# 10th VERSIM Workshop 2022
# Abstract and Programme Book

Sodankyla, Finland, 07 - 11 November 2022

VERSIM 2022

# A word from the organisers

Greetings and welcome to the 10th VERSIM workshop!

On behalf of the Local Organizing Commitee, I would like to welcome you to the Sodankylä Geophysical Observatory, just over 120 km above the artic circle. We are happy to host the VERSIM workshop for a third time, and we hope that you will have many rewarding scientific discussions while enjoying the natural wonder of Lapland. For those of you joining us online, we trust the hybrid mode will also let you benefit from interesting scientific exchanges with those present in person.

Following in the footsteps of previous workshops, we have tried our best to give enough time for questions, debates and networking, especially for those in the initial stages of their career. For this purpose, we are also proud to host the 1st VERSIM school for students and early career scientists, in the hopes of inspiring the newer generations to enter and continue to thrive in our field of research. One of the streghts of the VERSIM Workshops has always been its very informal nature, allowing for easier discussions between "young" and "older" scientists without specific formalities.

Finally, our program will include some leisure time with an excursion to Kakslauttanen Arctic Resort so our participants can enjoy a Lappish welcome.

The school starts at 09:30 on 05 November 2022 (Sat) in the Polaria building and ends at 17:00 the next day (Sun). There will be a social gathering afterwards for the participants.

The workshop will begin welcoming the onsite participants at 09:00 on 07 November 2022 (Mon) also in the Polaria building, with the workshop kick-off at 09:25.

**Dr. Jyrki Manninen**
Chair of the Local Organising Commitee

VERSIM 2022

# Behind the workshop

## Scientific Programme Commitee

Jacob Bortnik (UCLA, United States)

Mark Clilverd (BAS, UK)

Andrei Demekhov (PGI, Russia)

Janos Lichtenberger (Eötvös U., Hungary)

Jyrki Manninen (U. of Oulu, Finland)

Binbin Ni (Wuhan U., China)

Yoshiharu Omura (Kyoto U., Japan)

Craig Rodger (U. of Otago, New Zealand)

Ondrej Santolik (IAP, Czechia)

Rajesh Singh (IIG, India)

## Local Organising Committee

Jyrki Manninen (U. of Oulu, Finland)

Craig Rodger (U. of Otago, New Zealand)

Claudia Martinez-Calderon (Nagoya U., Japan)

Yikai Hsieh (Kyoto U., Japan)

## We thank our sponsors

Sodankylä Geophysical Observatory, University of Oulu, Finland

Institute for Space Earth Environmental Research, Nagoya University, Japan

Scientific Committee on Solar-Terrestrial Physics

International Union of Radio Science

International Association of Geomagnetism and Aeronomy

SCOSTEP Scientific Committee on Solar-Terrestrial Physics

SGO UNIVERSITY OF OULU

IAGA

U.R.S.I.

ISEE Institute for Space-Earth Environmental Research

VERSIM 2022

# About our location

## The Sodankylä Geophysical Observatory

In December 1913, the Finnish Academy of Science and Letters established the Sodankylä Geophysical Observatory (SGO). Its main purpose was to fill the need for continuous observations in the arctic regions to understand the nature of all kinds of geomagnetic and auroral phenomena.

For over 100 years, the observatory has made geophysical measurements and research. SGO not only provides a rich scientific history but, more recently, real-time information about the atmosphere, sun, solar wind and global space conditions.

Since August 1997, the observatory has been a separate department of the University of Oulu.

## Sodankylä : The Village

To get a better idea of our location, the village of Sodankylä is approximately 800 km north of Helsinki, the Finnish capital, and about 125 km northward from the Artic Circle.

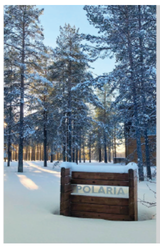
Sodankylä is situated in the heart of the Finnish Lapland, surounded by vast connifer forests, national parks, reindeers and the Northern Lights. Affectively called "The village", it is home to approximately 8000 people, hosts the the Midnight Sun Film Festival in June and is also known for having one of the oldest wooden churches in Finland (make sure to stop to check it out!).

## Polaria

The main building on site is shared between the Lapland's Research Institute of the Finnish Meteorological Institute and SGO.

More commonly known as Polaria, it was completed in 2001 and at the time was the largest office building in Finland entirely made of timber.

Unless otherwise stated, **the lectures and coffee breaks will be held in this building**.




## SCHEDULE AT A GLANCE

# Timetable

| EET | NOV. 5 | NOV. 6 | NOV. 7 | NOV. 8 | NOV. 9 | NOV. 10 | NOV. 11 |
|---|---|---|---|---|---|---|---|
| | School | | Workshop | | | | |
| 9:00–10:15 | Tutorial 1<br>C. J. Rodger | Visit to Kannuslehto (VLF Receiver) | Welcome Session | Session 5 | Session 9 | Session 11 | Session 15 |
| 10:45–12:00 | Tutorial 2<br>J. Lichtenberger | (continued) | Session 2 | Session 6 | Session 10 | Session 12 | Session 16 |
| 12:00–13:30 | Lunch Break | | | | | | |
| 13:30–14:45 | JC Activities +Networking | Tutorial 3<br>K. Shiokawa | Session 3 | Session 7 | Business Meeting | Session 13 | Session 17 |
| 15:15–16:45 | Tour of SGO | Tutorial 4<br>O. Santolik | Session 4 | Session 8 | Excursion | Session 14 | Session 18 |
| 17:00 | | School After-Party | | | | | |
| 18:00–20:00 | | | Ice Breaker (Town Hall) | | Banquet | | |

**TIP:** Some useful time zones: UTC = EET – 2, JST = EET + 7, CST = EET – 8

GET YOUR BEARINGS

# Map of the Observatory


Polaria · Niesta (lunch) · Parking · Aurora spots · Guest house

**TIP:** Follow the footpaths to the river for good aurora spots. Be careful not to fall into the river!

GET YOUR BEARINGS

# Map of Sodankylä, « The Village »

**Hotels**

A. Bear Hotel
B. Hotel Sodankyla

**Points of interest**

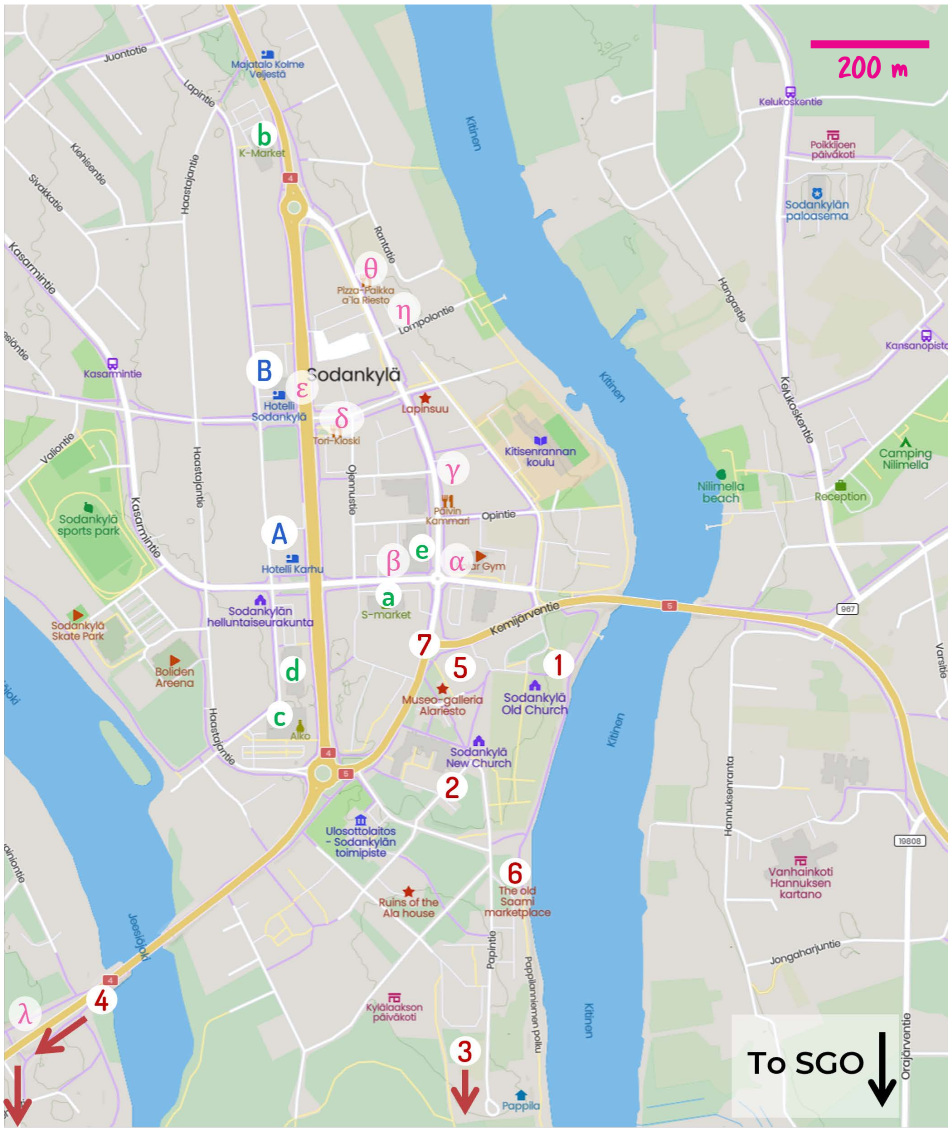
1. Old Church
2. New Church
3. Pappilanniemi Nature Walk
4. Heritage Museum
5. Alariesto Museum
6. Old Saami marketplace
7. Reindeer and the Lapp

**Grocery stores**

a. S-market
b. K-market
c. K-supermarket / Alko
d. LIDL (northernmost in the world!)
e. R-Kioski (convenience store)

**Restaurants**

α Lova Ravintola (restaurant)
β Kahvila Smak (coffee Shop)
γ North Pizza & Kebab
δ Tori Kioski (hamburgers)
ε Krouvi & Kievari (restaurant)
η Scanburger
θ Pizza Paikka
λ Rolls Express (hamburgers)




**TIP:** Interactive Google Maps link → **click here**

**TIP:** Finland has a limitation on the sale of alcohol depending on their alcohol percentage. If you'd like to indulge, make sure to go before closing time!

Alcohol < 5.5% @ Normal shops 09:00 – 21:00
Alcohol > 5.5% @ Alko usually 09:00 – 18:00 (closed Sun, Fri until 21:00)

GET YOUR BEARINGS

# What's cooler than being cold?

## What temperatures to expect?

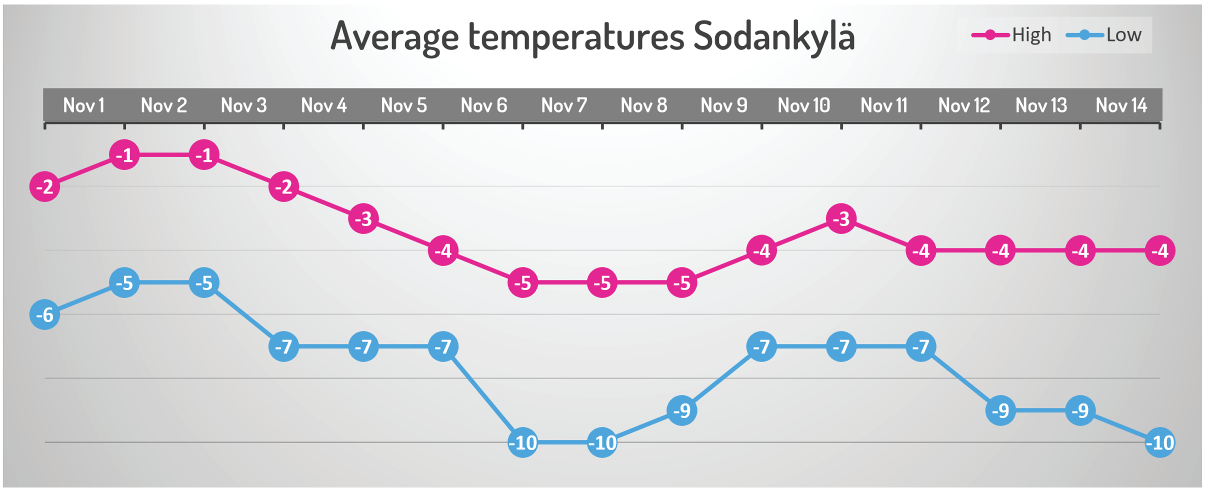
In November 2021, daily high temperatures were between -1°C and -6°C, rarely exceeding 4°C. Daily low temperatures ranged from -7°C to -13°C.

Please expect temperatures to remain **below zero** even during the day.

While the temperatures inside Polaria will be comfortable, make sure to bring proper warm or down jackets for any outside activity. For those of you sensitive to the cold, or those who will be braving the night to watch aurora, we recommend layering up with fleece, winter pants , insulated boots or even thermal undergarments. Hats, gloves and scarfs are also encouraged.

