Grand Challenge Initiative – Cusp: observational network for solar wind-driven dynamics of the top atmosphere (GCI-Cusp)

Jøran Moen[1,2], Andres Spicher[1], Toru Takahashi[1,3], Douglas E. Rowland[4], Craig Kletzing[5], James LaBelle[6], Miguel Larsen[7], Mark Conde[8], Yoshifumi Saito[9], Kolbjørn Blix[10]

1 University of Oslo, Oslo, Norway
2 University Centre in Svalbard, Longyearbyen, Norway
3 National Institute of Polar Research, Tokyo, Japan
4 NASA Goddard Space Space Flight Center, Greenbelt, Maryland, USA
5 University of Iowa, Iowa, USA
6 Dartmouth College, Hanover, New Hampshire, USA
7 Clemson University, South Carolina, USA
8 University of Alaska, Fairbanks, USA
9 JAXA Institute of Space and Aeronautical Science, Kanagawa, Japan
10 Andøya Space Center, Andenes, Norway

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

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1. Introduction

The magnetic cusp is a unique place in near Earth space, where energy from the solar wind transfers down into Earth's atmosphere and visualizes as *Daytime Auroras*. The *Grand Challenge Initiative – Cusp* is a gigantic rocket project that umbrellas nine sounding rocket missions, with in total twelve sounding rockets (Moen et al. 2018). In winter 2018/19 three missions (5 rockets) were successfully completed with acquisition of high-quality data while they traversed daytime cusp auroras over Svalbard. This report card is devoted to give an overview over which physical parameters are measured and some of the open science questions that these data are suitable to study.

Open access data in a standardized format are a prerequisite in order to enable efficient collaboration between many international teams of researchers, and also to inspire new research teams to take advantage of the heavy investments in experimental work. Due to complexities associated with rocket experiments, including spin modulations, wake effects etc., the data need to be skilfully prepared and calibrated, and adequate documentation has to follow in order to enable other than the rocket experiment team to make use of the data. The main purpose of this report card is to outline the ongoing development of a *multi-instrument cusp observing system* for efficiently exchange and reuse of data provided by the *GCI-Cusp* project. All *GCI-Cusp* partners are recommended to share equally their data in a combined database accessible through the SIOS Data Management System (SDMS)[1].

2. The state of the GCI-Cusp Earth observing system

The global picture of the Sun-Earth coupling is routinely monitored by the Super Dual Auroral Radar Network (SuperDARN) of radars, ground magnetometers, and numerous satellite missions. For detailed process studies, however, Svalbard is a unique observing platform to investigate multi-scale plasma processes. This is carried out on campaign basis by combined efforts in operating optical instruments and radars during sounding rocket campaigns. One aim of the *GCI-Cusp* project is to create an observing system for multi-scale process studies of the Sun-Earth coupling in the auroral *cusp*. Svalbard is the only place in the world where we can combine optics, radar and in-situ to study the *cusp*.

National Aeronautics and Space Administration (NASA), Japan Aerospace Agency (JAXA), SIOS, and the University of Oslo (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*[2].

1 https://sios-svalbard.org/metadata_search
2 https://sios-svalbard.org/News_20170406

The VISIONS-2 rockets, Visualizing Ion Outflow via Neutral Atom Sensing-2, were launched into a region of strong auroral and electrodynamic forcing, and observed its main target – atmospheric escape in the form of ion outflow. As shown in Figure 1 Left panel, the trajectories of the two rockets were almost coplanar, with one rocket (35.039 – pink trajectory) launched to 800 km apogee and the other (35.040-black) to 600 km apogee two minutes later. The resulting configuration has proven very valuable in studying the mechanisms that drive the ion outflow. In particular, studies of the variations in the plasma wave environment at the two different altitudes in conjunction with the ion measurements have been very illuminating. All the instruments functioned, and the data analysis is ongoing. Another rich dataset is the limb-imaging “Rocket-borne Auroral Imager” (RAI) dataset, which is providing altitude profiles of auroral and airglow emission at 630.0, 557.7, 864.4, and 391.4 nm, and is showing potential signatures of high altitude N2+ upwelling. The energetic neutral atom imaging analysis is in the early stages, but the instruments functioned well and returned data throughout the flight.

