Svalbard, Longyearbyen, Norway
3 NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
4 Department of Physics & Astronomy, University of Iowa, Iowa City, USA
5 Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire, USA

Corresponding author: Jøran Moen, j.i.moen@fys.uio.no
ORCID number 0000-0002-8176-0954

Keywords: aurora, geospace, polar ionosphere, magnetosphere, reconnection, solar wind forcing, wave-particle interaction, particle acceleration, heating, oxygen outgassing, turbulence, space weather, rockets

Introduction

The Grand Challenge Initiative (GCI) - cusp is a gigantic sounding rocket program that counts 12 sounding rockets of which the major part will be executed in 2018 and 2019. The investigations will cover the altitude range from 100 km to 1000 km for solar minimum conditions. The scope of GCI-cusp is to study the solar wind forcing of the upper polar atmosphere and the atmospheric response to it. The dynamics of the upper atmosphere is largely controlled by the geospace interactions with the solar wind and the Interplanetary Magnetic Field (IMF). The physical phenomena which couple the various regions of the magnetosphere, ionosphere, upper and lower atmosphere have a multi-scale nature. In the auroral zone, it is of particular importance to understand the details of the small-scale mechanisms that significantly affect the ionized and neutral atmosphere, and the way in which they couple into larger-scale processes which control the global system (e.g. Kelley, 2009; Kintner and Seyler, 1985]: The most obvious phenomenon in this region is turbulence in the ionized and neutral components of the polar atmosphere. Plasma processes of a widely diverse nature couple forces spanning scales from 1000 km to tens of cm, i.e. 8 orders of magnitude in spatial scales. While ground-based observations can nowadays provide information about the medium and large scales, detailed in situ measurements are required to study the smallest scales [Moen et al. 2002].

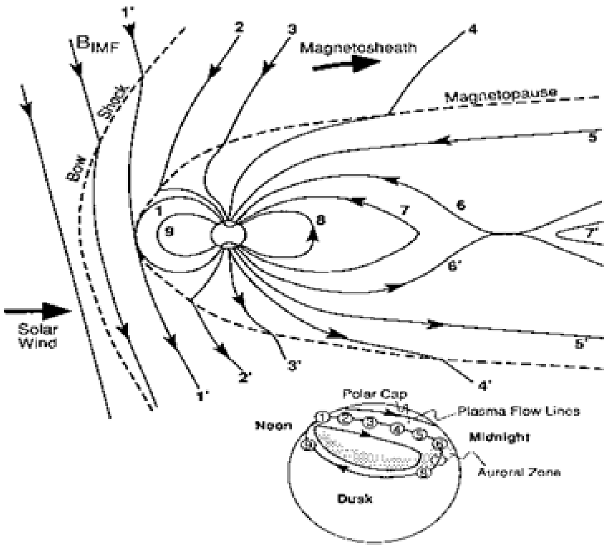


Figure 1: Illustration of how magnetic interactions between the interplanetary magnetic field (IMF) and the Earth magnetic field give rise to a twin cell circulation pattern in the polar cap ionosphere [Kivelson et al. 1995].

Above 100 km, the polar atmosphere is strongly forced by the solar wind, as visualized through e.g. the Aurora Borealis phenomenon. The solar wind drives a twin cell circulation pattern in the polar cap, which transports ionized matter (the ionosphere) across the polar cap from day to night [e.g. Dungey, 1961; Foster, 1984; Weimer, 1995; Cousins and Shepherd, 2010]. Momentum from this movement is transferred to the neutral atmosphere (the thermosphere) by collisions [Skjæveland et al., 2017 and references therein]. We have a reasonably good description of the dynamics of the large scale system, including the large scale currents systems [Kivelson et al., 1995]. Over the past couple of decades we have studied in quite detail the ionospheric signatures of Flux Transfer Events (FTEs) by ground-based and satellite measurements; these are ascribed to transient coupling of the interplanetary magnetic field (IMF) to the Earth magnetic field. In the auroral ionosphere, FTEs are associated with poleward moving auroral forms (PMAFs) [*Sandholt et al*., 1990], ion upflows [*Moen et al*, 2004], flow channels [*Rinne et al*, 2010], formation of polar cap patches [*Carlson et al*., 2006], and are also associated with radio wave scintillation events [*Carlson et al*., 2007; Jin et al, 2015; Oksavik et al. 2015] taken as an indicator of plasma turbulence [Moen et al, 2013, Spicher et al. 2015].

The study of auroral signatures, precipitating energetic particles, plasma convection from dayside reconnection, and global plasma instabilities associated with substorms represent important challenges in Solar-Terrestrial Physics that have profound effects on the ionosphere/thermosphere [e.g. Kelley, 2009]. Traditionally, the thermosphere was thought to be an inertial background of stable, slowly varying density, winds and temperature. However, recent papers identify an appreciable "meso-scale structure" (a few hundred kilometres wide, and few tens of minutes duration) [e.g. Moen, 2002; Oksavik et al. 2004, 2005, 2011; Rinne et al., 2007; Moen et al., 2013]. These have huge implications for the energy dissipation in the neutral atmosphere, because neutral winds driven by ion drag are significantly overestimated and heating rates are underestimated [Skjæveland et al., 2017]. The thermosphere is probably not a passive load on the magnetosphere; thermosphere dynamics also plays an active role in magnetospheric processes, but we do not know how. The unsatisfactory performance of existing atmospheric models is mainly a consequence of poor data coverage in this highly dynamic and structured region. It is necessary to consider the atmosphere as a whole, from the ground to the interactions with the solar wind, in order to understand the dynamics and behaviour of the coupled system.

The need for in-situ small-scale 3D measurements of waves, structures and turbulence in the altitude range 40-120 km by a structured program of sounding rockets is emphasized in the SIOS Optimization report, as it will be essential to make progress on understanding the vertical transport of energy and mass flow dynamics, including the role of meteor components [Ellis-Evans and Holmen, 2013]. However, in the auroral oval, the solar wind executes a strong heating and, probably, a structuring of the thermosphere. Hence the solar wind driven energy input into the ionosphere thermosphere system may probably not be neglected in global atmospheric models.

The GCI – Cusp is going to investigate the nature of magnetic coupling to the solar wind during quasi-steady IMF conditions. We are going study in detail the various wave-wave and wave-particle interactions and acceleration mechanisms downward for auroral precipitation and upward acceleration of oxygen particles escaping the gravitational bound, and there will be rockets to study ion flow channels and neutral wind flow. The Norwegian ICI series of rockets that has been developed to investigate the dynamics of the cusp ionosphere at finer scales [Lorentzen et al., 2010; Moen et al., 2012; Oksavik et al., 2012; Moen et al., 2013] will be further developed to perform 3D in-situ measurements of plasma turbulence. The auroral zone and the polar cap is a region with sheared flows, particle beams, unstable plasma gradients and is rich in waves, instabilities and turbulence phenomena [e.g. Kelley, 2009; Kintner and Seyler, 1985]. Plasma turbulence processes represent one of the outstanding major challenges in classical physics, where fundamental problems have not yet been adequately understood [e.g. Tsinober, 2009]. Turbulent, anomalous resistivity is likely to be an essential constituent in the description of the full ionospheric and magnetospheric current circuit, which may have a large impact on the energy transfer from the solar wind to the thermosphere.