More info: https://emptylighthouse.com/travel/sodankyl-finland-what-to-pack-what-to-wear-and-when-to-go

**TIP:** Do not forget lip balm!




## What about the weather?

In November, there's a 25% chance of snow or rain on any given day. Just in case make sure that your jacket is warm but also water proof or water resistant. When outside it will generally feel freezing cold with an occasional gentle breeze, so we suggest to dress in something toasty!

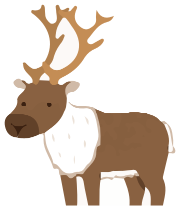
At this time of year Sodankylä gets about 5.4 hours of sunlight per day, with broad daylight from around 8:30 to 15:30.

**TIP:** A walk after lunch just before the sessions will let you enjoy nature and the sun's warmth.

**TIP:** As it gets dark quickly, if you will be walking along roads (especially nearby SGO) please make sure to wear reflective or visibility gear (hats, jackets, keychains).

GET YOUR BEARINGS

# The Reindeers and You



## Basic Information

Reindeer herding still plays an important role in the culture of indigenous Sámi in Lapland and elsewhere. Even today, it still is on of the cornerstones of Sámi culture, providing clothes, tradiaional handicrafts and food.

Fencing should limit the access to the SGO campus but reindeer are hungry, so you will often find them in the forest around or within SGO grounds in the fall trying to find lichen and other food sources. We don't usually see them often in November but they might still be around at the time of the workshop.

Your best chance to see them walk around SGO forests is in the very early morning just after sunrise or near the sunset. For those who will be watching aurora on SGO grounds, be aware reindeers could scare you as they walk around the forest late at night.

**TIP:** Hear a creepy cowbell in the forest late at night? it's just a male reindeer wondering about.

## Safety

Reindeer remain wild animals therefore be respectful of their space. Reindeer might get curious and try to get a better look at you but do not approach them too closely! Especially as October – November is rutting season.

**TIP:** If a reindeer (particularly male) starts making noises at you, you are too close! Slowly back away to a safer distance (> 100 m).

Reindeer remain in the move looking for more food and you are likely to encounter them on the road. A herd in the middle of the road is not an unusual sight in Lapland, so stay vigilant if you see a reindeer warning sign, especially when driving at night and in the early morning.

GET YOUR BEARINGS

# Aurora Hunting

## Best locations

On a good night, aurora can be observed from multiple locations in Sodankylä. Try looking for a spot away or hidden from street lights with view towards the north.

As SGO is surrounded by forests you will have darker observations spots there, but the river access is sometimes a bit tricky and cold. For approximate locations on good spots to observe aurora, please refer to the map in page 5.

Most of the spots are easy to find by following the footpaths. Take some time around lunch to scout the footpaths and the access to the riverside so you will have an easier time at night.

Once you reach the river, look towards the city lights, this is the general north direction.

On days of strong geomagnetic activity the auroral oval will move southwards and you might see auroras directly overhead.

^ Photo by C. Martinez from one of these spots in Oct. 2018

## Observation tips

★ Best time to watch is usually after 10 pm, ideal is close to midnight, even at low geomagnetic conditions.

★ Dress really warm!! You will be mostly standing in freezing negative temperatures waiting for things to happen.

★ Use red light headlamps and dim all your screens to minimum (camera, phone) so your eyes adapt to the darkness.

★ Bring water. Bring a friend. Or several!

★ Consider a neck warmer (or similar) around your camera to protect it from the frost.

★ Keep your phone in your jacket pocket or it will die! Consider taking a power bank with you.

★ Be careful near the river. You could easily fall into it.

★ Note that even if the river appears frozen, you need at least 5 cm of ice to safely walk on it. **Don't walk on it!**


Check real time data from all-sky cameras to see when the show starts.

https://www.sgo.fi/Data/RealTime/allsky.php

GET YOUR BEARINGS

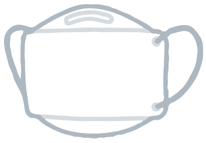
# Covid-19 Protocols

At the time of writing Finland has no mandatory regulations concerning COVID-19, yet we would like to make sure that the in-person participants are as safe as possible.

Here are a few recommendations to stay healthy:

## Masks

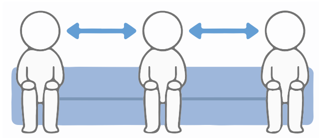
The use of masks is no longer necessary on university premises but feel free to do so at your own discretion. We encourage the use of masks whenever you are in crowded and/or in-door closed spaces, particularly inside the conference room or when talking in groups.



## Social distancing

When possible try to keep social distancing rules especially during the coffee breaks and lunch times, as people are less likely to wear masks.

If the weather is nice, take advantage to discuss and socialize outside.



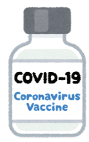
## Hygiene

Keep in mind to wash your hands regularly.

If you sneeze or cough without a mask, cover your mouth and nose with a tissue. If you don't have one, cough or sneeze into your elbow.

## Vaccines

Before travel we recommend you to take vaccinations and boosters according to the health guidelines from your doctor and country officials.




## Do you feel ill?

If you have any type of cold symptom, fever, sore throat, headache, or just generally feel unwell, stay at your accomodation. Contact the LOC to let them know of your condition. We will help you asses the situation and direct you to the proper medical care.

If you need urgent assistance from the authorities (police, paramedics, firefighters, social services) directly call the **emergency number: 112**

Calling the emergency number should be free of charge for EU numbers, and you can even use a mobile without SIM card to call.

WORSHOP

# Presentation Instructions

## For everyone

The workshop will be hybrid. Presenters participating online will be grouped in "Zoom sessions" according to their local times. Make sure you have the latest version of Zoom available.

Zoom links will be provided separately by email.

All presentations will be oral talks, there will be no posters.

Time alloted (including questions) : **Invited talks 25 min** **Standard talks 20 min**

## Onsite participants

All sessions will be held in the meeting room of Polaria (1F left).

Coffee breaks will also be at Polaria (1F hall area).

Lunch will be served at Niesta (see page 5). Niesta is about a 10 min walk from Polaria.

### Presenters

- ☆ Use your own laptop or the computer provided in the meeting room.
- ☆ Login to Zoom at least 10 min before presentation time.
  Share screen before stepping to the podium or when indicated by the chairperson.
- ☆ Check your presentations during breaks, before or after sessions.
  Please ask our local staff to help you out.

## Online participants

Please join the meeting using Zoom and at least 5 min before the start of the session.

Unless stated, all timings are provided in EET (Finnish local time).

### Presenters

- ☆ Use your full name and add two asterisks before it (ex. **Claudia Martinez)
- ☆ Check your microphone and sharing screen capabilities before your session.
  We will provide timings for you to check your presentation beforehand.
- ☆ Join Zoom at least 5 min before presentation time and share screen when indicated by the chairperson. Any problem? Ask the zoom host or co-host for help.

TIP: To avoid delays, make sure to respect presentation timings and familiarize yourself with the Zoom software usage.

## SCHOOL PROGRAM

# 5 & 6 November 2022

### SATURDAY - 05 November

08:45 - 09:00

Arrival & Welcome
Registration Area @ Polaria

09:00 - 10:15

**Tutorial 1.** "VLF as a tool in Geophysics and link to Space Weather" by C. J. Rodger

10:15 - 10:30

Coffee Break

10:45 - 12:00

**Tutorial 2.** "Remote sensing of the plasmasphere by whistlers" by J. Lichtenberger

12:00 - 13:30

Lunch break

13:30 - 14:45

[1] VERSIM Journal Club presentation

[2] Tell us about yourself and your research

14:45 - 15:15

Coffee Break

15:15 - 16:45

**Tour of SGO.** Get to know the instruments and facilities at SGO.

### SUNDAY - 06 November

08:30 - 09:00

Pick up at SGO guesthouse and hotels.
Travel to Kannuslehto.

10:00 - 12:30

**Visit of the VLF receiver.**

**Lunch:** Either picnic at Kannuslehto or late lunch at Niesta depending on weather.

12:30 - 13:30

Return to SGO

13:30 - 14:45

**Tutorial 3.** "Undertanding of magnetosphere dynamics using the MHD equation of motion" by K. Shiokawa [online]

14:45 - 15:15

Coffee Break

15:15 - 16:45

**Tutorial 4.** "Music of the Spheres: Spacecraft Measurements of Electromagnetic Waves" by O. Santolik

17:00 - 18:00

Social gathering for school participants and lecturers.

# WORKSHOP PROGRAM
# 7 November 2022

** Invited

## MORNING

09:00 - 09:25
Welcome and registration

09:25 - 09:35
Opening remarks by J. Manninen

09:35 - 10:15

Some recent advances in VERSIM science
M. Rycroft **

Coffe Break

10:45 - 12:00

**Session 2**

Machine-Learning Based Modeling and Interpretation of the Earth's Outer Radiation Belt Flux Dynamics
J. Bortnik **

Broadband and Narrowband VLF Observations Related to Transient Luminous Events
I. Kolmasova **

Lightning generated whistler wave ducting assessment with the Van Allen Probes
A. Wold

Lunch break @ Niesta

## AFTERNOON

13:30 - 14:15

**Session 3**

Electro Magnetic Ion Cyclotron wave-induced electron precipitation: ground-based and satellite observations
M. Clilverd **

GLD360 to RBSP: Mapping the Energy Input of Lightning Generated Whistlers into the Magnetosphere
A. Shane

New sferic filtering methods for VLF data preprocessing
J. Lichtenberger **

Coffe Break

15:15 - 16:45

**Session 4**

New Perspectives on Wave-Induced Electron Precipitation from Earth's Radiation Belt using Van Allen Probes, MMS, and ELFIN Observations: Insights on Loss Rates and Energy Inputs to Earth's Ionosphere and Atmosphere observations
D. Turner **

Effects of Wavelength-Scale Density Ducts on the Subpacket Structure of Chorus
M. Hanzelka

Multipoint observations of whistler-mode waves in plasmaspheric plumes
O. Santolik **

Theory Of Particle Diffusion, Drift And Advection Via Cyclotron Interactions
O. Allanson

# WORKSHOP PROGRAM

# 8 November 2022

** Invited

**MORNING**

09:00 - 10:15

**Session 5**

Local time and seasonal variations in the D-region ionosphere: Does it reflect SSW effects?

Y. Nozaki

Variations in the D-region ionosphere associated with Tonga volcanic eruptions of 15 July 2022 using VLF/LF transmitter signals

H. Ohya

Response of the D-region ionosphere to a X-class solar flare by OCTAVE VLF observations

M. Nakayama

Coffe Break

10:45 - 12:00

**Session 6**

Imaging the D-region ionosphere over large scales using an array of VLF receivers

R. Marshall

Very low frequency waves: tool to understand large meteorological systems effect on the lower ionosphere

A.K. Maurya

Lunch break @ Niesta

**AFTERNOON**

13:30 - 14:15

**Session 7**

Study on the longitudinal extent of QP emissions using conjugated events observed by PWING stations

C. Martinez-Calderon

Some statistical results of VLF bursty-patches observed in 2006-2022 campaigns at KAN

J. Manninen

Ground-based VLF Emissions Observed in the Frequency Range 16-39 kHz: Campaigns 2017-2018

L. Macotela

Coffe Break

15:15 - 16:45

**Session 8**

A survey of Cluster Wideband measurements during Auroral Kilometric Radiation source crossings

D. Pisa

Geomagnetically Induced Currents and Harmonic Distortion: Contrasting Power Network Measurements and Wideband VLF

C.J. Rodger

First Results from VIPER - The VLF Trans-Ionospheric Propagation Experiment Rocket Campaign

J. Bortnik

New results for sudden enhancements of PLHRs observed at KAN

J. Mannninen

## WORKSHOP PROGRAM

# 9 November 2022

** Invited

### MORNING

09:00 - 10:15

**Session 9**

First results of the WHU VLF wave detection system at the Chinese Great Wall Station in Antarctic

B. Ni **

Evolution of the Electron Zebra Stripes in the Earth's Inner Magnetosphere

M. Pandya

The Impact of Sudden Stratospheric Warmings and Elevated Stratopause Events on the VLF signal in high latitudes

H. Schneider

Coffe Break

10:45 - 12:00

**Session 10**

The Connection Between the October Effect in VLF Observations and neutral Atmosphere Dynamics

V. Wendt

The CANVAS Mission: Quantifying the Very-Low-Frequency Radio Energy Input from the Ground into the Earth's Magnetosphere

R. Marshall

Combined VLF and magnetic observations for improved space situational awareness

E. Tanskanen **

Lunch break @ Niesta

### AFTERNOON

13:00 - 13:30

**Business Meeting**

Come decide the future of VERSIM!

Everyone is welcome.

13:30 - 19:30

**Excursion**

Kakslauttanen Arctic Resort

Details will be given to onsite participants during the workshop.