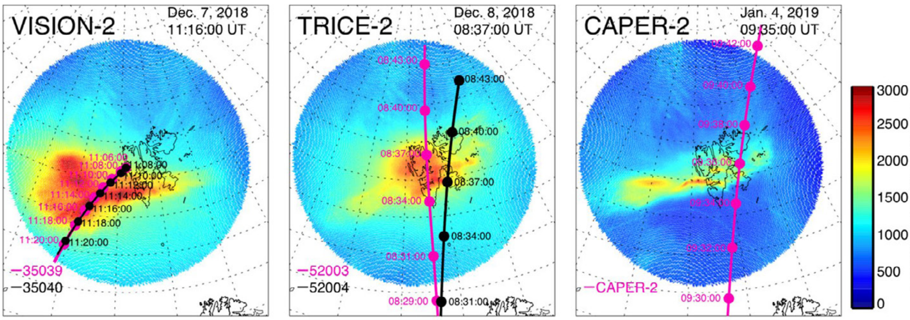

Figure 1: The all-sky image of the auroral 630.0 nm oxygen line has been projected onto a geographic map assuming 250 km as the peak altitude of the aurora emission. The emission intensity is colour coded with Rayleigh bar on the right. The rocket trajectories are overlaid. Left panel: VISIONS-2, two rockets launched from Svalrak, Ny-Ålesund Dec 7, 2018, the first at 11:06 UT and the other two minutes later at 11:08 UT. The auroral image was taken at 11:16 UT. Middle panel: TRICE-2, two rockets launched simultaneously from Andøya Space Center, December 8, 2018. The auroral omages was taken at 08:37 UT. Right panel: CAPER-2, one single rocket launched from Andøya Space Center on January 4, 2019. The all-sky image was taken ab 08:35 when the rocket entered the cusp aurora.

The TRICE-2 rockets, Twin Rockets to Investigate Cusp Electrodynamics, were launched from Andøya Space Center over Svalbard on December 8, 2018. The mission consisted of two, well-instrumented sounding rockets, launched two minutes apart through the auroral cusp. The high-flier (payload 52.003) reached an apogee of 1040 km and the low-flier (52.004) reached the top height of 755 km altitude. The TRICE-2 strategy was to fly two sounding rockets along same magnetic coordinates. However, as illustrated in Figure 1 middle panel, the low-flyer trajectory (black) diverted slightly to the east of the high-flier (pink). Nevertheless, the TRICE-2 mission was very successful in high resolution observation of ion steps caused by variability in the solar wind plasma injections; i.e. contain signatures of magnetic reconnection in the cusp as well as other cusp electrodynamics. Combined with ground radar and optical data, the TRICE-2 data provide a unique opportunity to have a great potential to study spatial and temporal variability in the energy transfer from the solar wind to the top atmospheres which is the mission main objective.

CAPER-2, Cusp Alfvén and Plasma Electrodynamics Rocket, was launched from Andøya Space Center on January 4, 2019 and reached an apogee of 774 km over Svalbard. As illustrated in the Figure 1 right panel, the traversing of the cusp was starting around apogee. CAPER-2 was dedicated to explore the physical nature of Magnetosphere-Ionosphere (MI) coupling in terms of waves and acceleration processes. There are 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. CAPER-2 observed strong Langmuir waves for the first half of the cusp traversal. CAPER-2 observed several intense wave signatures comprising continuous strong Langmuir waves for the first half of the cusp traversal. CAPER-2 also observed whistler mode waves in front of and within the cusp, suggesting a method of remotely detecting the cusp using VLF waves. The CAPER-2 observations are thus well suited to make significant advances in our understanding of wave-wave and wave-particle interactions the polar cusp.

Sounding rocket data are notoriously difficult to access and, as their existence is often unknown by other researchers, and their use is frequently confined to the rocket teams. We aim to make a step forward by making data from the GCI cusp openly accessible and in a standardized format. This is a prerequisite to enhance usability, transparency and reproducibility, allowing to facilitate international collaboration, and to inspire new research teams to take advantage of the heavy investments in experimental work. This also complies with the new requirement for several scientific journals to make the data and related products available in a repository practicing the FAIR principles[3], i.e. making data findable, accessible, interoperable and reusable (Wilkinson et al. 2016). This has the aim to "accelerate scientific discovery and enhance the integrity, transparency, and reproducibility of this data"[4].