Sounding rockets were prioritized in the Norwegian prioritization report of SIOS, because of the high science potential this technique has in combination with radars and optical instrumentation. Svalbard is in fact the only place in the world where these three techniques can be used simultaneously to observe the solar wind – upper atmosphere interactions. This first SESS report on the SIOS sounding rockets will provide an: i) overview of the gigantic GCI-Cusp sounding rocket program, ii) a rather detailed description of the motivation and the performance of the SIOS InfraNor ICI-5 sounding rocket, and three NASA rocket missions to be launched in the winter of 2018/2019, the plan for developing and sharing data through the SIOS rocket data base, and then a brief summary.

Grand Challenge Initiative – Cusp rocket program

The GCI-Cusp program is a large-scale international collaboration for targeting advancement in specific, fundamental issues in space and Earth science. The GCI concept idea was initiated in 2012 by the University of Oslo (UiO) and the Andøya Space Center (ASC). The idea was simply to umbrella several individual rocket missions in one bigger program with six rockets or more. The GCI-cusp concept was then further developed in close collaboration with the National Aeronautics and Space Administration, (NASA), and the Japanese Aerospace Exploration Agency, JAXA. In 2016, it culminated in the first GCI program - "GCI-Cusp" - to determine the multi-scale physics of heating and precipitation in the ionosphere specific to the geomagnetic cusp region [http://spa.agu.org/spa-section-newsletter-volume-xxiii-issue-23/].

The GCI-Cusp program is an open initiative that has received great attention in the science community. The strategy is to advance the common understanding of the fundamental physics of Solar-Terrestrial interaction in the magnetic cusp by coordinated experimental and theoretical research using ground-based instruments, modelling, sounding rocket investigations, and satellite-based instruments.

Open data access between the collaborating teams is a prerequisite in order to develop efficient collaboration between many international teams. NASA, JAXA, SIOS, and UiO signed a joint venture agreement in Tokyo 6 April, 2017 stating that all partners will share equally the combined database produced by GCI-Cusp [https://www.uio.no/om/aktuelt/pressemeldinger/2017/international-campaign-to-explore-auroral-cusp.html].

Figure 2: Dr. Ole Jørgen Lønne (Interim Director, SIOS), Dr. Saku Tsuneta (Director General, ISAS/JAXA), Dr. Elsayed Talaat, Heliophysics Division Chief Scientist, signed for Mr. Steven Clarke, Director Heliophysics Division, Science Mission Directorate, NASA, and Prof. Ole Petter Ottersen (Rector, UiO). The signing ceremony was observed by the Norwegian ambassador to Japan, Erling Rimestad. Photo Yngve Vogt, University of Oslo.

Table 1. Overview of the rocket missions currently included in the GCI-cusp program. VISIONS-2 successfully launched 7 December 2018, and TRICE-2 successfully launched 8 December 2018 (up to date 12 December 2018)

Mission name	#rockets	Launch Site	Time	Lead nation	Co-Nations	Main Objective
TRICE-2	2	ASC	DEC2018	US	NO, UK	SolarWind-Magnetosphere coupling
VISIONS-2	2	Svalrak	DEC2018	US	NO,CA, UK	Ion upflow
CAPER-2	1	ASC	JAN2019	US	NO	Magnetosphere-Ionosphere coupling
G-Chaser	1	SC	JAN2019	US	NO, JP	Student rocket
AZURE	2	ASC	2019	US		Neutral&plasmadynamics
SIOS ICI-5	1	Svalrak	DEC2019	NO	US,CA	Plasma turbulence
C-REX 2	1	ASC	DEC2019	US		Neutral&plasmadynamics
CHI	1	Svalrak	DEC2019	US	JP	Neutral&plasmadynamics
SS-520-3	1	Svalrak	JAN2020	JP	NO	Ion upflow

Student participation in plasma model development and a dedicated student rocket is an essential aspect of the GCI concept. NASA has provided a full-size two-stage rocket for students to become part of the gigantic GCI-cusp rocket program. This rocket named G-CHASER is scheduled from Andøya in January 2019. Strategic use of public outreach, particularly via the tool of social media, is also a vital component of the GCI-Cusp program.

The rockets will be launched from Andøya Space Center and from Ny-Ålesund, Svalbard. The GCI-cusp program currently comprises twelve rockets listed in **Table 1** The core GCI-Cusp observational activities will be conducted in the high northern latitude region surrounding the Svalbard archipelago from late 2018 to early 2020.

Just before Easter 2017 a delegation from the University of Oslo and SIOS travelled to Japan to sign

a joint venture agreement with the American space agency, NASA, and the Japanese Aerospace Exploration Agency, JAXA. Their aim is to understand more about what happens when violent solar storms hit the Earth.

SIOS ICI-5 Rocket experiment

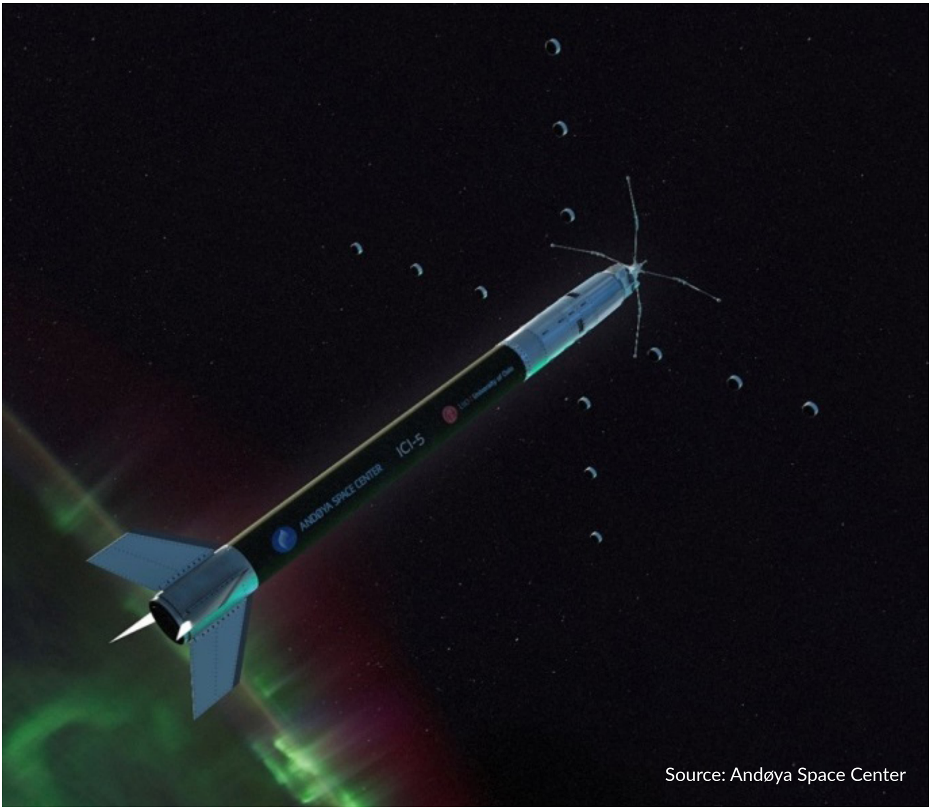


Figure 3: The envisioned ICI-5 rocket flight through aurora, with 12 daughters deployed from the 4DSpace module (Credit: Trond Abrahamsen, ASC).