19:30 - 21:30

**Banquet**

Kakslauttanen Arctic Resort

Photo credit: @kakslauttanen_arctic_resort

WORKSHOP PROGRAM

# 10 November 2022

** Invited

## MORNING

### 09:00 - 10:15

**Session 11**

Neutral Atmosphere Dynamics in VLF Observations

M. Fullekrug

09:25-09:45 Session 11 ULF modulation of energetic electron precipitation in the D-region ionosphere in magnetically quiet time using OCTAVE VLF/LF observations

K. Tanaka

09:45-10:05 Session 11 Development of a plasmapause model derived from Van-Allen-Probe data and IMAGE RPI data via automatic detection

D. Banys

Coffe Break

### 10:45 - 12:00

**Session 12**

Whistler-Mode Chorus Wave Vector and Poynting Vector Directions from Van Allen Probes and MMS Observations

D. Hartley

Spacecraft Observations of VLF Transmitter Signals and Their Effects

F. Nemec **

Constraining the Ionospheric Composition Using Whistlers Detected by the Swarm Mission

M. Jenner

Lunch break @ Niesta

## AFTERNOON

### 13:30 - 14:15

**Session 13**

Temporal variability of waves and wave-particle interactions in Earth's magnetosphere

C. Watt **

Validation of AWDANet's chorus inversion method

L. Murar-Juhasz

Full Wave Modeling of Small Scale Plasma Irregularities and Effects on Whistler Mode Chorus Propagation

P. Hosseini

Coffe Break

### 15:15 - 16:45

**Session 14**

Exploration of Earth's Upper Atmosphere by Ground Based Observation of Very Low Frequency (VLF) Waves: Indian Scenario

A.K. Singh

Role of Mesoscale Convective System (MCS) generated Gravity Waves (GWs) in Atmosphere-ionosphere coupling

R. Singh **

Whistler Mode Propagation in Inhomogenous Plasma with Curved Geomagnetic Geometry and Implications for Wave-Particle Interactions

M. Golkowski **

A Review of Spacecraft Observations of Large Scale Dayside VLF Saucers

C. Moser

## WORKSHOP PROGRAM

# 11 November 2022

** Invited

### MORNING

09:00 - 10:15

**Session 15**

Nonlinear Signatures of VLF Triggered Emissions

Y. Omura **

Energetic electron precipitation associated with nonlinear wave-particle interactions between electrons and very oblique chorus waves

Y. Hsieh

Recent results on ionospheric disturbances and EMIC/ELF/VLF waves obtained by ground and satellite measurements by the PWING project

K. Shiokawa **

Coffe Break

10:45 - 12:00

**Session 16**

Examination of Radiation Belt Dynamics during Substorm Clusters: Magnetic Local Time Variation and Intensity of Precipitating Fluxes

C.J. Rodger **

PIC simulations of banded chorus generation due to parallel electron plateau

K. Min

Lower ionosphere Electron Density and Effective Recombination Coefficients from Multi instrument Satellite Observation s and Ground VLF Measurements during Solar Flares

V. Zigman

Lunch break @ Niesta

### AFTERNOON

13:30 - 14:15

**Session 17**

Persistent, Energetic Pulsating Aurora Observed During the LAMP Sounding Rocket Mission Launch Window

A. Jaynes **

Statistical Survey of Arase Satellite Data Sets in Conjunction With The Finnish Riometer Network

N. Thomas

Studies of pulsating aurorae during Arase

K. Hosokawa **

Coffe Break

15:15 - 16:05

**Session 18**

Recent Analytical Results for Nonlinear Wave-Particle Interactions

J. Albert **

On the Vlasov Simulation of VLF Chorus Containing Falling Tone Elements-Implications for Generation Region Location

D. Nunn **

16:05 - 16:15

Closing remarks by J. Manninen

**This is the end! Thank you for joining us**

VERSIM 2022

# Participant List

Jay Albert
Oliver Allanson
Daniela Banys
Rachel Black
Jacob Bortnik
James Cannon
Mark Clilverd
Lynette Finnie
Martin Fullekrug
Mark Golkowski
Deyu Guo
Miroslav Hanzelka
David Hartley
Keisuke Hosokawa
Poorya Hosseini
Yikai Hsieh
Reko Hynönen
Allison Jaynes
Martin Jenner
Antti Kero
Ivana Kolmasova
Alexander Kozlovsky
Janos Lichtenberger
Yangxizi Liu
Liliana Macotela
Jyrki Manninen
Robert Marshall
Claudia Martinez-Calderon
Ajeet Kumar Maurya
Kyungguk Min
Chrystal Moser
Lilla Murar-Juhasz
Masaharu Nakayama
Frantisek Nemec
Binbin Ni
Andreas Nikiforou
Yuma Nozaki
David Nunn
Hiroyo Ohya
Yoshiharu Omura
Megha Pandya
David Pisa
Tero Raita
Daniel Ratliff
Craig J. Rodger
Michael Rycroft
Ondrej Santolik
Helen Schneider
Alexander Shane
Ruslan Sherstyukov
Kazuo Shiokawa
Ashok Kumar Singh
Rajesh Singh
Kentaro Tanaka
Eija Tanskanen
Neethal Thomas
Drew Turner
Esa Turunen
Thomas Ulich
Pekka Verronen
Clare Watt
Vivien Wendt (Matthias)
Alexandra Wold
Vida Žigman

# Abstracts

# Recent Analytical Results for Nonlinear Wave-Particle Interactions

Jay M. Albert[1*]

[1] Air Force Research Lab, USA

*Corresponding Author: jay.albert@us.af.mil

Test particles resonantly interacting with large amplitude plane waves show behavior different from the diffusive motion with small waves. Analytical results, describing phase buncing and phase trapping, have been developed for models based on low-dimensional gyro-averaged Hamiltonians, particularly the pendulum Hamiltonian [1]. However, recent numerical work has focused attention on other modes of nonlinear motion, associated with small pitch angle, for which the pendulum approximation is invalid. The so-called second model of resonance is more general but remains simple enough to allow analysis [2, 3], while retaining these low pitch angle effects [4]. Here recent application to whistler mode waves is reviewed, and application to EMIC waves [5] is considered.

## References

[1] Albert, J. M., Artemyev, A., Li, W., Gan, L., and Ma, Q. (2022), Analytical results for phase bunching in the pendulum model of wave-particle interactions. *Front. Astron. Space Sci.*, 971358.

[2] Albert, J. M., Artemyev, A. V., Li, W., Gan, L., & Ma, Q. (2021), Models of resonant wave-particle interactions. *JGR: Space Physics*, 126, e2021JA029216.

[3] Artemyev, A. V., Neishtadt, A. I., Albert, J. M., Gan, L., Li, W., and Ma, Q. (2021), Theoretical model of of the nonlinear resonant interaction of whistler-mode waves and field-aligned electrons. *Phys. Plasmas* 28, 052902.

[4] Albert, J. M., Artemyev, A., Li, W., Gan, L., and Ma, Q. (2022), Equations of motion near cyclotron resonance. *Front. Astron. Space Sci.*, 9.910224.

[5] Bortnik, J., Albert, J. M., Artemyev, A., Li, W., Jun, C.-W., Grach, V. S., & Demekhov, A. G. (2022), Amplitude dependence of nonlinear precipitation blocking of relativistic electrons by large amplitude EMIC waves. *GRL*, 49, e2022GL098365.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Theory Of Particle Diffusion, Drift And Advection Via Cyclotron Interactions

Oliver Allanson[1*], Joseph Spencer[1], Thomas Elsden[2], Adnane Osmane[3], Thomas Neukirch[4], Clare Watt[5], and Andrew Hillier[1]

[1] University of Exeter, UK
[2] University of Glasgow, UK
[3] University of Helsinki, Finland
[4] University of St Andrews, UK
[5] Northumbria University, UK

*Corresponding Author: o.allanson@exeter.ac.uk

There is a growing body of observational, theoretical and experimental evidence to indicate that a proper description of radiation belt charged particle transport will require new mathematical models, i.e. new partial differential equations. One leading candidate is to extend the 'standard diffusion equation' to a more general Fokker-Planck equation in order to include advection coefficients. Ideally, these advection (first-order transport) coefficients should be parameterized by plasma and VLF/ELF electromagnetic wave parameters in a similar manner to that used for the diffusion coefficients. To the authors knowledge, this goal has not yet been achieved.

In general, advection coefficients are in fact a combination of both 'drift coefficients' and derivatives of the diffusion coefficients. In the standard quasilinear formalism, this combination produces advection coefficients that are identically zero because of specific constraints imposed via the Hamiltonian structure, with a derivation often attributed to Landau/Lichtenberg & Lieberman [1].

In this paper we present a new theory that incorporates and builds upon the 'weak turbulence/quasilinear results' of [2,3] and demonstrates the breaking of the 'Landau-Lichtenberg-Liebermann condition' for the case of high wave amplitudes, or equivalently small timescales.

We therefore obtain

(i) the standard quasilinear results for small wave amplitudes;
(ii) and non-zero advection coefficient - as well as diffusion coefficients - that are valid for short timescales (high wave amplitudes).

These limiting timescales are determined by the electromagnetic wave amplitude. This also demonstrates that one can use what may be considered 'quasilinear methods' to obtain interesting new results for 'nonlinear/high-amplitude' waves in radiation belt modelling.

**References**

[1] A.J. Lichtenberg, and M.A. Lieberman, "Regular and Chaotic Dynamics", 2nd Ed., Springer, 1991
[2] D.S. Lemons , "Pitch angle scattering of relativistic electrons from stationary magnetic waves: Continuous Markov process and quasilinear theory", Physics of Plasmas 19, 012306, 2012
[3] O. Allanson, T. Elsden, C. Watt, and T. Neukirch, "Weak Turbulence and Quasilinear Diffusion for Relativistic Wave-Particle Interactions Via a Markov Approach", Frontiers in Astronomy and Space Sciences, 8:805699, 2022

# Development of a plasmapause model derived from Van-Allen-Probe data and IMAGE RPI data via automatic detection

D. Banyś[1*], J. Feltens[2], N. Jakowski[1], M. M. Hoque[1], R. Zandbergen[3], W. Enderle[4]

[1] Institute for Solar-Terrestrial Physics, German Aerospace Center (DLR), Germany
[2] Telespazio-VEGA Deutschland GmbH c/o European Space Operations Centre (ESA/ESOC/OPS-GN), Germany
[3] European Space Operations Centre (ESA/ESOC/OPS-GN), Germany - retired
[4] European Space Operations Centre (ESA/ESOC/OPS-GN), Germany
*Corresponding Author: Daniela.Banys@dlr.de

The outer boundary of the plasmasphere, the plasmapause, is characterised by a sharp electron density gradient which changes under varying space weather conditions. With NEPPM (Neustrelitz ESOC Plasmapause Model), we introduce a new model of the plasmapause location Lpp based on electron density measurements made by the Van Allen probes from 2012 to 2016 and the IMAGE satellite from 2000 to 2005 that were automatically processed, yielding an improved performance for plasmapause detection. The model provides a simple elliptical approach determined by the semi-major axis, the eccentricity, and the orientation angle. The Lpp varies as a function of Dst index and magnetic local time (MLT), resulting in a tighter fit compared to the GCPM. The distinctive bulge in the evening hours follows the level of solar activity. Moreover, the model branches into consistent 2D and 3D approaches.
The NEPPM further enhances the NPSM (Neustrelitz Plasmasphere Model, cf. [1]) which was derived from dual frequency GPS measurements on-board the CHAMP satellite mission. The combined data base is well suited for the extension with whistler data, providing L-shell related electron density data.

**References**

[1] N. Jakowski, M. M. Hoque, A new electron density model of the plasmasphere for operational applications and services, SWSC, 2018, DOI:10.1051/swsc/2018002

# Machine-Learning Based Modeling and Interpretation of the Earth's Outer Radiation Belt Flux Dynamics

Jacob Bortnik[1*], Donglai Ma[1], Xiangning Chu[2], Seth G. Claudepierre[1], Adam C. Kellerman[1], and Qianli Ma[1, 3]

[1] Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA, USA
[2] Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, CO, USA
[3] Center for Space Physics, Boston University, Boston, MA, USA

*Corresponding Author: jbortnik@gmail.com

The Earth's radiation belts consist of high-energy electrons and protons trapped in the geomagnetic field, which constitute a hazard for spacecraft and astronauts. Accurate specification and prediction of the dynamic variability of radiation belt fluxes have been a long-standing, and extremely challenging problem which has traditionally been addressed using a quasilinear diffusion framework, driven by parameterized and deterministic diffusion coefficients and boundary conditions. In the first part of this presentation, we show an alternative approach to radiation belt modeling, by using the Outer Radiation belt Electron Neural network (ORIENT) model to reproduce radiation belt fluxes in the range of ~50 keV [1] to several MeV [2], driven solely by solar wind conditions and geomagnetic indices, based on data from the Van Allen Probes mission. ORIENT model results show a high overall correlation to the observed data (in the range of 0.78-0.95) on out-of-sample performance, which is assessed on a test dataset, as well as an out-of-sample 30-day period from February 25 to March 25 in 2017, when a geomagnetic storm took place.