In order to achieve this, data from the VISIONS-2 sounding rocket are used as a pioneering example, with the ambition to inspire other sounding rocket PIs in the future. The plan is to archive Visions-2 data on the Space Physics Data Facility (SPDF)[5] and on NIRD[6] , and make

3 https://publications.agu.org/author-resource-center/text-requirements/ (11.10.2019)

4 https://copdess.org/enabling-fair-data-project/ (11 October2019)

5 https://spdf.gsfc.nasa.gov/

6 https://archive.norstore.no/

it findable through SIOS[7] using NetCDF format, following examples of the latest NASA missions GOLD and ICON[8] The metadata are designed to account for preferences of SPDF and SIOS to follow the International Solar Terrestrial Programme (ISTP) Guidelines[9] and Attribute Convention for Data Discovery (ACDD).

Due to the complexities of spacecraft experiments, including spin modulations, charging or wake effects etc. (Mozer 2016; Paulsson et al. 2018), the data need to be skilfully prepared for it to be useful for scientific purposes. Documents describing the instruments and the calibration methods will be provided and each instrument team on VISIONS-2 and ICI-5 will follow the level definitions mentioned below, loosely inspired (and simplified) by the Magnetospheric Multiscale Mission (MMS) data level description (Baker et al. 2016) and adapted to satisfy attributes from the ISTP guidelines. The levels are labelled by "Hn", standing for "High Resolution data" with "n" taking values between 0 and 3:

- Raw: Raw telemetry data received on the ground and raw data that have been reconstructed, but unprocessed (remove artefacts, combine frames etc.)
- H0 (Level 0): Uncalibrated raw data at full resolution, i.e. quantity versus time.
- H1 (level 1): Calibrated (SI units) data.
- H2 (level 2): Processed calibrated units.
- H3 (level 3): Higher-order products.

Furthermore, refinements and updated versions of the data may be generated in the future when new calibrations are available. Those will be annotated by different versions V01, V02, V03, etc. Release notes describing changes in the new versions will also be provided from the source webpages.

3. Unanswered questions

Further three rocket missions are scheduled in November/December 2019, the Cusp Heating Investigation (CHI), the Cusp-RegionEXperiment (C-REX-2) and the SIOS Investigation of Cusp Irregularities (ICI-5). CHI will measure the flow of plasmas and neutral gasses in the cusp, testing current model of how they interact with one another and become heated and accelerated in the process. C-REX-2 measures wind and ion velocity at around 400 km in altitude on the cusp to trace causes of increased densities there. The mission differentiates between possible causes such as changes in wind, temperature or ion velocity. C-REX will be launched at Andøya, North-Norway over Svalbard, and CHI will be launched from

7 https://sios-svalbard.org/metadata_search

8 e.g. https://spdf.gsfc.nasa.gov/pub/data/gold/documentation/GOLD%20Public%20Science%20Data%20Products%20Guide%20-%20Rev%203.0.pdf

9 https://spdf.gsfc.nasa.gov/sp_use_of_cdf.html

Ny-Ålesund, Svalbard. The aim is a simultaneous launch and the two rockets will provide complementary data sets. ICI-5 was launched in the morning of 26 November 2019. Following the launch, it was quickly reported that the science team picked a prime science event. All payload events were reported as nominal and a solid track was provided by both the Norwegian and NASA ground assets. After data review, it was apparent that a roll rate anomaly was experienced, precluding the instruments from functioning as intended, i.e. no scientific data. The ICI-5 objective was to discover the drivers of plasma turbulence in the cusp auroral region, and specifically determine the size of turbulent eddy structures, and to explore why cusp aurora disturbs radio signals. Efforts will be made to redo the experiment.

Table 1 lists the physical parameters for each *GCI-Cusp mission*. Table 2 lists the science objectives for each *GCI-Cusp* mission. Rocket science is highly competitive, and the research questions selected for each mission are indeed questions of fundamental importance in space science and of relevance to Earth space climate and Earth system models.