The first SIOS sounding rocket, Investigation of Cusp Irregularities (ICI-5) is part of the SIOS InfraNor infrastructure project. The main objective of the SIOS rocket program is to study *Vertical coupling processes in the atmosphere from ground to space.*

Vertical coupling in the atmosphere is a complex interplay of processes over a wide range of spatial (cm to hundreds of km) and temporal scales (seconds to months), some of which, in addition, involve large-scale horizontal transport processes. We will investigate processes that are crucial for vertical coupling. Characterizing the evolution of ionospheric irregularities/turbulence and the transfer of energy between the different scales can be regarded as a study of fundamental plasma physics from a theoretical point of view, and is critical in order to understand energy transport and deposition in the ionosphere. SIOS rockets will also provide key knowledge for ionosphere space weather forecast models, as turbulent plasma regions interfere and distort trans-ionosphere satellite signals.

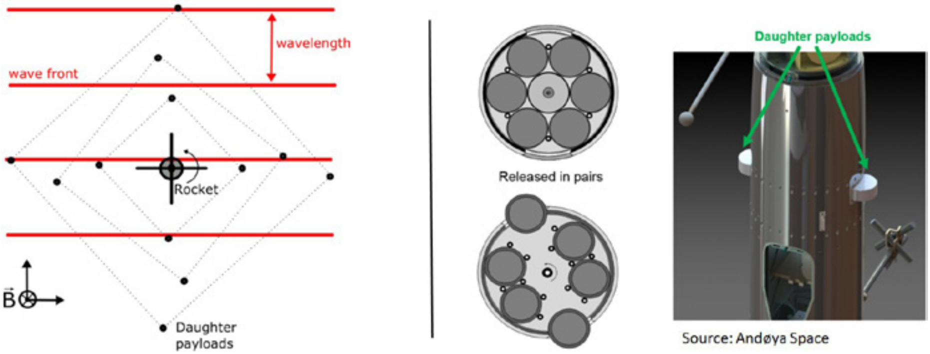
The ICI-5 main objective is to explore the physical properties of plasma turbulence in the F-region cusp ionosphere. In order to achieve this we need to develop a 3D in-situ measurement technique for ICI-5. From the multi-point measurements by the 12 daughter configuration we will determine the spatial scales of the turbulent structures (eddies), explore the 3D nature of the turbulent structures in the F-region cusp ionosphere, and examine the drivers of turbulence/plasma structuring in the auroral cusp.

Turbulence: Characterizing turbulence (both in fluids and in plasmas) remains a grand challenge as central issues are not yet adequately explained [Kintner and Seyler, 1985; Tsinober, 2009; Petrosyan et al, 2010; Bruno and Carbone, 2013]. Significant progress has been made for the characterization of solar atmosphere/wind turbulence [see reviews from Petrosyan et al., 2010; Bruno and Carbone, 2013]. However, for the high latitude ionosphere, where turbulence is common [e.g. Kelley, 2009], our knowledge about the nature of the turbulence is still very limited. There are indications that part of the fluctuations observed could be described by electrostatic fluid-like turbulence theory [Kintner and Seyler, 1985], but many questions remain to be solved, including(1) which models do best describe the turbulence? (2) Are the observed structures due to linear superposition of decoupled normal modes (waves), or due to turbulent interactions across a wide range of scales caused by plasma instabilities? (3) How is the energy distributed between the scales? To address such questions, investigations of the spatial and temporal evolution of the irregularities are crucial, **which require multi-point measurements**. For making progress in the study of high-latitude F region turbulence with space weather impacts, theoretical work and novel experimental concepts are thus necessary.

In general, the development of turbulence and irregularities occurs when free energy is redistributed through some instability mechanism and, consequently, both the source of energy and the instability are coupled processes [Treuman and Baumjohann, 1997]. In the classical view, three sources of free energy are believed to be dominant in the Polar regions: the density gradients and associated polar cap patches, flow shears and the particle precipitation [e.g. Keskinen and Ossakow, 1983; Tsunoda, 1988; Carlson et al., 2012; Moen et al., 2013]. Associated with them are macro-instability processes, with the gradient drift instability (GDI) [e.g. Linson, 1970] and the Kelvin-Helmholtz instability (KHI) [Keskinen et al., 1988] believed to be dominant mechanisms.

Major challenge: UiO has invented a multi-Needle Langmuir Probe System (m-NLP) [Bekkeng et al., 2010; Jacobsen et al. 2010] to make high-resolution density measurements along the rocket trajectory. However, as these measurements are one-dimensional, they do not allow us to determine the spatial extent of ionospheric plasma irregularities, nor do they provide any unambiguous answer whether the observed structures are due to the linear superposition of decoupled normal modes (waves), or due to turbulent interactions across a wide range of scales caused by some plasma instability. The former are propagating waves with dispersion relations that are known, whereas the latter are simply varying structures convected and distorted by the larger-scale flow of the system. In the case of linear superposition of different wave modes, the dispersion relation is expected to follow a theoretical expectation depending on the wave mode [e.g Narita et al., 2003; 2011; Hnat et al., 2016]. Hence, a key for characterizing the ionospheric irregularities observed by the m-NLP along the rocket is to calculate the dispersion relation from the data. To achieve this unambiguously, simultaneous multi-point data are necessary [e.g. Pinçon et al, 2000; Narita et al., 2010]. In general, the spatio-temporal ambiguity for the dynamics of one-dimensional structures may be removed using two spacecraft. At least four spacecraft arranged in a tetrahedral configuration measuring fields and flows in three dimensions are necessary for determining the motion of three-dimensional structures [Pinçon et al., 2000]. In the high-latitude ionosphere at F region altitudes, fluctuations in density are accompanied by motions which are essentially perpendicular to the magnetic field. The turbulent structures are thus expected to be almost two-dimensional, as the correlation length along the magnetic field is much larger than across it [Similon and Sudan, 1990]. We will thus launch a sounding rocket with 12 "daughter" payloads in a plane perpendicular to the magnetic field, and make use of this quasi-2D property to explore the nature of turbulence in the cusp ionosphere. While the ICI-5 experiment is specially designed to make the first 4D measurements of turbulence in the cusp, it is worth mentioning that recent sounding rocket missions have performed multi-point in-situ measurements elsewhere in the ionosphere, for example the Cascades 2 (The Changing Aurora: In-Situ and Camera Analysis of Dynamic Electron precipitation Structures-2) [e.g. Mella, 2011; Lundberg, 2012], and the Leewaves experiment measuring between about 70 km and 100 km altitude [Sjolander et al. 2015].