Such machine learning models are valuable for specification and forecast of the radiation belt electron fluxes, and demonstrate that our ORIENT model incorporates the dynamical response of the radiation belt fluxes to their driving parameters (geomagnetic indices and solar wind parameters) correctly. However, it is difficult (if not impossible) for human users to understand how the model works internally and what factors it uses to make its decisions. In the second part of this presentation, we show work that aims to "open the black box" of the ORIENT neural network model [3]. Using the Deep SHAPley additive explanations (DeepSHAP) method, for the first time, we show that the `black box' ORIENT model can be successfully interpreted. Two significant electron flux enhancement events observed by Van Allen Probes during the storm time of 17–18 March 2013 and non–storm time of 19–20 September 2013 are investigated using the DeepSHAP method, and it is shown how various aspects of the inputs control the behavior of the electron fluxes at different energies, times, and L-shells. This work shows tremendous promise for the use of machine learning models not only as a prediction tool, but also for scientific insight discovery.

## References

[1] Ma, D., X. Chu, J. Bortnik, S. G. Claudepierre, W. K. Tobiska, A. Cruz, S. D. Bouwer, J. F. Fennell, and J. B. Blake (2022). Modeling the dynamic variability of sub-relativistic outer radiation belt electron fluxes using machine learning. *Space Weather*, doi: https://doi.org/10.1029/ 2022SW003079
[2] Chu, X., Ma, D., Bortnik, J., Tobiska, W. K., Cruz, A., Bouwer, S. D., ... Reeves, G. (2021). Relativistic electron model in the outer radiation belt using a neural network approach. *Space Weather* , 19 (12), doi: https://doi.org/10.1029/2021SW002808
[3] Ma, D., J. Bortnik, X. Chu, S. G.Claudepierre, Adam Kellerman, and Qianli Ma, Opening the Black Box of the Radiation Belt Machine Learning Model, *Geophysical Research Letters* [under review]

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# First Results from VIPER – The VLF Trans-Ionospheric Propagation Experiment Rocket Campaign

John W Bonnell[1], Oleksiy V. Agapitov[1], Roger Roglans[1], Marilia Samara[2], Ellen Robertson[3], Jim LaBelle[4], George B Hospodarsky[5], Robert Andrew Marshall[6], Wei Xu[6], Ning Kang[7] and Jacob Bortnik[7*]

[1] University of California Berkeley, Berkeley, CA, USA
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[3] Catholic University of America, Washington, USA
[4] Dartmouth College, Department of Physics & Astronomy, Hanover, NH, USA
[5] University of Iowa, Department of Physics and Astronomy, Iowa City, IA, USA
[6] University of Colorado at Boulder, Aerospace Engineering Sciences, Boulder, CO, USA
[7] University of California Los Angeles, Atmospheric and Oceanic Sciences, Los Angeles, CA, USA

*Corresponding Author: jbortnik@gmail.com

The transmission of terrestrial VLF emissions through the ionosphere has a measurable and often significant effect upon both energetic and relativistic electron populations in the inner magnetosphere. Both natural (e.g., lightning strikes) and artificial (e.g. ground VLF transmitter radiation) sources contribute significantly to these VLF emissions. Models exist of this VLF penetration process, and satellite measurements show the spatial and diurnal variations in wave amplitudes at the upper bounds of the ionosphere (600-800 km altitude) but these have considerable uncertainties and it has been suggested previously that significant errors between modeled and observed VLF wave power could exist [1]. In addition, no measurements of the actual electrodynamics of the attenuation and propagation process from the interior of the Earth-Ionospheric waveguide, through its boundary in the D and E region of the ionosphere, and into the ionosphere and magnetosphere above currently exist.

With this deficit in the observational database in mind, on 26 May 2021, we flew the VIPER sounding rocket out of the NASA Wallops Flight Facility through the nighttime D and E region, up to an altitude of 160 km. The VIPER payload carried a fully 3D electromagnetic field measurement and relevant plasma, and neutral particle measurements through the radiation fields of an existing VLF transmitter (USN call sign NAA; 24.0 kHz; Cutler, Maine) in order to explore the electrodynamics of the VLF absorption, reflection, and transmission process. Several ground-based 2D and 3D VLF receiver systems provided complimentary observations of the NAA transmitter and natural emissions throughout the flight.

For this session, we shall present the first results of the ground based and in situ observations from VIPER, our initial interpretations of those results, and plans for future analysis.

**References**

[1] Starks, M. J., R. A. Quinn, G. P. Ginet, J. M. Albert, G. S. Sales, B. W. Reinisch, and P. Song (2008), Illumination of the plasmasphere by terrestrial very low frequency transmitters: Model validation, J. Geophys. Res., 113, A09320, doi:10.1029/2008JA013112.
[2] Bonnell, J. et al. (2021), First Results from VIPER – The VLF Trans-Ionospheric Propagation Experiment Rocket Campaign, *American Geophysical Union* December 2021 Fall Meeting, New Orleans, Lousianna, USA.

# Electro Magnetic Ion Cyclotron wave-induced electron precipitation: ground-based and satellite observations

Mark A. Clilverd[1*], Craig J. Rodger[2], Aaron T. Hendry[2], Malcolm Crack[2], Alexander Lozinski[1], Tero Raita[3], Thomas Ulich[3], and Jean-André Sauvaud[4]

[1] British Antarctic Survey (UKRI-NERC), Cambridge, UK.
[2] University of Otago, Dunedin, New Zealand.
[3] Sodankylä Geophysical Observatory, University of Oulu, Finland.
[4] CESR/University of Toulouse-CNRS, Toulouse, France.

*Corresponding Author: macl@bas.ac.uk

The study of Electro Magnetic Ion Cyclotron (EMIC) wave-induced electron precipitation has a legacy in early work suggesting EMIC waves could precipitate relativistic electrons [1]. Here we present an analysis of an example of EMIC-induced electron precipitation observed by ground-based VLF subionospheric propagation receivers in Finland, combined with EMIC wave signatures in ground-based magnetometers in Finland, and Antarctica. Electron precipitation spectral information is provided by low Earth orbit satellite data which considers the energy range of scattered electrons during the potential EMIC wave event. We investigate the high energy resolution DEMETER IDP electron measurements in the 80 keV - 2 MeV range, when the detector was looking into the bounce-loss-cone, i.e., flying over the North Atlantic region.

In order to assess the effect of potential proton precipitation contamination of the IDP detector [2] we use nearby POES proton flux measurements, compensating for the IDP protective aluminum foil through a calculation of the attenuation of the proton spectrum using the integrated MULASSIS transport code [3]. Our results are considered in the context of recent work indicating a wide energy range of non-relativistic electron precipitation is present in EMIC-induced precipitation [4], in addition to the relativistic energy electrons suggested from the original theoretical suggestions.

**References**

[1] Thorne and Kennel, 1971. Relativistic electron precipitation during magnetic storm main phase, J. Geophys. Res., 76(19), 4446– 4453, doi:10.1029/JA076i019p04446
[2] Sauvaud et al., 2013. Inner radiation belt particle acceleration and energy structuring by drift resonance with ULF waves during geomagnetic storms, J. Geophys. Res. Space Physics, 118, 1723– 1736, doi:10.1002/jgra.50125
[3] Lozinski et al., 2019. Solar cell degradation due to proton belt enhancements during electric orbit raising to GEO, Space Weather, 17, 1059–1072. https://doi.org/10.1029/2019SW002213
[4] Hendry et al., 2021. Evidence of sub-MeV EMIC-driven trapped electron flux dropouts from GPS observations, Geophys. Res. Lett., 48, e2021GL092664, doi:10.1029/2021GL092664.

# Neutral Atmosphere Dynamics in VLF Observations

Martin Füllekrug[1*]

[1] Centre for Space, Atmospheric and Oceanic Science, University of Bath, UK

*Corresponding Author: eesmf@bath.ac.uk

Transmitters at Very-Low Frequencies (VLF) from ~18-25 kHz offer resilient communication for safety critical applications. The emitted electromagnetic waves are commonly used to remote sense the lower D-region ionosphere which is influenced by a variety of short-lived natural processes associated with lightning discharges and/or space weather events. Here we analyse the relatively slowly varying day-to-day variation of the VLF signal transmitted from Anthorn in Cumbria (GQD in northwest UK) received at Bath in Somerset (southwest UK). The day-to-day variation recorded over one month exhibits a time varying mean and standard deviation which are attributed to the temporal variability of a mean diurnal variation. Assuming that the mean diurnal variation is mainly dominated by solar short wave radiation, the residual signal can be interpreted to result from neutral atmosphere dynamics. In this case, it might be possible that VLF observations have the ability enable the identification of travelling neutral density waves in the upper middle atmosphere which are difficult to assess by other remote sensing techniques.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Whistler Mode Propagation in Inhomogenous Plasma with Curved Geomagnetic Geometry and Implications for Wave-Particle Interactions

Mark Gołkowski[1*], Vijay Harid[1], Raahaim Khatun-E-Zannat[1] and Oleksiy Agapitov[2]

[1] Department of Electrical Engineering, University of Colorado Denver, Denver, CO, USA.
[2] Space Sciences Laboratory, University of California, Berkeley, CA, USA.

*Corresponding Author: mark.golkowski@ucdenver.edu

Whistler mode waves in the Earth's magnetosphere continue to be investigated due to their key role in the energy dynamics of the near-Earth space environment. The propagation of whistler mode waves are governed by the background cold plasma density and can be modeled accurately using fluid equations. Nevertheless, the anisotropy, inhomogeneity, and scale of the magnetosphere present challenges and detailed knowledge of cold plasma density distributions is often not available. A significant body of evidence suggests that a smooth cold plasma density distribution is not always realistic [1,2] and the typical raytracing formalism may become invalid. Consquently, full-wave simulations are needed to accurately evaluate the impact of fluctuations in cold plasma density.

We use a finite difference time domain (FDTD) model to determine key wave parameters in a dipole geomagnetic geometry in the presence of field-aligned density enhancements. In the case of a smooth plasmasphere, the FDTD code reproduces the linear increase in wave normal angle with latitude as predicted by raytracing. However, once ducts are introduced, the waves show a combination of guiding and refraction that is considerably more complex. The ducts also enforce strong spatial modulation and focusing of wave amplitudes which is consistent with spacecraft observations. The results suggest that density enhancements can have a significant impact on the distribution of whistler-mode wave power and should be carefully included in global magnetospheric models.

## References

[1] Hosseini, Poorya, Oleksiy Agapitov, Vijay Harid, and Mark Gołkowski. "Evidence of small scale plasma irregularity effects on whistler mode chorus propagation," *Geophysical Research Letters*, vol. 48, no. 5, 2021

[2] Hanzelka, Miroslav, and Ondřej Santolík. "Effects of ducting on whistler mode chorus or exohiss in the outer radiation belt." *Geophysical Research Letters* vol. 46, no. 11, 2019

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Effects of Wavelength-Scale Density Ducts on the Subpacket Structure of Chorus

Miroslav Hanzelka[1*], and Ondřej Santolík[1, 2]

[1] Department of Space Physics, Institute of Atmospheric Physics of the Czech Academy of Sciences, Prague, Czech Republic

[2] Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic

*Corresponding Author: mirekhanzelka@gmail.com

The chorus whistler-mode emission, one of the primary drivers of radiation belt electron energization and precipitation, exhibits significant amplitude modulations on millisecond timescales. These modulations, called subpackets, are accompanied by fast changes in the wave vector direction [1]. Understanding the evolution of wave propagation properties inside chorus elements is essential for modeling nonlinear chorus-electron interactions, but the origin of these rapid changes remains to be explained.

We propose that the variations in wave normal angle come from the propagation of subpackets inside wavelength-scale, field-aligned cold plasma enhancements (density ducts), and we show that a full-wave simulation on a filamented density background predicts wave vector and amplitude evolution similar to Van Allen Probe spacecraft observations. The simulation also explains the low correlation between subpackets detected by close-separation multipoint measurements [2] as a result of group velocity dispersion.

We further demonstrate that commonly assumed propagation in wide density ducts, which can be studied with ray tracing methods, suggests a much more regular evolution of wave propagation properties. Moreover, the highly inhomogeneous background caused by wavelength-scale irregularities changes the whistler-mode dispersion relation and elongates the magnetic polarization ellipse, a feature missing in wide-duct simulations but present in spacecraft data. This observation indirectly confirms the existence of wavelength-scale field-aligned density fluctuations, which were previously predicted from laboratory experiments and theoretical studies [3,4].