The science objective for each mission is indeed very specific. However, data from each mission have the potential for a wide range of research questions in Earth system science and planetary science; i.e. the data have great potential for re-use in general research topics of fundamental relevance in space plasma physics (Table 3).

The topside neutral ionosphere is indeed affected by the solar wind coupling towards the Earth ionosphere and thermosphere system. Weather systems include the atmosphere up to 150 km, however it is uncertain how much the solar wind coupling to the polar atmosphere may affect weather and regional climate prediction models. Energetic particle precipitation modifies atmospheric chemistry in the mesosphere-stratosphere which in turn modifies the vertical energy transport that indeed is relevant for climate models (Semeniuk 2011).

We are now mobilizing for the *Grand Challenge Initiative - Mesosphere and Lower Thermosphere* (*GCI-M/LT*). In the stratosphere and mesosphere, between 10-90 km altitude, the residual meridional circulation is driven by dissipating gravity waves. Gravity wave forcing is included in global circulation models (GCM) merely as a factor, but is not properly modeled. This indeed introduces uncertainties in climate scenario predictions (Shepherd 2014). The GCI-M/LT project will investigate sub-grids scale processes in the mesosphere-lower thermosphere in order to develop more realistic models for global circulation. 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 was emphasized in the SIOS Infrastructure Optimization Report (Ellis-Evans and Holmén 2013). This will be essential in order to make progress in understanding the vertical transport of energy and mass flow dynamics, including the role of meteor components (Ellis-Evans and Holmén 2013).

Table 1: The physical parameters measured/to be measured by each rocket mission are marked by crosses. E (Electric field), B (Magnetic field), Ne (electron density), HF/ELF/VLF (High Frequency/Extreme Low Frequency/Very Low Frequency), e-flux (electron fluxes), i-flux (ion fluxes), Vi (ion velocity), Vn (Neutral wind), Te (electron temperature), N (neutral density), velocity of H+, He+, O+, Phase space of H+, He+, O+, core ground experiments ASC (All-Sky Camera), EISCAT Svalbard Radar to measure Ne,Vi, Te, Ti and Cutlass High Frequency Radar to measure Vi flow field and plasma irregularities.

Mission/ Parameter	TRICE-2	VISIONS-2	CAPER-2	AZURE	ICI-5	C-REX 2	CHI	SS-520-3
E	x	x	x		N/A			x
B	x	x	x		N/A			x
Ne	x	x	x		N/A			x
HF/ELF/VLF	x	x	x					
e-flux	x	x	x		N/A			x
i-flux	x	x						
Vi				x		x	x	
Vn				x		x	x	
Te		x						x
N								x
velocity H+, He+, O+								x
Phase space H+, He+, O+								x
narrowband auroral / airglow imaging		x						
Key Ground Support for the completed missions								
ASC	x	x	x	-	x	-	-	-
EISCAT	x	x	x	-	x	-	-	-
Cutlass HF	x	x	x	-	N/A	-	-	-

Table 2: Specific science objectives of each mission.

Mission name	Specific mission objectives	#rocket	Launch Site	Launch date	Lead
TRICE-2	Magnetopause reconnection -steady or pulsed	2	ASC	8DEC2018	US
VISIONS-2	Energization of O+- Ion upflow/outflow	2	Svalrak	7DEC2018	US
CAPER-2	Alfvén wave acceleration of auroral particles	1	ASC	4JAN2019	US
G-Chaser	Student rocket Technology testing	1	ASC	13JAN2019	US
AZURE	Auroral effects on the atmosphere/energy gain or loss	2	ASC	6APR2019	US
SIOS ICI-5	Plasma instabilities processes/turbulence in the cusp ionosphere	1	Svalrak	DEC2019	NO
C-REX 2	Neutral & plasma winds to study enhanced density at 400 km	1	ASC	DEC2019	US
CHI	Auroral forcing of cusp upwelling effects	1	Svalrak	DEC2019	US
SS-520-3	Energization of O+- Ion upflow	1	Svalrak	TBD	JP

Table 3: The GCI-Cusp missions have the potential to address fundamental questions in space physics.