Choice of method: During the ICI-5 sounding rocket flight, 12 daughter payloads separated over two stages will be released from the rocket, each carrying a m-NLP instrument. The daughter payloads will be ejected 4 by 4 in two perpendicular directions (making three squares around the rocket) and travel at approximately m/s relative to the main rocket body, perpendicular to the main rocket axis and hence at right angle to the background magnetic field. A sketch illustrating the configuration is shown on the left side of Figure 4. The functionality of the ejection of the daughter payloads and the communication to the main rocket was successfully tested for the first time on 27 September 2018, on the Nammo Nucleous hybrid rocket test flight from Andøya Space Center [Kolbjørn Blix, private communication]. The rocket is shown from above and the dots represent the daughter payloads. The red lines represent wave fronts. The images on the right side in Figure 4 show the modules and their location on the rocket. Assuming that the daughter payloads are released after 150 s of flight and that they provide ionospheric data for about 300 s, we can expect a final separation between the daughter payloads and the rocket of a few km. This will allow to explore whether there are evidences of dispersion relations at different scales, as well as the nature of the plasma turbulence at the explored scales [e.g. Narita, 2011].



Source: Andøya Space Center

Figure 4: The principle of 4DSpace multi-point measurements Cf. text for explanation.

For this, data analysis techniques for multi-point measurements applicable to the ICI-5 will be necessary. Such techniques are generally challenging [De Wit, 2003], and we will approach the analysis of the ICI-5 and daughter payloads data based on previous methods which have shown successful results for multi-satellite experiments such as Cluster [Escoubet et al., 2001, Pinçon et al., 2008; Horbury and Osman, 2008].

According to our knowledge, the auroral cusp is highly structured [e.g. Jin et al., 2015]. We will thus launch ICI-5 to intersect the auroral cusp. We have successfully done this with both ICI-2 [Lorentzen et al., 2011] and ICI-3 [Spicher, 2016] (note that ICI-4 had different scientific objectives). With ICI-5 we aim to meet an additional requirement. We want solar EUV ionized plasma to enter the polar cap through the cusp inflow region. Therefore, we will centre the four hours launch window on 11 LT = 10 GMT = 13 Magnetic Local Time (MLT).

Svalbard is the only place in the world to conduct simultaneous ground-based and sounding rocket observations in the cusp ionosphere. The SuperDARN CUTLASS HF radar, which continuously monitors HF backscatter over Svalbard, is a crucial tool to determine the launch conditions. The 32-meter steerable dish of EISCAT Svalbard (ESR) in Longyearbyen is ideal to observe flow channel boundaries and to map and track the movement of solar EUV ionized plasma/formation of polar cap patches. Finally, the ground-based optics from the Kjell Henriksen Observatory (KHO), Longyearbyen, and Sverdrup Station, Ny-Ålesund, will be used to locate the cusp and Birkeland current arcs. We will make use of the ACE spacecraft to provide IMF conditions, giving us one hour lead time information about the solar wind stimuli of the cusp. We will also access data from the GPS scintillation receiver network at Ny-Ålesund, Longyearbyen and Bear Island.

ICI-5 instrument payloads

The ICI series of rockets makes use of the 356 mm cross section, 2915 mm long payload, mounted on a VS30+Improved Orion motor configuration. With a payload weight of ~130 kg the rocket will reach an altitude of 350 km which is ideal for our investigation. The rocket is spin-stabilized at a rate of 3 rps.

For our science objective, it is critical for us to measure the plasma velocity, plasma density and the electron precipitation. Below is a brief description of our instrumentation:

i) 4-Needle Langmuir probe (4-NLP, University of Oslo) for high-resolution (m-scale) absolute electron density measurements. The experiment consists of four identical needle probes with a diameter of about 0.5 mm and a length of 5 cm. The probes are biased to typically +3V to +7V with respect to the rocket potential in order to measure the saturated electron currents. The Langmuir probes are mounted on the electric field booms in the front of the payload. The instrument's dynamic range is from nA to µA, with 16 bits resolution. Automatic gain control can also be enabled.

ii) The 4DSpace daughter payload module (4DSpace, University of Oslo) is containing six daughter payloads. ICI-5 will accommodate two 4DSpace sections, i.e. 12 daughters. The daughter payloads will be deployed pair-wise from each module. Each daughter will be equipped with a smaller, special version of the UiO-mNLP. This will give a multi-dimensional measurement of the electron density. The daughter payloads communicate with the rocket, and the data is fitted into the main PCM data stream.

iii) Electric Field Wave Experiment (EFW - University of Oslo). The ICI payload has two crossed (orthogonal) double probes in front. The quasi-static electric field is assumed to be perpendicular to the magnetic field and can be determined from two double probes spinning with the rocket. The probes are spheres with 3 cm diameter separated by more than 2 m. The electric field measurements have 16 bits resolution, and with the selected dynamic range this corresponds to a resolution of about 5µV/m.

iv) The Bifocal Sensor (BSM-Iowa University) probes the electron distribution function in the energy range 1eV-20keV, with a nominal operating energy range of 10-2000eV tailored for ICI-5 science. The sensor is a top-hat electrostatic analyzer with deflecting optics that define two entrance apertures – one with coarse (~10°) angular resolution and one with fine resolution (~1.75°). Voltages on the outer electrodes allow electrons through one of these apertures, after which they pass through two concentric toroids which select electrons by energy, with an intrinsic energy resolution $\Delta E/E$ ~15%. The voltages on the electro-optical surfaces are swept to cover the desired energy range from 100 eV-1 keV. Electrons within the selected energy window at each step impact a micro-channel plate, producing a measurable charge pulse of ~2M electrons per incident electron, which impact a segmented anode that registers the incident electron azimuthal velocity angle. With a 180° field-of-view, the azimuthal resolution is 22.5°. The intrinsic time resolution is 16 msec/ 16 energy steps (or 32 msec/ 32 energy steps).

v) Sounding Rocket Attitude Determination System, version 3, (SRADS3-University of Oslo). SRADS3 consists of a low-cost and miniaturized system for sounding rocket three-axis attitude determination. The system makes use of a three-axis gyro, two digital Sun sensors (using a pinhole camera; the trajectory will be sunlit above about 100-200 km depending on launch time) and two three-axis magnetometers. One magnetometer is mounted internally in the payload and an optional one is mounted externally on one of the E-field booms. Finally, a three-axis accelerometer is completing the system. The data from these sensors are combined with mathematical models of the sensors, the Earth magnetic field and the position of the Sun. This data fusion (post-processing) is done by an extended Kalman filter (EKF) and smoother, in order to reconstruct the spacecraft attitude.

Sounding rocket missions in the winter 2018/19

In this section we will briefly describe the NASA sounding rockets mission to be launched in December 2018 and January 2019. They are both of high relevance to SIOS. That is **T**win **R**ocket **I**nvestigation of **C**usp **E**lectrodynamics **2 (**TRICE-2; PI: Craig Kletzing, Iowa University) and **VIS**ualizing **I**on **O**utflow via **N**eutral atom **S**ensing-2 (VISIONS-2; PI: Douglas Rowland, NASA Goddard Space Flight Center), and **C**usp **A**lfven and **P**lasma **E**lectrodynamics **R**ocket **2** (CAPER-2: PI : Jim Labelle). University of Oslo will fly the multi-Needle Langmuir Probe (m-NLP) on all these rockets.