## References

[1] Santolík, O., Kletzing, C. A., Kurth, W. S., Hospodarsky, G. B., & Bounds, S. R. (2014). Fine structure of large-amplitude chorus wave packets. Geophys. Res. Lett., 41, 293-299. doi: 10.1002/2013GL058889
[2] Santolík, O., D. A. Gurnett, J. S. Pickett, M. Parrot, & N. Cornilleau-Wehrlin (2003). Spatio-temporal structure of storm-time chorus. J. Geophys. Res., 108(A7), 1278, doi:10.1029/2002JA009791.
[3] Weibel, E. S. (1977). Self channeling of whistler waves. Phys. Lett. A, 61 (1), 37-39. doi: 10.1016/0375-9601(77)90256-0
[4] Eliasson, B., & Shukla, P. K. (2004). Theoretical and numerical studies of density modulated whistlers. Geophys. Res. Lett., 31 (17), L17802. doi: 10.1029/2004GL020605

# Whistler-Mode Chorus Wave Vector and Poynting Vector Directions from Van Allen Probes and MMS Observations

David P. Hartley[1*], Lunjin Chen[2], Ivar W. Christopher[1], Matthew R.Argall[3], NargesAhmadi[4], CraigA. Kletzing[1], Ondrej Santolik[5, 6], and Ivana Kolmasova[5, 6]

[1] University of Iowa, USA
[2] University of Texas at Dallas, USA
[3] University of New Hampshire, USA
[4] University of Colorado at Boulder, USA
[5] Institute ofAtmospheric Physics, Czech Republic
[6] Charles University, Czech Republic

*Corresponding Author: david-hartley@uiowa.edu

Whistler-mode chorus waves are known to play a key role in the dynamics of the Earth's outer radiation belt, driving rapid acceleration of electrons up to relativistic energies as well as causing losses of particles to the atmosphere during microbursts and diffuse auroral precipitation. In some instances, such as near plasmaspheric plumes, chorus waves may be a source of plasmaspheric hiss as they propagate up to high latitudes, across the plasmapause boundary, and into the plasmasphere. A parameter key to these mechanisms is the orientation of the wave vector with respect to the background geomagnetic field, which determines the wave propagation path, and is required for calculating the resonance condition of the wave-particle interaction. The wave vector may be calculated solely from magnetic field observations, however, this results in an ambiguity as to whether it is directed with a component parallel or antiparallel to the background field. Electric field observations are required to determine the Poynting vector, which removes this ambiguity in the wave vector direction.

The orientation of the wave vector for whistler-mode chorus is examined using survey and burst mode observations from the Van Allen Probes EMFISIS Waves instrument as well as burst mode measurements from the Magnetospheric Multiscale (MMS) FIELDS instrument suite, considering both the polar and azimuthal wave vector angles. In general, it can be demonstrated that for the bulk of observations the wave vector is approximately aligned with the background magnetic field. However, near gradients in the plasma density, such as those observed on the boundary of plasmaspheric plumes, the wave vector can become more oblique. The obliquity of the wave vector is shown to be directly related to both the density gradient proximity and magnitude.

Sheath impedance effects on electric field observations are also discussed, with the impact of these measurement uncertainties on the electric field wave amplitude, as well as the Poynting vector direction and magnitude, quantified for Van Allen Probes measurements. Preliminary results indicate that similar effects may also be apparent in MMS observations of the whistler-mode wave electric field.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Studies of pulsating aurorae during Arase era

Keisuke Hosokawa[1*], Yoshizumi Miyoshi[2], Mitsunori Ozaki[3], Shin-Ichiro Oyama[2,4,5], Yasunobu Ogawa[4], Satoshi Kurita[5], Yoshiya Kasahara[3], Yasumasa Kasaba[6], Satoshi Yagitani[3], Shoya Matsuda[3], Fuminori Tsuchiya[6], Atsushi Kumamoto[6], Ryuho Kataoka[4], Kazuo Shiokawa[2], Yoshimasa Tanaka[4], Satonori Nozawa[2], Mariko Teramoto[8], Iku Shinohara[9], and Ryoichi Fujii[10]

[1] University of Electro-Communications, Japan
[2] Institute for Space-Earth Environmental Research, Nagoya University, Japan
[3] Kanazawa University, Japan
[4] National Institute of Polar Research, Japan
[5] University of Oulu, Finland
[6] Research Institute for Sustainable Humanosphere, Kyoto University, Japan
[7] Tohoku University, Japan
[8] Kyushu Institute of Technology, Japan
[9] Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency, Japan
[10] Research Organization of Information and Systems, Japan

*Corresponding Author: keisuke.hosokawa@uec.ac.jp

Pulsating aurora (PsA) is one of the major types of aurora often seen in the lower latitude part of the auroral region in the morning side. PsA is known to have two distinct periodicities. One is the main pulsation whose period ranges from a few to a few tens of seconds. The other is so-called internal modulation which is ~3 Hz luminosity modulation during the ON phase of main pulsation. Previous studies indicated that ~50% of PsA are accompanied by the internal modulation (i.e., internal modulation is often seen, but not always observed during PsA). Recent coordinated ground/satellite observations of PsA suggested that these two periodicities are closely associated with the intensity modulation of whistler mode chorus waves in the morning side magnetosphere. In particular, the association between the main pulsation and bursts of chorus was confirmed by several recent papers [1, 2]. However, it has still been under debate which characteristics of chorus waves control the existence/ absence of internal modulation. This review talk will be focused on several results from recent coordinated ground/satellite observations of PsA [3, 4] since the launch of the Arase satellite. Especially, we will introduce conjugate high-time resolution measurements of fine-scale temporal/spatial variations of chorus waves in space and PsA seen from the ground. In addition, we will talk about recent ground-based radar observations of PsA showing the simultaneous precipitation of sub-relativistic electrons during PsA [5], which will be one of the primary scientific objectives of EISCAT_3D currently being prepared in Scandinavia.

## References

[1] Nishimura, Y. et al. Identifying the driver of pulsating aurora. Science 330, 81–84 (2010).
[2] Kasahara, S. et al. Pulsating aurora from electron scattering by chorus waves. Nature 554, 337–340 (2018)
[3] Ozaki, M., Miyoshi, Y., Shiokawa, K. et al. Visualization of rapid electron precipitation via chorus element wave–particle interactions. Nat Commun 10, 257 (2019).
[4] Hosokawa, K., Miyoshi, Y., Ozaki, M. et al. Multiple time-scale beats in aurora: precise orchestration via magnetospheric chorus waves. Sci Rep 10, 3380 (2020).
[5] Miyoshi, Y., Hosokawa, K., Kurita, S. et al. Penetration of MeV electrons into the mesosphere accompanying pulsating aurorae. Sci Rep 11, 13724 (2021).

# Full Wave Modeling of Small Scale Plasma Irregularities and Effects on Whistler Mode Chorus Propagation

Poorya Hosseini[1,2*], Vijay Harid[1], Oleksiy Agapitov[3], and Mark Golkowski[1]

[1] University of Colorado Denver, USA
[2] The Johns Hopkins University Applied Physics Laboratory, USA
[3] University of California Berkeley, USA

*Corresponding Author: poorya.hosseini@jhuapl.edu

Whistler mode chorus waves are known to play an important role in radiation belt dynamics. We focus on the propagation of chorus from an equatorial source region to midlatitudes. The impact of randomly distributed field-aligned density irregularities on whistler-mode wave propagation is investigated using full wave FDTD simulations and compared to multi-point spacecraft observations. The irregularities are modeled as randomized density perturbations between 1-10% of the nominal background density value with scales of ~10-60 km transverse and ~50-500 km along the background magnetic field. The density irregularities affect whistler wave propagation and lead to spatial modulation of wave average power density accompanied by spreading of the wave normal angle distribution. Wave power variation is shown to statistically increase with the depth of density irregularities. The simulation results are in good agreement with the observed correlations of chorus power and variation of the plasma density from multi-point observations by the four MMS spacecraft and early observations on the CLUSTER spacecraft. The results challenge the often made assumptions of either a smooth plasmasphere or very large duct structures that extend along the entire field line.

# Energetic electron precipitation associated with nonlinear wave-particle interactions between electrons and very oblique chorus waves

Yikai Hsieh[1*] and Yoshiharu Omura[1]

[1] Research Institute for Sustainable Humanosphere, Kyoto University, Japan

*Corresponding Author: yikai_hsieh@rish.kyoto-u.ac.jp

Electrons trapped in the Earth's magnetic field can be scattered by whistler-mode chorus emissions and precipitate into the Earth's upper atmosphere. Whistler mode chorus waves propagating in the Earth's inner magnetic field are not always parallel or quasi-parallel to the magnetic field line. Sometimes the waves are observed with very large wave normal angles. We aim to figure out the relation between the large wave normal angles and electron precipitation. In this study, our target chorus emissions contain large wave normal angles, which are 90% of the resonance cone angle. We use test-particle simulation to trace the behaviors of electrons interacting with the waves and create a Green's function set for electrons initially at kinetic energies 10-6000 keV and equatorial pitch angles 5-89 degrees. We also calculate the Green's function sets for parallel and slightly oblique chorus waves for comparison. The simulation results show that the very oblique chorus waves contribute to more electron precipitation than the other two chorus wave models, especially at 50-100keV. At this range, the electron precipitation rates of the very oblique case are about 1.5 and 1.2 times those of the parallel and slight oblique cases, respectively. Checking the highest initial equatorial pitch angles of the precipitated electrons, we find that the very oblique chorus waves can precipitate electrons from greater than 45 degrees. In contrast, the other chorus waves can only precipitate electrons from less than 30 degrees. Furthermore, we theoretically derive the precipitation rate and verify that nonlinear trapping via the n = -1 anomalous cyclotron resonance contributes to effective electron precipitation in the very oblique chorus wave-particle interactions.

# Persistent, Energetic Pulsating Aurora Observed During the LAMP Sounding Rocket Mission Launch Window

Allison N. Jaynes[1*], Riley N. Troyer[1], Kazushi Asamura[2], Niharika Godbole[3], Alexa J. Halford[4], Don L. Hampton[5], Keisuke Hosokawa[6], Hyomin Kim[7], Vincent Ledvina[8], Marc R. Lessard[3], Kristina A. Lynch[9], Maya Mandyam[10], Masahito Nosé[11], Matthew G. McHarg[10], Yoshi Miyoshi[11], Taku Namekawa[2], Sungjun Noh[7], Nikolaos Paschalidis[4], Takeshi Sakanoi[12], Youra Shin[7], Mykhaylo Shumko[4], Emma L. Spanswick[13], Jules Van Irsel[9], Roger H. Varney[14], and John Williams[10]

[1] University of Iowa, USA
[2] Japan Aerospace Exploration Agency, USA
[3] University of New Hampshire, USA
[4] NASA Goddard Space Flight Center, USA
[5] University of Alaska Fairbanks, USA
[6] University of Electro-Communications, Japan
[7] New Jersey Institute of Technology, USA
[8] University of North Dakota, USA
[9] Dartmouth College, USA
[10] US Airforce Academy, USA
[11] Nagoya University, USA
[12] Tohoku University, Japan
[13] University of Calgary, Canada
[14] University of California Los Angeles, USA

*Corresponding Author: allison-n-jaynes@uiowa.edu

Pulsating aurora constitutes a significant amount of energy that is transferred from the magnetosphere to the ionosphere, yet the amount of energy and the associated energy spectra are not well predicted. During the LAMP sounding rocket mission launch window, a network of ground observation assets were operating to observe pulsating aurora. During this two-week period in March 2022, we captured allsky, radar, and riometer observations of persistent pulsating aurora lasting nearly continuously for ~6 hours of local time. Using an inversion technique, we derive the electron energy spectra from the incoherent scatter radar observations of electron density. The energy spectra reveal a dynamic energy content, varying significantly over the course of each event. Intermittently, some periods of time showed higher flux in the >30 keV energy band than the portion of the spectrum below 30 keV. The Arase satellite mission, capable of observing *in situ* particle injections as well as associated plasma waves in the inner magnetosphere, broadens our view of the event. Arase observed strong electron injections and measured increased chorus wave amplitudes during the times when the pulsating aurora energy spectra was highly energetic. We present two case studies of electron injections leading to an intensification of chorus which in turn leads to a harder energy spectrum in the observed pulsating aurora. This further supports the idea that substorms and/or particle injections are related to the total energy content of pulsating aurora (following Troyer et al., 2022), and highlights the importance of studying the two phenomena as an inter-connected system.

# Constraining the Ionospheric Composition Using Whistlers Detected by the Swarm Mission

Martin Jenner[1*], Pierdavide Coïsson[1], Gauthier Hulot[1], and Dalia Buresova[2]

[1] Université Paris Cité, Institut de physique du globe de Paris, CNRS, F-75005 Paris, France
[2] Institute of Atmospheric Physics of the Czech Academy of Sciences, Prague, Czechia

*Corresponding Author: jenner@ipgp.fr

Since its launch, the Swarm mission detected over 40 000 whistlers in the 10 Hz to 120 Hz frequency range. These signals have been recorded during burst mode sessions of the Absolute Scalar Magnetometer (ASM) [1], when the sampling rate of the instrument is raised from 1 Hz to 250 Hz. These sessions are currently operated 2 weeks per month. Whistlers are generated by the electromagnetic signal from lightning discharges leaking into the ionosphere. They propagate upward through the ionosphere where they can be detected by the instruments of Swarm's satellites at their respective orbital altitudes (Alpha at 475 km and Bravo at 510 km).

The analysis of the spectrum of each whistler allows us to derive its dispersion (following the definition of Eckersley [2]). This dispersion depends on the local intensity of the Earth magnetic field, and on the composition of the ionosphere. Using a main field model to approximate the geomagnetic propagation conditions, we can investigate the influence of ionospheric composition on the propagation of the signal.