Fundamental Questions	TRICE-2	VISIONS-2	CAPER-2	AZURE	ICI-5	C-REX 2	CHI	SS-520-3
Magnetic reconnection	x	x	x		x	x	x	x
Particle acceleration	x	x	x				x	x
Atmospheric heating		x		x	x	x		x
Plasma instabilities	x	x	x	x			x	x
Plasma Turbulence	x	x	x		x			x

4. Recommendations for the future

The greatest success with the *GCI-Cusp* collaboration so far, is that we so far have been successful with the launches, and that we are developing a *multi-scale Cusp atmosphere observing system*. We adapt to the SIOS data management system and the Space Physics Data Facility (SPDF) for storing and making data openly accessible and reusable for new research projects developed, within and outside the *GCI-Cusp* consortium, and hence to maximize the return of the investments made by each participation, and puts the Svalbard oriented research into a global context. We also hope that in the near and distant future, other rocket experiments will follow the footsteps of the GCI-Cusp with VISIONS-2, and make their data standardized in a similar way.

The GCI-Cusp programme has already resulted into its successor initiative. That is a new international effort to create the *Grand Challenge Initiative Mesosphere/Lower Thermosphere (GCI-M/LT)* that was initiated at the CEDAR 2018 workshop in Santa Fe. If SIOS decides to participate in *GCI-M/LT*, it will be an excellent opportunity to close further knowledge gaps defined by SIOS. As reported in the SIOS Infrastructure Optimisation Report (Ellis-Evans and Holmén 2013), there is an observational gap in the altitude range 40-80 km, that only can be filled by rockets. Taken together, GCI-Cusp and *GCI-M/LT* will be an important contribution to optimize an ESS monitoring program for vertical coupling of atmospheric layers.

Recommended future investments:

i) New SIOS infrastructure investment plans should consider a high-resolution time and space 4D all-sky imaging system to enhance the features of the cusp-observational network, i.e. 3 identical imagers placed at 3 different sites. Key parameters derived from routine ground optical and radar instruments should be given status as SIOS core data.

ii) SIOS should make a strategic effort to also become a central partner in the GCI-M/LT rocket initiative, by prioritizing to investment into the planned SIOS ICI-6 sounding rocket.

5. Data availability

The objective is to have the first release of VISIONS-2 data before 31 December 2019. This will include data from the VISIONS-2 experiments listed in Table 4 .

Table 4: List of the instruments on-board both VISIONS-2 payloads (35.039 and 35.040) with the data levels (see section 2) expected at the time of data release. The abbreviations stand for Fields and Thermal Plasma (FTP) instrument, Cubesat Electric Field Instrument (CEFI), multi-needle Langmuir probe system (mNLP), the Energetic Electron Analyzer/Energetic Ion Analyzer (EEA/EIA), Acute precipitating electron spectrometer (APES), MIniaturized Low-energy Energetic Neutral Atom imager (MILENA), Rocket-borne Auroral Imager (RAI), and miniaturized plasma imagers (MPI). This list may be subject to minor changes. The name of the instruments PIs and data repositories are also included.

Mission/ Parameter (instrument)	VISIONS-2 35.040	VISIONS-2 35.039	Provider, access
Magnetic field (FTP/CEFI)	H2	H2	Pfaff/Rowland/spdf
DC electric field (FTP)	H2		Pfaff/Rowland/spdf
VLF (FTP/CEFI)	H2	H2	Pfaff/Rowland/spdf
HF (FTP)	H2		Pfaff/Rowland/spdf
Langmuir probe (FTP/CEFI)	H1	H1	Pfaff/Rowland/spdf
Electron temperature (FTP/CEFI)	H2	H2	Pfaff/Rowland/spdf
Electron density (mNLP)		H1	Moen/NIRD
Electron particle data (EEA)	H2		Clemmons/Rowland/spdf
Electron particle data (APES)	H0		Michell/Rowland/spdf
Electron particle data (MILENA)	H0	H0	Collier/Rowland/spdf
Ion particle data (EIA)	H2		Clemmons/spdf
In-situ auroral imager (RAI)		H0	Hecht/spdf
Ion Velocity (MPI)		H2	Burchill/spdf
Trajectory, attitude, mechanical	H1	H1	Rowland/spdf
All-Sky Imager	H2	H2	Moen/NIRD

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