TRICE-2 was already planned when the GCI-Cusp program was agreed with NASA and JAXA in 2016. The VISIONS-2 proposal was the first mission to take advantage of the added value being under the GCI-Cusp umbrella. TRICE-2 and VISIONS-2 consist of two rockets each, and TRICE-2 will be highly complementary to VISIONS-2.

The TRICE-2 main objective is to investigate whether the magnetic reconnection at the magnetopause is steady or pulsed. As magnetic reconnection is the major external driver for vertical dynamics in the auroral zone atmosphere, this is a key Earth system science question. Magnetic reconnection is anticipated to modulate the thermosphere as well as the ionosphere.

With a single rocket or satellite it is not possible to unambiguously distinguish between steady state reconnection from multiple reconnection sites and pulsed reconnection. The TRICE-2 approach will be to fly two sounding rockets simultaneously from Andøya over Svalbard, one high-flying and one low-flying, both at the same magnetic coordinates. Except when they are on the top of each other, there will always be one lagging behind the other, allowing to assess whether the magnetic reconnection process is a steady state or time varying.

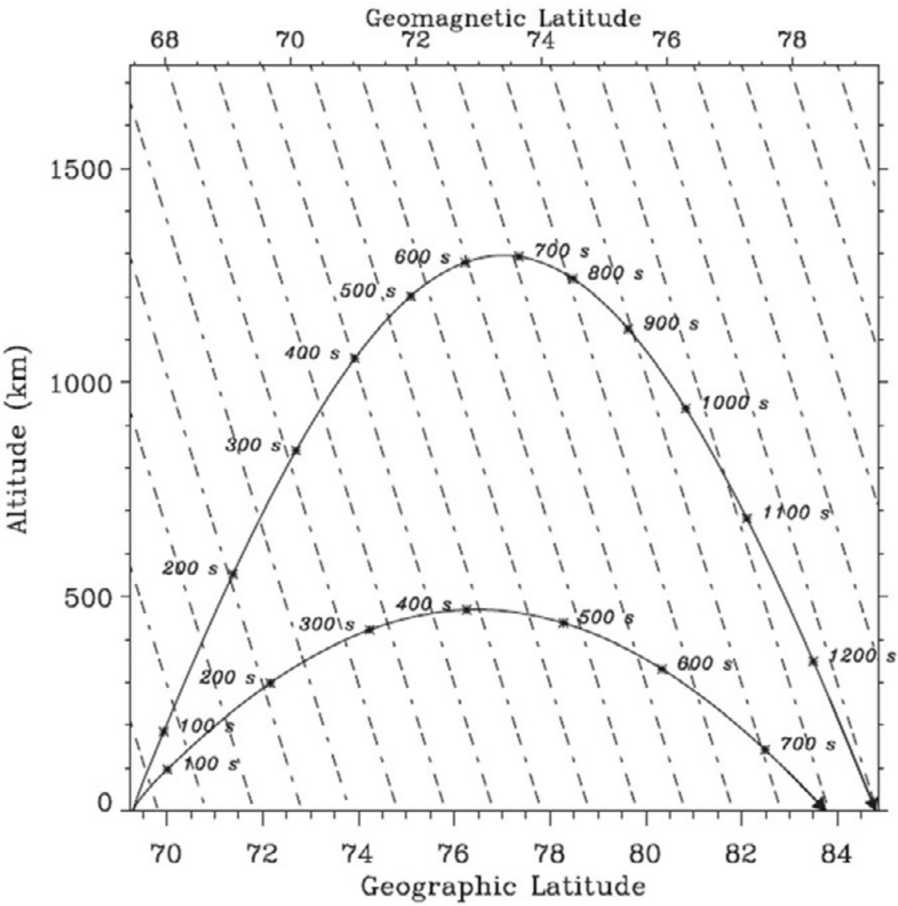


Figure 5: Range vs. altitude of the two payloads as function of time since launch of each payload. The Earth's magnetic field lines have been added to illustrate how the two payloads map from one altitude to the other (Courtesy: Craig Kletzing).

The two rockets are nearly identically instrumented and equipped with electric/magnetic field and wave package, particle spectrometer for electron and ion particle fluxes and the UiO multi-needle Langmuir probe system. This allows us to measure Electromagnetic Energy (Poynting) flux and Alfvén waves in accelerating electrons that may carry these currents and may be triggering plasma instabilities/turbulence, i.e., the electromagnetic and particle energy input heating essential to model the thermosphere effect. TRICE-2 is planned to fly from Andøya Space Center, Norway, in December 2018, through the cusp over Svalbard.

VISIONS-2's main objective is to investigate upward acceleration of ions along the magnetic field lines in order to understand the wave-particle interaction that accelerates oxygen ions above 10eV to escape the Earth gravitation. Upflowing ions were mapped to the auroral oval by satellites in Shelley et al. [1976], and the initial upflow acceleration above 300 km altitude was attributed to magnetic reconnection cusp-auroral events [Moen et al., 2004]

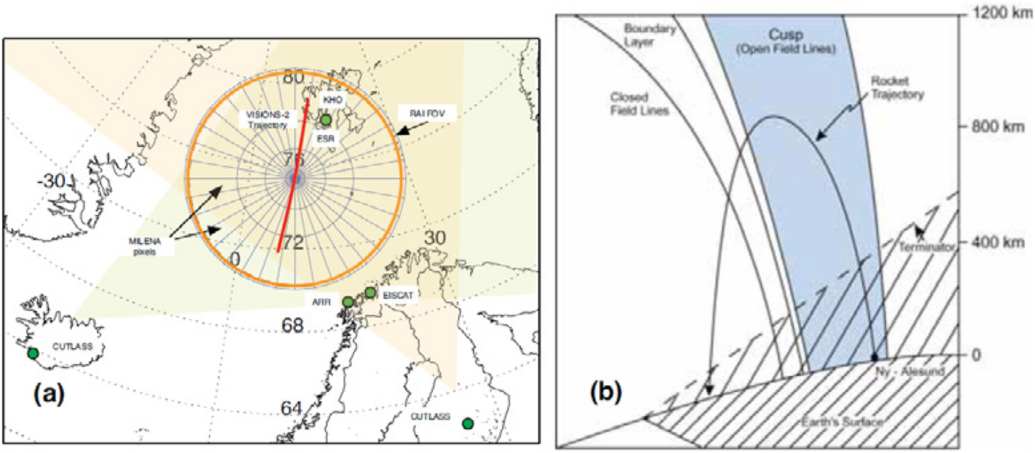


Figure 6: The VISIONS-2 experiment combines rocket and ground-based instrumentation to measure the nature and extent of ion outflow in the cusp. (a) The nominal trajectory, showing launch from Ny-Ålesund, and the radar fields of view; (b) a side view, showing the altitude / latitude extent of the trajectory, along with realistic magnetic field geometry, and a typical terminator for mid-December. (Courtesy; PI. Douglas Rowland)