Our forward model is a ray tracing algorithm following the approach defined by Haselgrove [3]. It uses a dipolar geomagnetic approximation, and the density profiles of the major charged species to compute the signal trajectory. The algorithm outputs the dispersion and the propagation path of the signal for any selected frequency. We used the 13$^{th}$ International Geomagnetic Reference Field (IGRF-13) [4] to derive the local dipolar approximation of the Earth magnetic field. The ionospheric profiles were computed using the International Reference Ionosphere 2016 (IRI) [5]. More realistic electron profile derived from ionosonde data coupled with data from the Electric Field Instrument (EFI) of the Swarm mission were also used when available as an experimental reference.

We investigated a theoretical development of the refractive index under the cold plasma hypothesis within the Extremely Low Frequency (ELF) band. It suggests a proportionality relation between Eckersley's dispersion and the integral of the square root of the charged particles densities along the propagation path. We tested this approach using the dispersion of selected Swarm whistlers compared to those calculated via ray tracing. We also investigated a method to improve the density integral estimations made with IRI utilizing the whistler dispersion data.

## References

[1] Léger, J.-M., Jager, T., Bertrand, F., Hulot, G., Brocco, L., Vigneron, P., Lalanne, X., Chulliat, A., Fratter, I., 2015. In-flight performance of the Absolute Scalar Magnetometer vector mode on board the Swarm satellites. Earth Planet Sp 67, 57. https://doi.org/10.1186/s40623-015-0231-1
[2] Eckersley, T.L., 1935. Musical Atmospherics. Nature 135, 104–105. https://doi.org/10.1038/135104a0
[3] Haselgrove, J., 1957. Oblique Ray Paths in the Ionosphere. Proc. Phys. Soc. B 70, 653–662. https://doi.org/10.1088/0370-1301/70/7/302
[4] Alken, P., Thébault, E., Beggan, C.D., et al., 2021. International Geomagnetic Reference Field: the thirteenth generation. Earth Planets Space 73, 49. https://doi.org/10.1186/s40623-020-01288-x
[5] Bilitza, D., Altadill, D., Truhlik, V., Shubin, V., Galkin, I., Reinisch, B., Huang, X., 2017. International Reference Ionosphere 2016: From ionospheric climate to real-time weather predictions. Space Weather 15, 418–429. https://doi.org/10.1002/2016SW001593

# Broadband and Narrowband VLF Observations Related to Transient Luminous Events

I. Kolmašová[1,2*], O. Santolík[1, 2], M. Tomicic[3], H. Špačková[1, 4], T. Farges[5], Popek[1], P. Zacharov[1], and R. Slošiar[6]

[1] Department of Space Physics, Institute of Atmospheric Physics, Czech Academy of Sciences, Czechia
[2] Faculty of Mathematics and Physics, Charles University, Czechia
[3] DTU Space, Technical University of Denmark, Denmark
[4] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, Czechia.
[5] CEA, DAM, DIF, France
[6] SOSA (Slovak Organization for Space Activities), Slovakia
*Corresponding Author: iko@ufa.cas.cz

We present an analysis of narrowband and broadband VLF measurements conducted during three different TLE-producing thunderstorms occurring in Europe. 1) A small-scale continental spring thunderstorm lasting four hours produced several elves and sprites in April 2017 [1]. 2) A nearly stationary winter thunderstorm, which was composed of short-living storm cells developing in low CAPE conditions, occurred above Adriatic sea, lasted about 9 hours, and produced 63 elves and no observable sprites in December 2020 [2]. 3) A linearly organized frontal convective summer thunderstorm moving across Europe for about fourteen hours produced 68 sprites (including 21 sprite-halo pairs and one sprite-halo-elves event) in August 2017.

The optical data were captured by low-light cameras installed in Nýdek, Czechia (49.7°N, 18.8°E) and Rustrel, France (43.94°N, 5.48°E). The broadband measurements were conducted in Rustrel, France and in central France (46.1°N, 2.8°E). The narrow-band VLF receiver was located in Bojnice, Slovakia (48.8°N, 18.6°E). For presented analysis, we have chosen the recordings of carriers of the VLF transmitters DHO38 (Germany, 53.1°N, 7.6°E) and NSY (Sicily, 37.1°N, 14.4°E), as their signal paths to the receiver were close to the TLE producing storms. For individual storms, we used the lightning data provided by the lightning detection networks EUCLID, GLD360 and WWLLN.

We have found step-like perturbations of the transmitter signal called Long Recovery Early Events (LOREs) associated with all elves detected in the small spring storm, when the amplitude of the narrow band signal abruptly increased in all cases. During the winter storm, only one quarter of elves caused detectable LOREs. In all these cases, the amplitude of the transmitter signal abruptly decreased and the associated elves occurred at altitudes higher than 85 km. The elves related to LOREs were the brightest ones recorded during the winter storm. The broadband VLF recordings of sferics parent to TLEs clearly showed that sky waves generated by elves producing strokes were much more intense than these for which elves were not detected. On the other hand, the shapes of the VLF sferics belonging to sprite producing strokes generally did not differ from these for which sprites were not observed.

Our results indicate that the VLF propagation in the Earth-ionosphere waveguide is a complex physical process that depends probably non-linearly on different parameters. Understanding the mechanisms behind the occurrence/absence of LORE events or explaining the varying strength of sky wave amplitudes are challenging research topics that would require combining observations with modelling.

**References**

[1] Kolmašová, I., Santolík, O., Kašpar, P., Popek, M., Pizzuti, A., Spurný, P., et al. (2020). Journal of Geophysical Research: Atmospheres, 125, e2020JD032825. doi:10.1029/2020JD032825.
[2] Tomicic, M., O. Chanrion, T. Farges, J. Mlynarczyk, I. Kolmašová, et al., under review in Journal of Geophysical Research: Atmospheres.

# New sferic filtering methods for VLF data preprocessing

János Lichtenberger[1,2*], Gergely Máthé[3], Dávid Koronczay[1,2], Orsolya Ferencz[1], Péter Steinbach[2], Lilla Juhász[2], Mark Clilverd[4], Craig Rodger[5], Dmitry Sannikov[6], Nina Cherneva[6] , Rustam Karimov[7] and István Csabai[3]

[1] Department of Geophysics and Space Sciences, Eötvös University, Budapest, Hungary
[2] ELKH-ELTE Space Research Group, Budapest, Hungary
[3] Department of Physics of Complex Systems, Eötvös University, Budapest, Hungary
[4] British Antarctic Survey, Cambridge, United Kingdom
[5] Department of Physics, University of Otago, Dunedin, New Zealand
[6] Institute of Cosmophysical Research and Radio Wave Propagation, Paratunka, Russia
[7] Institute of Cosmophysical Research and Aeronomy, Yakutsk, Russia

*Corresponding Author: lityi@sas.elte.hu

Radio waves generated by terrestrial lightnings play important role in near-Earth space physics. They can be used to monitor the plasmasphere (whistlers) and are key players in wave-particle interaction in Radiation Belts and slot region. However, the VLF signals recorded on the ground (and sometimes on-board) contain the signals from the lightnings not only in 'useful' format, but as bad noises (atmospherics).
During manual, human aided processing of such data may be simple as human brain can easily 'filter' visually the atmospheric on a spectrogram. But this is not the case for automated, mass processing of the data, generally because the sferics are the most intense signals in the data.
Before any real data processing/analysis, the sferics have to be filtered. For automatic, mass processing of VLF data recorded on the ground such a sferic filter would also need to be time and location independent, all filtering parameter have to be derived from the signal itself.
In this talk, we present two algorithms developed for this purpose. One is inspired by an old analogue method [1] to repress the atmospherics, while the other one uses the latest machine learning approaches to identify the waveform of the atmospherics in the signal. Therefore second one may be used not only for sferic-filtering, but for lighting detection as well.

**References**

[1] Dowden, R. L. (1963). Minimum-Reading Phase-Sensitive Detector, *Proc. I.R.E.,* 51, 231.

# Ground-based VLF Emissions Observed in the Frequency Range 16-39 kHz: Campaigns 2017–2018

Liliana Macotela[1*] and Jyrki Manninen[2]

[1] Department of Electronic & Electrical Engineering, University of Bath, Bath, UK

[2] Sodankylä Geophysical Observatory, University of Oulu, Sodankylä, Finland

*Corresponding Author: edith.macotelacruz@oulu.fi

Analysis of very low frequency (VLF) radio waves provides us with the remarkable possibility of investigating the response of both the lower ionosphere and magnetosphere to a diversity of transient and long-term physical phenomena originating on Earth (e.g., atmospheric waves) or in space (e.g., CMEs). In this work, broadband VLF data measured at Kannuslehto, in northern Finland, is used to characterize a new type of VLF emissions displaying a strip-like structure observed in the 16–39 kHz frequency range. Analysing campaigns 2017 and 2018, we found that this emission can be observed either in high frequency ranges or spanning from low to high frequency ranges. We also found that the events are occurring during evening hours. Finally, we discuss whether their origin might be due to plasma instabilities in the magnetosphere, as in the case of auroral hiss.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# New results for sudden enhancements of PLHRs observed at KAN

Jyrki Manninen[1*], and Lauri Yliriesto[1]

[1] Sodankylä Geophysical Observatory, University of Oulu, Sodankylä, Finland
*Corresponding Author: Jyrki.Manninen@oulu.fi

During last 17 years a special type of the power line harmonic radiation event has observed. Sudden enhancement (SE_PLHR) starts simultaneously from 50 Hz up to 5 kHz, but it decays usually exponentially with diminishing frequency within 20-40 seconds. In the beginning all 50 Hz harmonics are enhanced contrary to constant PLHRs, which appear in certain pairs. For the first time, such event was observed in September 2005. After that the number of events has been increased year by year. They seemed to occur in the morning and evening hours, not on daytime.

Now we will present new results as SE_PLHRs are compared with magnetic activity.

# Some statistical results of VLF bursty-patches observed in 2006-2022 campaigns at KAN

Jyrki Manninen[1*], Veera Vuolteenaho[1], and Claudia Martinez-Calderon[2]

[1] Sodankylä Geophysical Observatory, University of Oulu, Sodankylä, Finland
[2]Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan
*Corresponding Author: Jyrki.Manninen@oulu.fi

Since 2006 so called VLF bursty-patches have been observed at Kannuslehto (67.74º N, 26.27º E, L=5.5) in Northern Finland. These bursty-patches are noteworthy in the sense that they appear at frequencies well above the local equatorial electron gyrofrequency at L=5.5. According to the classical theory, if VLF emissions propagate field-aligned we should only observe them below half of the local equatorial electron gyrofrequency at the detection point. While unducted propagation is possible to the ground, it is also likely that emissions generated at lower L-shells, could have jumped field lines in the magnetosphere or inside the ionosphere to reach the higher L-shells of Kannuslehto.

VLF bursty-patches have had several names in different times. They have been called as VLF noise burst [1], very narrow band VLF hiss [2], bursty-patch [3], RRE, recently revealed emission [4], bird emissions [5], narrow-band noise VLF emission [6], high-frequency VLF patches [7], KHF-VLF [8], and VLF bursty-patches [9].

Currently, not much is known about VLF bursty-patches but recent studies have shown a possible link with solar activity. Here we will present new statistical results about the relationship between VLF bursty-patches with magnetic and solar activity.

## References

[1] Dingle B., Carpenter D.L. (1981) Electron precipitation induced by VLF noise bursts at the plasmapause and detected at conjugate ground stations. J. Geophys. Res 86(A6):4597-4606.
[2] Manninen J. (2005) Some aspects of ELF_VLF emissions in geophysical research. Sodankyla Geophysical Observatory Publications. № 98. 177 p. Oulu Univ Press Finland.
[3] Shiokawa K., Yokoyama Y., Ieda A., Miyoshi Y., Nomura R., Lee S., Connors M. (2014) Ground- based ELF/VLF chorus observations at subauroral latitudes VLFchain campaign. J Geophys Res Space Physics 119:7363-7379.
[4] Manninen J., Turunen T., Kleimenova N., Rycroft M., Gromova L., Sirvio I. (2016) Unusually high frequency natural VLF radio emissions observed during daytime in Northern Finland. Environ Res Lett 11:124006.
[5] Manninen J., Turunen T., Kleimenova N.G., Gromova L.I., Kozlovsky A.E. (2017) A New Type of Daytime High-Frequency VLF Emissions at Auroral Latitudes ("Bird Emissions") Geomagn Aeron 57(1):32-39.
[6] Titova E.E., Demekhov A.G., Manninen J., Pasmanik D.L., Larchenko A.V. (2017) Localization of the sources of narrow-band noise VLF emissions in the range 4-10 kHz from simultaneous ground-based and Van Allen Probes satellite observations. Geomagn Aeron 57(6):706-718.
[7] Manninen, J., N. Kleimenova, T. Turunen, A. Nikitenko, L. Gromova, and Yu. Fedorenko (2021). New type of short high-frequency VLF patches ("VLF birds") above 4-5 kHz. J. Geophys. Res., Space Physics, 126, e2020JA028601.
[8] Martinez-Calderon C., J.K. Manninen, J.T. Manninen, and T. Turunen (2021). A review of unusual VLF bursty-patches observed in Northern Finland. Earth, Planets and Space, 73:191

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Imaging the D-region ionosphere over large scales using an array of VLF receivers

Robert. A. Marshall[1*], Forrest Gasdia[1], and James M. Cannon[1]

[1] Department of Aerospace Engineering Sciences, University of Colorado Boulder, USA

*Corresponding Author: robert.marshall@colorado.edu

Solar X-rays, auroral and radiation belt electrons, and other energetic particles deposit their energy at altitudes corresponding to the D-region of the Earth's ionosphere. Subionospheric Very-low-frequency (VLF) remote sensing remains the most effective method for continuous measurement of the D-region, thanks to the efficient reflection of probe VLF waves from transmitters and lightning at these altitudes. These VLF waves are sensitive to changes in D-region conditions, so that VLF measurements are indicative of the changing D-region state. However, it is extremely challenging to infer properties of the ionization sources (e.g. solar X-ray or radiation belt particle flux) from these VLF measurements, because the ionization process, D-region chemistry, and VLF signal propagation together form a complex and underdetermined system for inversion.