VISIONS-2 will be the first mission to combine ENA imaging of cusp ion outflow with direct measurements of the drivers, including multispectral optical imaging of aurora, corresponding to regions of electron and proton precipitation, as well as direct in-situ measurements of fields and particles that provide very strong constraints on the remote sensing inversion and modelling. VISIONS-2 will fly from Ny-Ålesund, Norway, in December 2018, through the magnetic cusp, to an apogee near 800 km. During the flight, it will remotely sense ion outflow and its drivers over a region approximately 1000 km in diameter, providing critical information about the patchiness and burstiness of cusp ion outflow, as well as detailed information about the mechanisms that drive this outflow, leading to a new understanding of the mechanisms that couple the magnetosphere:

1) What is the total low-altitude (<1000 km) ion outflow at energies > 10 eV from the cusp under typical Bz south conditions?
2) How spatially and temporally variable is this outflow?
3) How is the outflow tied in detail to drivers and sources of free energy (e.g. auroral electron precipitation, convection, Joule heating)?

CAPER 2 is dedicated to explore the physical nature of magnetosphere-ionosphere (MI) coupling in terms of waves and acceleration processes. There are at least two separate electron acceleration processes of broad significance to space plasma physics: acceleration in electrostatic electric fields and in time-varying electromagnetic fields associated with Alfvén waves. In addition, a host of microscopic wave modes play a role in redistributing energy from the resulting electron beams to the thermal plasma, including most ubiquitously Langmuir waves. While many previous rocket experiments have probed nightside processes such as polar substorms, the proposed CAPER-2 will make significant advances in understanding electrodynamics associated with MI coupling in the cusp.

In particular, direct measurements of Alfvén waves associated with electron acceleration, via their electric and magnetic fields, have not been explored in the cusp, and the detailed interaction of the electron beam with Langmuir wave electric fields, as well as statistics of the resulting complex structure in the fields remains to be studied. The CAPER-2 instrument package includes the first ever wave-particle correlator measurements in the cusp.

Critical Ground based Observations

The large-scale context of the detailed rocket measurements will be mapped by a suite of ground-based instruments, including the EISCAT and SuperDARN radars, as well as with optical measurements from Ny-Ålesund and the Kjell Henriksen Observatory (KHO) near Longyearbyen. The cusp is often thought of as a dayside feature, but during the northern hemisphere's winter season, the cusp's ionospheric footpoint is often in darkness and directly over Svalbard. This enables the use of optical imaging for cusp studies.

SIOS rocket data base

From experience, old sounding rocket data are difficult to get a hand on. Such data are often stored on the private computers, and the focus has been on exchanging within the team of each rocket mission and not to provide easy access for external research teams. For example, it would be a big effort, if at all possible, to gather all the electron density altitude profiles that have been obtained over several solar cycles since the 1960s. This has made it difficult for the sounding rocket science community to provide added value to others across research disciplines and, thus, to reach a broad community. A key vision for the GCI-CUSP project is to reverse this tendency and to create standardized, long-lived datasets accessible to a broad community. Bringing observations together in a coherent, integrated and sustained program is indeed one of the backbones of the GCI-CUSP program, as mentioned in section 2.

The idea is that all the GCI-Cusp partners should share equally their data in a combined database accessible through the SIOS Data Management System (SDMS) [https://sios-svalbard.org/SDMS]. Each PI and his team coordinate their own dataset which has been standardized according to conventions agreed upon, and SDMS establishes a virtual data centre offering unified access to the relevant data. In particular, the (meta)data should be findable, accessible, interoperable and reusable. This will increase the efficiency in exchanging and comparing data between experiment teams.

Actions towards the creation of standardized GCI-Cusp datasets have already started. This was done through a GCI – CUSP data workshop in Santa Fe, New Mexico, USA, during the CEDAR meeting (24 June, 2018). During this workshop, several strategies were addressed, comprising the use of common metadata convention and data formats (CDF/netCDF), and the procedure for making the data available. It has been agreed upon that standardized calibrated data (SI units) should be made available to the community after the first scientific article has been published. In particular, for the multi-needle Langmuir probe systems, articles about the data, its quality and the extraction procedure will be written. It is also planned to use the data from the VISIONS sounding rocket (from 2013) as a precursor for GCI-Cusp dataset to check how well this standardization works, and discover any hiccups/challenges. From late autumn 2018 (October), teleconference meetings will be organized monthly to coordinate data sharing actions.

Summary

The GCI-cusp program is a game changer in providing sounding rocket infrastructure for science. Instead of individual rocket teams working separately, the GCI-cusp program umbrellas 9 missions that consist of 12 rockets. In this way, by multi-lateral collaboration, resources and results are combined and shared in an unparalleled capacity building to attack and close grand challenge questions of solar wind driven dynamics of the polar atmosphere, that is: the time-spatial variability in magnetopause reconnection, the wave-particle physics and acceleration processes of magnetosphere-ionosphere interaction, and the resulting vertical and horizontal coupling dynamics of the ionosphere and the thermosphere.

The participating research teams fund their own research on selected topics. University of Oslo, for example, that is in charge of the SIOS ICI-5 mission, flies the multi-Needle Probe instruments on 6 out of the 12 rockets (Figure 7), and will take part in the data analysis across five GCI-Cusp missions.

We aim to adapt the SIOS Data Management System (SDMS). Standardized data formats, and provision of SI unit data values will be crucial in order to stimulate efficient collaboration across teams, including the ground-based instrument research community, space plasma physics and atmosphere modellers. To bridge space science to Earth System Science is a SIOS goal.

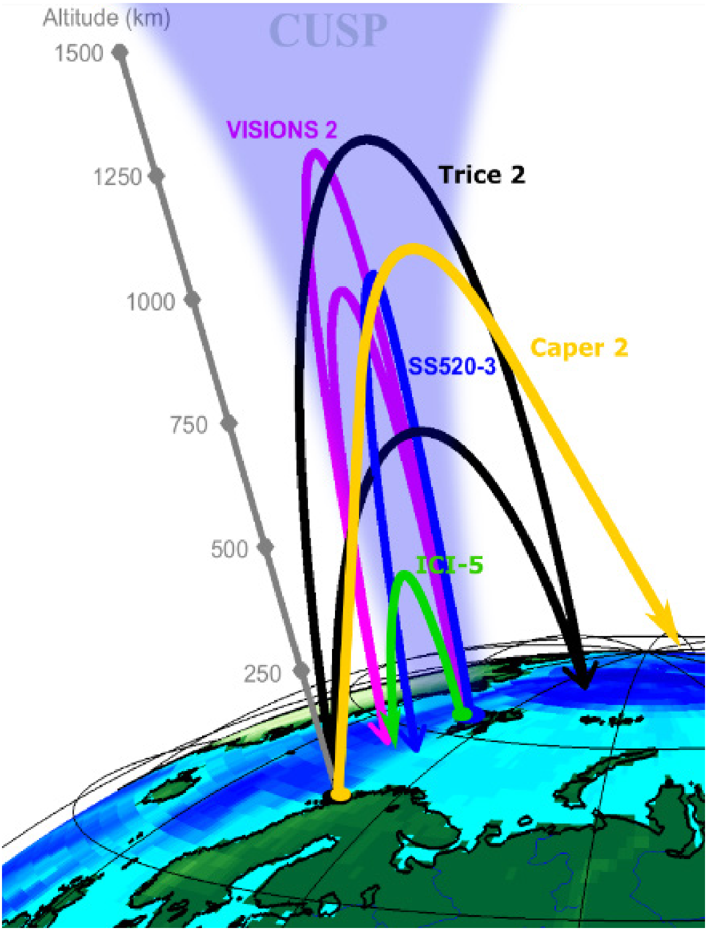


Figure 7: Trajectory of the GCI-Cusp rockets with the m-NLP fom UiO onboard.

Acknowledgement

The Norwegian contribution to the Grand Challenge Initiative- Cusp program is funded by grants from the Research Council of Norway and the Norwegian Space Center. Thanks to the SIOS staff for their assistance, and a particular thank to Kolbjørn Blix at Andøya Space center who has played a major role in developing the GCI-cusp strategy.

References

Bekkeng, T. A., Jacobsen, K. S., Bekkeng, J. K., Pedersen, A., Lindem, T., Lebreton, J.-P., and Moen, J. I., (2010), Design of multi-needle Langmuir probe system, *Meas. Sci. Technol.*, 21(8),085903.

Bruno, R. and Carbone, V., (2013), The solar wind as a turbulence laboratory, *Living Rev. Sol. Phys.*, 10: 2, doi:10.12942/lrsp-2013-2.

Carlson, H. C., J. Moen, K. Oksavik, C. P. Nielsen, I. W. McCrea, T. R. Pedersen, and P. Gallop, (2006), Direct observations of injection events of subauroral plasma into the polar cap, *Geophys. Res. Lett.*, 33, L05103, doi: 10.1029/2005GL025230.

Carlson, H. C., T. Pedersen, S. Basu, M. Keskinen, and J. Moen, (2007), Case for a new process, not mechanism, for cusp irregularity production, *J. Geophys. Res.*, 112, A11304, doi: 10.1029/2007JA012384.

Carlson, H. C., (2012), Sharpening our thinking about polar cap ionospheric patch morphology, research, and mitigation techniques, *Radio Sci.*, 47(4), RS0L21.

Cousins, E. D. P. and Shepherd, S. G., (2010), A dynamical model of high-latitude

convection derived from SuperDARN plasma drift measurements, *J. Geophys. Res. Space Physics*, 115(A12). A12329.

de Wit, T., (2003), Numerical schemes for the analysis of turbulence: A tutorial, Springer Berlin Heidelberg, 615, 315 342, doi:10.1007/3-540-36530-3_15.

Dungey, J. W., (1961), Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, 6:47–48.

Ellis-Evans, C. and K. Holmen, (2013), SIOS Infrastructure Optimisation Report SIOS Work Package 3, Deliverable 3.4, 2013.

Escoubet, C. P., Fehringer, M., and Goldstein, M., (2001), Introduction

The Cluster mission, *Ann. Geophys.*, 19, 1197-1200, doi:10.5194/angeo-19-1197-2001.

Foster, J. C., (1984), Plasma convection in the vicinity of the dayside Cleft, *J. Geophys. Res.*, 89(A2), 855–865, doi: 10.1029/JA089iA02p00855.

Hnat, B., O'Connell, D., Nakariakov, V. M., and T. Sundberg, (2016), Statistically determined dispersion relations of magnetic field fluctuations in the terrestrial foreshock, *The Astrophysical Journal*, 827 (2), 9. doi:10.3847/0004-637X/827/2/91

Horbury, T. S. and Osman, K. T., (2008), Multi-Spacecraft Turbulence Analysis Methods, in Multi-Spacecraft Analysis Methods Revisited, Gotz Paschmann and Patrick W. Daly (Eds.), *ISSI Scientific Reports Series, ESA/ISSI*, p. 55-64.

Jacobsen, K. S., Pedersen, A., Moen, J. I., and Bekkeng, T. A., (2010), A new Langmuir probe concept for rapid sampling of space plasma electron density *Meas. Sci. Technol.*, 21(8), 085902.

Jin, Y., J. I. Moen, and W. J. Miloch, (2015), On the collocation of the cusp aurora and the GPS phase scintillation: A statistical study, *J. Geophys. Res. Space Physics*, 120, 9176–9191, doi: 10.1002/2015JA021449.

Kelley, M. C., (2009), The Earth's ionosphere plasma physics and electrodynamic, 2nd., Elsevier Academic Press, USA.

Keskinen, M. J. and Ossakow, S. L., (1983), Theories of high-latitude ionospheric irregularities: A review, *Radio Sci.*, 18(6), 1077-1091.

Keskinen, M. J., Mitchell, H. G., Fedder, J. A., Satyanarayana, P., Zalesak, S. T., and Huba, J. D., (1988), Nonlinear evolution of the Kelvin-Helmholtz instability in the high-latitude ionosphere, *J. Geophys. Res.*, 93(A1), 137-152.

Kintner, P. M. and Seyler, C. E., (1985), The status of observations and theory of high latitude ionospheric and magnetospheric plasma turbulence, *Space Sci. Rev.*, 41(1), 91-129.

Kivelson, M. G., and Russel, C. T., (1995), Introduction to Space Physics, Cambridge University Press.

Linson, L. M. and Workman, J. B., (1970), Formation of striations in ionospheric plasma clouds, *J. Geophys. Res.*, 75(16), 3211-3219.

Lorentzen, D. A., J. Moen, K. Oksavik, F. Sigernes, Y. Saito, and M. G. Johnsen, (2010), In situ measurement of a newly created polar cap patch, *J. Geophys. Res.*, 115, A12323, doi: 10.1029/2010JA015710.

Lundberg, E. T., Kintner, P. M., Lynch, K. A., and Mella, M. R. (2012). Multi-payload measurement of transverse velocity shears in the topside ionosphere. *Geophys. Res. Lett.*, 39(1). L01107. doi:10.1029/2011GL050018

Mella, M. R., K. A. Lynch, D. L. Hampton, H. Dahlgren, P. M. Kintner, M. Lessard, D. Lummerzheim, E. T. Lundberg, M. J. Nicolls, and H. C. Stenbaek-Nielsen (2011), Sounding rocket study of two sequential auroral poleward boundary intensifications, *J. Geophys. Res.*, 116, A00K18, doi: 10.1029/2011JA016428

Moen, J., Walker, I. K., Kersley, L., and Milan, S. E, (2002), On the generation of cusp HF backscatter irregularities, *J. Geophys. Res*, 107(A4), SIA 3-1-SIA 3-5.

Moen, J., K. Oksavik, and H. C. Carlson, (2004), On the relationship between ion upflow events and cusp auroral transients, *Geophys. Res. Lett*., 31, L11808, doi: 10.1029/2004GL020129.