Here we present a new method to estimate the D-region state using an array of overlapping VLF signal paths covering an extended region of some thousands of kilometers. An array of VLF receivers is notionally designed to cover radiation belt latitudes over Canada, corresponding to L-shells between L = 3 and L = 7, where radiation belt precipitation occurs. The inversion procedure then uses the amplitude and phase of VLF transmitter signals measured at these VLF receivers to infer D-region properties in a grid over the array. This inversion procedure uses a Local Ensemble Transform Kalman Filter (LETKF) to estimate the state of the ionosphere by minimizing both data errors and forward model errors. In this talk we describe the design of this array of VLF receivers, the LETKF-based inversion procedure, and some of the limitations of this inversion method. Finally, we describe the design of a new VLF receiver that will be deployed to make up the Array for VLF Imaging of the D-region (AVID) to monitor radiation belt precipitation and measure precipitation scale sizes. Once operational in 2023, this array will make continuous observations of the D-region over a large portion of Canada using continuous ground-based VLF observations of transmitter signals.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# The CANVAS Mission: Quantifying the Very-Low-Frequency Radio Energy Input from the Ground into the Earth's Magnetosphere

Robert A. Marshall[1*], David M. Malaspina[2,3], Scott E. Palo[1], Thierry Dudok de Wit[4,5], Guillaume Jannet[4,5], Riley A. Reid[1], James M. Cannon[1], Sebastian Wankmueller[1], Paraksh Vankawala[1], and Aldo Aguilar-Nidalini[1]

[1] Department of Aerospace Engineering Sciences, University of Colorado Boulder, USA
[2] Department of Astophysical and Planetary Sciences, University of Colorado Boulder, USA
[3] Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, USA
[4] Centre Nationale de Recherche Scientifique (CNRS), Orléans, France
[4] Laboratoire de Physique et Chimie de l'Environment et de l'Espace (LPC2E), Orléans, France

*Corresponding Author: robert.marshall@colorado.edu

Very-low-frequency (VLF) radio waves emitted by ground-based sources, including lightning and VLF transmitters, can impact the lower ionosphere and magnetosphere through their interaction with the local plasma and energetic particle environments. Quantifying the impacts of these waves on these environments requires an accurate assessment of the propagation and attenuation of these waves. The Climatology of Anthropogenic and Natural VLF wave Activity in Space (CANVAS) mission is designed to measure VLF waves from low Earth orbit (LEO) originating from these ground-based sources. The mission aims to characterize the VLF environment in LEO to address two main goals: i) constrain the VLF wave injection from the ground into the magnetosphere, and ii) improve models of VLF wave attenuation during propagation through the ionosphere. In addition, CANVAS measurements can be used to improve models of the effects of these waves on radiation belt electron scattering.

The CANVAS payload includes three-axis magnetic search coil and two-axis electric field dipole antennas, to measure five components of the propagating electromagnetic waves. The search coils are deployed one meter from the spacecraft using a carbon fiber deployable boom, in order to isolate them from spacecraft noise. The electric field system is composed of four 40 cm monopole antennas, making two orthogonal dipole antennas, integrated into the spacecraft "crown". Custom analog and digital electronics provide spectral data spanning 0.3–40 kHz at one-second cadence, providing a single "fast survey" data mode continuously for the duration of the mission.

The CANVAS spacecraft is a 4U CubeSat with a total mass under 6 kg. The spacecraft structure and avionics are custom-designed and built at CU Boulder, while the radios and attitude determination and control system (ADCS) are vendor-supplied components. The mission is designed to operate at 400-500 km altitude in a moderate-inclination orbit (~50 degrees), to ensure global coverage of lightning-generating regions; globally, most lightning is confined to within +/-50 degrees latitude. A one-year mission will ensure seasonal coverage to observe the variability in global lightning.

This paper presents a detailed overview of the CANVAS science goals, payload, spacecraft, and mission. The instrument is now completed and undergoing functional testing and performance characterization, and the spacecraft is beginning integration, expected to be completed in Fall 2022. The CANVAS mission is expected to be ready for launch in early 2023.

# Study on the longitudinal extent of QP emissions using conjugated events observed by PWING stations

Claudia Martinez-Calderon[1*], T. Oonishi[1], K. Shiokawa[1], J. Manninen[2], M. Ozaki[3], S. Oyama[1], and the PWING team.

[1] Institute for Space-Earth Environmental Research, Nagoya University, Japan
[2] Sodankylä Geophysical Observatory, University of Oulu, Finland
[3] Kanazawa University, Japan
*Corresponding Author: claudia@isee.nagoya-u.ac.jp

Quasi-periodic (QP) VLF emissions have been directly linked to electron precipitation of the same periodicity, consequently they play a role in the regulation of radiation belt particles [1]. Particularly, since QP waves are known to considerably spread across L-shells through unducted propagation. Previous studies have shown that QP events showing one-to-one correspondence between three satellites in the inner magnetosphere had a longitudinal extent of at least 2.26 MLT [2]. Here, we use the VLF receivers from the PWING project at sub-auroral latitudes to further investigate the longitudinal expansion of QP conjugated events observed at multiple stations.

Starting from a list of 44 events detected by the VLF receiver at Kannuslehto, Finland (KAN, MLAT = 67.7°, L = 5.5) between January 2017 and December 2018, we check whether these events were simultaneously observed by any of the other 8 PWING receivers. We found that, on average, QP emissions at KAN had a longer observation time (up to 10 hours) than at other stations. Only three other stations (IST, MAM, GAK) detected QP waves at the same time as KAN, and all were situated eastwards from KAN. Conjugated events were only detected between KAN and IST, separated by ~61°, and amounted to 10% of the total cases. This suggests that the vast majority of QP emissions can barely expand up to 4 MLT.

A preliminary comparison with geomagnetic data shows that the conjugated cases were Type 2 or mixed (Type 1 and 2 combined).

**References**

[1] Hayosh, M., Němec, F., Santolík, O., & Parrot, M. (2014). Statistical investigation of VLF quasiperiodic emissions measured by the DEMETER spacecraft. Journal of Geophysical Research: Space Physics, 119(10), 8063-8072.
[2] Martinez-Calderon, C., F. Němec, Y. Katoh, K. Shiokawa, C. Kletzing, G. Hospodarsky, O. Santolik et al. "Spatial extent of quasiperiodic emissions simultaneously observed by Arase and Van Allen Probes on 29 November 2018." Journal of Geophysical Research: Space Physics 125, no. 9 (2020): e2020JA028126.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# The Connection Between the October Effect in VLF Observations and neutral Atmosphere Dynamics

V. Matthias[1*], D. Banys[1], M. Hansen[1] and M. Clilverd[2]

[1] Institute for Solar Terrestrial Physics, German Aerospace Center, Neustrelitz, Germany
[2] British Antarctic Survey, UKRI_NERC,Cambridge,UK
*Corresponding Author: author1@mail.address

The October effect is long known as a strong decrease in VLF amplitudes occurring every October. However, neither it's formation mechanism nor the characteristic of the October effect are known. Simultaneously with the October effect we observe a regional temperature increase between 55 and 75 km, i.e. in the region where VLF radio waves are reflected. In theory an increase in temperature can lead to an increased collision frequency and thus an increased VLF signal absorption resulting in a decreased VLF amplitude. Thus, there seems to be a connection between the October effect and the neutral atmosphere dynamics. Here we want to investigate the characteristics of the October effect in VLF signals in connection to neutral atmosphere temperature using different transmitter and receiver combiations as well as MLS satellite observations. We found that the October effect is strongest in polar latitudes and vanishes in low latitudes for temperature and VLF observations. Finally a possible formation mechanism for the October effect will be discussed.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Very low frequency waves: tool to understand large meteorological systems effect on the lower ionosphere

Ajeet K. Maurya[1*]

[1] Department of Physics, Babasaheb Bhimrao Ambedkar University, Lucknow, India

*Corresponding Author: ajeet.iig@gmail.com

The lower ionosphere due to its latitude and low electron density remains least studied despite its important role in sun-earth connections. The very low frequency waves due to their frequency range, emerges as a cost-effective tool for continues monitoring of lower ionosphere affected due to various geophysical and solar events. In this present work, we present lower ionospheric disturbance during the four large meteorological systems, classified as hurricane/cyclones. The disturbances were detected by very low frequency (VLF) waves (3-30kHz) signals recorded at VLF receiving stations in the north America Pari (35.2˚N,82.9˚W) and Briarwood (33.43˚N,82.58˚W) operated by low frequency group (LF) at Georgia Institute of Technology, Atlanta US. The cyclone event over Indian region is monitored using NWC signal recorded at UltraMSK recording station, Dehradun, India. The effect of first event hurricane Jimena (26 Aug-9 Sep 2015; category 4), in the Pacific Ocean is analyzed using NPM in Pearl harbor (21.35∘N/157.9∘W, 26.1kHz) and NWC in Exmouth (21.8∘S/114.1∘E, 19.8kHz) transmitter passing over the path of hurricane and recorded at Pari. The NPM signal amplitude showed a maximum perturbation of 2.6 dB on 28 August while the NWC amplitude showed ~5.2 dB of maximum change on 27 August 2015. The second hurricane Joaquin occurred during (28 September-9 October 2015; category 4) in Pacific Ocean. The VLF signal from NAU transmitter recorded at Briarwood station is analyzed and have reported a maximum amplitude perturbation of ~7.8 dB on 4 October 2016.The third event analyzed is hurricane Lester (category 4) occurred during 24 August to 7 September 2015. The NPM transmitter signal recorded at Pari station is analyzed which show maximum perturbation of ~3.1dB on 31 August 2016. The 4th event is very sever cyclonic event Tauktae 14-19 May 2021, show ~2.3dB change during the VSCS phase of cyclone. The results suggest that the hurricane/cyclone caused the neutral densities of the mesosphere and lower thermosphere to lift or sink and bringing the lower ionosphere with it, an effect that may be facilitated by gravity waves generated due to strong convective processes during these events. The overall analysis suggests that possibly the severe convective storms, perturb the lower ionosphere that results clear anomalies in the amplitude of VLF signals.

# PIC simulations of banded chorus generation due to parallel electron plateau

Kyungguk Min[1*]

[1] Department of Astronomy and Space Science, Chungnam National University, Korea
*Corresponding Author: kyungguk@me.com

Magnetospheric chorus often arises in two spectral bands in frequency with a gap in intensity at half the electron cyclotron frequency, $f_{ce}/2$, in which case it is called "banded chorus." Despite routine satellite observations of banded chorus and many models proposed, its generation process is still debated. One simple idea suggests that the two bands are generated by two different electron populations with different temperatures. A small, but key, feature in this configuration is found in between these two populations where the electron distribution is rather flat at energies of 1-10 keV, called the plateau or beam. This plateau at this energy range is believed to suppress nonlinear growth of chorus at the spectral gap [1].

This paper presents the results of one-dimensional particle-in-cell simulations in a dipole-like background magnetic field, investigating the role of the plateau population on the spectral gap formation. In simulations, the initial energetic electron plasma is configured so that without the plateau population, chorus elements spaning from below to above $f_{ce}/2$ are generated without a gap at $f_{ce}/2$. The electron plateau population is modeled by a shell distribution. The simulation results show that even a small fraction of electron plateau is quite effective in suppressing the chorus growth at $f_{ce}/2$, suggesting that the cyclotron damping by the plateau is not the main source for the gap formation. The quantative role of the added plateau population in the gap formation is under investigation and the preliminary result will be also shown.

**References**

[1] Li, J., Bortnik, J., An, X. *et al.* Origin of two-band chorus in the radiation belt of Earth. *Nat Commun* **10,** 4672 (2019). https://doi.org/10.1038/s41467-019-12561-3.