Moen, J., Oksavik, K., Abe, T., Lester, M., Saito, Y., Bekkeng, T. A., and Jacobsen, K. S., (2012), First in-situ measurements of HF radar echoing targets, *Geophys. Res. Lett*., 39(7), L07104.

Moen, J., Oksavik, K., Alfonsi, L., Daabakk, Y., Romano, V., and Spogli, L., (2013), Space weather challenges of the polar cap ionosphere, *J. Space Weather Space Clim*., 3, A02.

Narita, Y., K.-H. Glassmeier, S. Schäfer, U. Motschmann, K. Sauer, I. Dandouras, K.-H. Fornaçon, E. Georgescu, and H. Rème, (2003), Dispersion analysis of ULF waves in the foreshock using cluster data and the wave telescope technique, *Geophys. Res. Lett*., 30, 1710, doi:10.1029/2003GL017432, 13.

Narita, Y., Glassmeier, K.-H., and Motschmann, U., (2010), Wave vector analysis methods using multi-point measurements, *Nonlin. Processes Geophys*., 17, 383-394, doi:10.5194/npg-17-383-2010.

Narita, Y., S. P. Gary, S. Saito, K.-H. Glassmeier, and U. Motschmann, (2011), Dispersion relation analysis of solar wind turbulence, *Geophys. Res. Lett*., 38, L05101, doi:10.1029/2010GL046588.

Oksavik, K., J. Moen, and H. C. Carlson, (2004), High-resolution observations of the small-scale flow pattern associated with a poleward moving auroral form in the cusp, *Geophys. Res. Lett*., 31(11), L11807, doi:10.1029/2004GL019838.

Oksavik, K., J. Moen, H. C. Carlson, R. A. Greenwald, S. E. Milan, M. Lester, W. F. Denig, and R. J. Barnes, (2005), Multi-instrument mapping of the small-scale flow dynamics related to a cusp auroral transient, *Ann. Geophysicae*, *23*, 2657-2670.

Oksavik, K., J. I. Moen, E. H. Rekaa, H. C. Carlson, and M. Lester, (2011), Reversed flow events in the cusp ionosphere detected by SuperDARN HF radars, *J. Geophys. Res*., 116, A12303, doi:10.1029/2011JA016788.

Oksavik, K., Moen, J., Lester, M., Bekkeng, T. A., and Bekkeng, J. K., (2012), In situ measurements of plasma irregularity growth in the cusp ionosphere, *J. Geophys. Res*, 117(A11), A11301.

Oksavik, C. van der Meeren, D. A. Lorentzen, L. J. Baddeley, and J. Moen, (2015), Scintillation and loss of signal lock from poleward moving auroral forms in the cusp ionosphere, *J. Geophys. Res*., 120 (10), 9161–9175, DOI: 10.1002/2015JA021528.

Petrosyan, A., Balogh, A., Goldstein, M L. et al. (2010), Turbulence in the Solar Atmosphere and Solar Wind, *Space Sci. Rev*.,135, doi:10.1007/s11214-010-9694-3.

Pinçon, J. L. and Motschmann, U., (2000) (Electronic edition 1.1), (1998 paper edition), *Multi-Spacecraft Filtering: General Framework*, in Analysis methods for multi-spacecraft data, Gotz Paschmann and Patrick W. Daly (Eds.), *ISSI Scientific Report SR-001 ISSI/ESA*, pp-65-78.

Pinçon, Jean-Louis; Glassmeier, Karl-Heinz (2008), Multi-Spacecraft Methods of Wave Field Characterisation, in Multi-Spacecraft Analysis Methods Revisited, Gotz Paschmann and Patrick W. Daly (Eds.). *ISSI Scientific Reports Series, ESA/ISSI*., p. 47-54.

Rinne, Y., Moen, J., Oksavik, K., and Carlson, H. C., (2007). Reversed flow events in the winter cusp ionosphere observed by the European Incoherent Scatter (EISCAT) Svalbard radar, *J. Geophys. Res. Space Physics*, 112(A10). A10313, doi: 10.1029/2007JA012366.

Rinne, Y., J. Moen, H. C. Carlson, and M. R. Hairston (2010), Stratification of east-west plasma flow channels observed in the ionospheric cusp in response to IMF BY polarity changes, *Geophys. Res. Lett*., 37, L13102, doi:10.1029/2010GL043307.

Sandholt, P.E., M. Lockwood, T. Oguti, S. W. H. Cowley, K. S. C. Freeman, B. Lybekk, A. Egeland, and D. M. Willis (1990), Midday auroral breakup events and related energy and momentum transfer from the magnetosheath, *J. Geophys. Res*., *95*, 1039-1060.

Shelley, E. G., R. D. Sharp, and R. G. Johnson (1976), Satellite observations of an ionospheric acceleration mechanism, Geophys. Res. Lett.,

3(11), 654– 656.

Similon, P. L. and Sudan, R. N., (1990), Plasma turbulence, *Annu. Rev. Fluid Mech*., 22, 317-347.

Sjolander, K.; Karlsson, T.; Lockowandt, C., (2015), Sounding Rockets within Swedish National Balloon and Rocket Programme- Providing Access to Space from Esrange, Proceedings of the 22nd ESA Symposium on European Rocket and Balloon Programmes and Related Research, Tromso, Norway, 7-12 June 2015 (ESA SP-730, September 2015) edited by L. Ouwehand. ESA Communications, ESTEC, Noordwijk, The Netherlands. ISBN 978-92-9221-294-0. ISSN 1609-042X., p.429

Skjæveland, Å.S., H.C. Carlson, J. I. Moen, (2017), A statistical survey of heat input parameters into the cusp thermosphere, *J. Geophys. Res. Space Physics*, Volume 122, Issue 9, pp 9622–9651, DOI: 10.1002/2016JA023594.

Spicher, A., Miloch, W. J., Clausen, L. B. N., and Moen, J. I., (2015), Plasma turbulence and coherent structures in the polar cap observed by the ICI-2 sounding rocket, *J. Geophys. Res*, 120(12), 10,959-10,978, 2015JA021634.

Spicher, A., Ilyasov, A. A., Miloch, W. J., Chernyshov, A. A., Clausen, L. B. N., Moen, J. I., Abe, T., and Saito, Y., (2016), Reverse flow events and small-scale effects in the cusp ionosphere, *J. Geophys. Res.*,121(10), 10,466-10,480, 2016JA022999.

Treuman, R. A. and Baumjohann, W., (1997), Advanced space plasma physics, Imperial College Press, UK.

Tsinober, A., (2009), An informal conceptual introduction to turbulence, Springer, Netherlands, Dordrecht.

Tsunoda, R. T., (1988), High-latitude F region irregularities: A review and synthesis, *Rev. Geophys.*, 26(4), 719–760, doi: 10.1029/RG026i004p00719.

Weimer, D. R., (1995), Models of high-latitude electric potentials derived with a least error fit of spherical harmonic coefficients, *J. Geophys. Res.*, 100(A10), 19595–19607, doi: 10.1029/95JA01755.