# A Review of Spacecraft Observations of Large Scale Dayside VLF Saucers

Chrystal Moser-Gauthier[1*] and James W. LaBelle [2]

[1] Space Science Center, University of New Hampshire, Durham, NH, USA
[2] Department of Physics and Astronomy, Dartmouth College, Hanover, NH, USA

*Corresponding Author: Chrystal.Moser@unh.edu

Auroral whistler-mode radio emissions in the very-low frequency (VLF) range known as VLF Saucers are observed as a pattern of descending and ascending features in frequency-time spectrograms, producing an image resembling nested saucers. They result when VLF receivers on a moving platform measure whistler waves propagating off of the resonance cone condition at a confined source. The mechanism requires an unusually stationary source in the otherwise highly dynamic auroral environment. Observations of relatively small-scale saucers in the nightside aurora have been reported from many spacecraft, but more rarely reported are large-scale saucers appearing on the dayside. The Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER) and Cusp Alfvén and Plasma Electrodynamics Rocket (CAPER-2) both observed these features, the former in the dayside ionosphere at an altitude of 660 km (James et al., 2012), and the latter in the cusp ionosphere at altitudes between 400–700 km (Moser et al., 2021). Both studies employed two-dimensional ray tracing analysis to determine the source height of these saucers and concluded that the source originated above the respective spacecraft at altitudes from 2800–4000 km. DEMETER observed several examples on the dayside under different conditions. CAPER-2 observed a single event but included particle instruments which detected Alfvénically accelerated electrons in the cusp at or above the altitudes of the saucer sources, suggesting that the cusp may be the source of the saucer event. There remain many aspects of this VLF phenomenon that are not definitively known.

**References**

[1] James, H. G., Parrot, M., and Berthelier, J.-J. (2012), Very-low-frequency saucers observed on DEMETER, *J. Geophys. Res.*, 117, A09309, doi:10.1029/2012JA017965.

[2] Moser, C., LaBelle, J., Hatch, S., Moen, J. I., Spicher, A., Takahashi, T., et al. (2021). The cusp as a VLF saucer source: First rocket observations of long-duration VLF saucers on the dayside. *Geophysical Research Letters*, *48*, e2020GL090747. https://doi. org/10.1029/2020GL090747

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Validation of AWDANet's chorus inversion method

Lilla Murár-Juhász[1*], János Lichtenberger[1, 2] and Yoshiharu Omura[3]

[1] Eötvös Loránd University, Hungary
[2] ELKH-ELTE Space Research Group, Hungary
[3] Kyoto University RISH, Japan
*Corresponding Author: lilla@sas.elte.hu

AWDANet (Automatic Whistler Detector and Analyzer Network) [1] is a worldwide system of VLF receivers, which main goal is to monitor the electron density of the plasmasphere at the equatorial region via automatic detection and analysis of lightning whistlers. During geomagnetically disturbed times, some of the receivers located at high latitudes can correspond to greater McIlwain's L parameter than the plasmapause L value, $L_{pp}$. Whistler-mode chorus emissions can be detected on those AWDANet receivers during these events.

The generation process of chorus emission was explained by nonlinear wave growth theory of Omura et al., 2008, 2011 [2,3]. Their derivation found direct connection between the frequency sweep rate of an individual chorus emission and the electron density of its source population (few keV to 100 keV) at the equatorial region. That relationship enables us to use chorus emissions recorded by AWDANet on the ground to get information about their source population at the source region.

Juhasz et al., 2019 [4] published a direct method to obtain the approximate bi-Maxwellian parameters of the source population from the starting frequency and frequency sweep rate of individual chorus emissions. Their method was successfully tested on the in situ measurements of EMFISIS and HOPE instruments on-board Van Allen Probes.

As a next step, the above mentioned chorus inversion method was expanded on emissions recorded by AWDANet. Our validation process requires chorus emissions recorded both on Van Allen Probes and by AWDANet, which signals have to have good signal to noise ratio and have to be confinable on spectrogram. They also have to fulfill requirements, like no overlapping emissions, no gap at 0.5 $f_{ce}$. These requirements significantly reduce the number of usable chorus emissions. Here we are presenting case studies of the validation process. Additionally, we are introducing other chorus inversion techniques applicable on "weaker and more noisy" chorus emissions recorded on the ground.

**References**

[1] Lichtenberger, J., Cs. Ferencz, L. Bodnár, D. Hamar, and P. Steinbach (2008), Automatic Whistler Detector and Analyzer system: Automatic Whistler Detector, *J. Geophys. Res.*, 113, A12,201, doi:10.1029/2008JA013467.

[2] Omura, Y., Katoh, Y., & Summers, D. (2008). Theory and simulation of the generation of whistler-mode chorus. *Journal of Geophysical Research*, 113, A04223. https://doi.org/10.1029/2007JA012622

[3] Omura, Y., & Nunn, D. (2011). Triggering process of whistler mode chorus emissions in the magnetosphere. *Journal of Geophysical Research*, 116, A05205. https://doi.org/10.1029/2010JA016280

[4] Juhász, L., Omura, Y., Lichtenberger, J., & Friedel, R. H. W. (2019). Evaluation of plasma properties from chorus waves observed at the generation region. *Journal of Geophysical Research: Space Physics*,. 124, 4125– 4136. https://doi.org/10.1029/2018JA026337

# Response of the D-region ionosphere to a X-class solar flare by OCTAVE VLF observations

Masaharu Nakayama[1*], Hiroyo Ohya[1], Fiminori Tsuchiya[2], Kazuo Shiokawa[3], Kenro Nozaki[4] and Hiroyuki Nakata[1]

[1] Graduate School of Science and Engineering, Chiba University, Japan
[2] PPARC, Tohoku University, Japan
[3] ISEE, Nagoya University, Japan
[4] The University of Electro-Communications, Japan
*Corresponding Author: mrakn_tech@chiba-u.jp

When solar flares occur, electron density in the ionosphere (60-100 km altitude) increases because of intense X-rays. So far, relationship between VLF (3-30 kHz) and X-ray flux has been reported [1], although there are few reports for horizontal inhomogeneity of the reflection height in the D-region ionopshere. The purpose of this study is to reveal horizontal homogeneity of electron density in the D-region ionosphere during a X-class solar flare using multi-path VLF/LF (30-300 kHz) transmitter signals of "Observation of CondiTion of ionized Atmosphere by VLF Experiment (OCTAVE)" network. When solar flares occur, VLF/LF amplitude and phase vary with decreasing the reflection height. The transmitters used in this study were NWC (21.817°S, 114.167°E, 19.8 kHz), JJI (32.05°N, 130.82°E, 22.2 kHz), JJY (37.37°N, 140.85°E, 40.0 kHz; 33.47°N, 130.18°E, 60.0 kHz), and BPC (34.63°N, 115.83°E, 68.5 kHz). The receivers were located at KAG (Tarumizu, Kagoshima, Japan, 31.59°N, 130.55°E), PKR (USA, 65.125°N, 147.488°W), and RKB (Rikubetsu, Hokkaido, 43.45°N, 143.77°E), which are part of OCTAVE network. A X2.2-class solar flare occurred at 08:57 UT on 6 September, 2017. During the solar flare, amplitudes of variations in the VLF/LF amplitude ($\Delta A$) and phase ($\Delta P$) were 2.65-14.73 dB and 31.0-150.25 degrees, respectively. Using wave-hop method, we estimated reduction in reflection height ($\Delta h$ ) from the observed $\Delta A$ and $\Delta P$ . When the reference height was assumed to be 78.08-84.99 km, the $\Delta h$ were estimated to be 1.0-4.8 km for BPC-KAG, BPC-RKB, JJY40-KAG, JJY60-RKB and JJY40-RKB paths. The difference in the $\Delta h$ for each path would be caused by distance between the sub-solar point and each path, and sunset effects. In this presentation, we will discuss the horizontal inhomogeneity of the reflection height during the solar flare in detail.

## References

[1] J.-P. Raulin, F. C. P. Bertoni, H. R. Gavili ́an, W. Guevara-Day, R. Rodriguez, G. Fernandez, E. Correia, P. Kaufmann, A. Pacini, T. R. C. Stekel, W. L. C. Lima, N. J. Schuch, P. R. Fagundes and R. Hadano, "Solar flare detection sensitivity using the South America VLF Network (SAVNET)", *Journal of Geophysical Research*, **115**, 2010.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Spacecraft Observations of VLF Transmitter Signals and Their Effects

František Němec[1*], Ondřej Santolík[2, 1], Michel Parrot[3], George B. Hospodarsky[4], and William S. Kurth[4]

[1] Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
[2] Department of Space Physics, Institute of Atmospheric Physics of the Czech Academy of Sciences, Prague, Czech Republic
[3] LPC2E/CNRS, Orléans, France
[4] Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA
*Corresponding Author: frantisek.nemec@mff.cuni.cz

Electromagnetic signals radiated by powerful military very low frequency (VLF) transmitters represent, along with plasma waves generated via wave-particle interactions and lightning generated whistlers, an important class of emissions propagating throughout the inner magnetosphere. We use data obtained by the low-altitude DEMETER spacecraft and Van Allen Probes spacecraft close to the equatorial plane at larger radial distances to analyze the intensities, propagation, and effects of these emissions.

Particular attention is paid to the distinction between ducted and nonducted propagation. Both the Doppler shift analysis (DEMETER) and detailed multicomponent wave analysis (Van Allen Probes) are used for this purpose. We show that although the nonducted propagating signals are detected more often, occupying a larger portion of the magnetosphere, they tend to be less intense. The total power of ducted and nonducted signals is thus roughly the same.

We further investigate the transmitter signal effects on the ionosphere, demonstrating that they can induce considerable density and temperature inhomogeneities. These may, in turn, facilitate a transionospheric propagation of other emissions. Finally, we search for the presence of possible transmitter-triggered emissions. Although this phenomenon appears to be quite rare, several such events are identified and analyzed.

# First results of the WHU VLF wave detection system at the Chinese Great Wall Station in Antarctic

Binbin Ni[1*], Xudong Gu[1*], Shiwei Wang[1], Ze-jun Hu[2], Bin Li[2], Fang He[2], Qingshan Wang[1], Wei Xu[1], Xiangcai Chen[2], Hongqiao Hu[2]

[1] Department of Space Physics, Wuhan University, Wuhan, China
[2] Polar Research Institute of China, Shanghai, China
*Corresponding Authors: bbni@whu.edu.cn, guxudong@whu.edu.cn

A Very Low Frequency (VLF) wave detection system has been designed at Wuhan University (WHU) and recently deployed by the Polar Research Institute of China at the Chinese Great Wall station (GWS, 62.22° S, 58.96°W) in Antarctica. With a dynamic range of ~110 dB and timing accuracy of ~100 ns, this detection system can provide observational data with a resolution that can facilitate space physics and space weather studies. This paper presents the first results of the wave measurements by the WHU VLF wave detection system at GWS to verify the performance of the system. With the routine operation for over three months, the system can acquire the dynamic changes of the wave amplitudes and phases of various ground-based VLF transmitter signals. A preliminary analysis indicates that the properties of the VLF transmitter signals observed at GWS during the X-class solar flare events are consistent with previous studies. As the HWU-GWS path crosses the South Atlantic Anomaly (SAA) region, the observations also imply a good connection in space and time between the VLF wave disturbances and the lower ionosphere variation potentially caused by magnetospheric electron precipitation during the geomagnetic storm period. It is therefore expected that the acquisition of VLF wave data at GWS, in combination with datasets from other facilities, can be beneficial for space weather studies related to the radiation belt dynamics, terrestrial lightning discharge, whistler wave propagation, and the lower ionosphere disturbance, etc., in the Antarctic region.

**References**

[1] Chen, Y., Yang, G., Ni, B., Zhao, Z., Gu, X., Chen, Z., & Wang, F. (2016). Development of ground-based ELF/VLF receiver system in Wuhan and its first 476 results. Advances in Space Research, 57, 1871-1880. https://doi.org/10.1016/ j.asr.2016.01.023.

[2] Chen, Y., Ni, B., Gu, X., Zhao, Z., Yang, G., Zhou, C., & Zhang Y. (2017). First observations of low latitude whistlers using WHU ELF/VLF receiver system. Science China Technological Sciences, 60, 166-174. https://doi.org/10.1007/s11431-016-6103-5.

[3] Zhou, R., Gu, X., Yang, K., Li, G., Ni, B., Yi, J., et al. (2020). A detailed investigation of low latitude tweek atmospherics observed by the WHU ELF/VLF receiver: I. Automatic detection and analysis method. Earth and Planetary Physics, 4, 120–130. https://doi.org/10.26464/epp2020018.

[4] Yi, J., Gu, X, Cheng, W., Tang, X., Chen, L., Ni, B., et al. (2020). A detailed investigation of low latitude tweek atmospherics observed by the WHU ELF/VLF receiver: 2. Occurrence features and associated ionospheric parameters. Earth and Planetary Physics, 4, 238-245. https://doi.org/10.26464/epp2020023.

[5] Gu, X., Peng, R., Wang, S., Ni, B., Luo, F., Li, G., & Li, Z. (2021). Responses of the very low frequency transmitter signals during the solar eclipse on Dec 26, 2019 over a North-South propagation path. IEEE Transactions on Geoscience and Remote Sensing, 60, 2000207. https://doi.org/10.1109/TGRS. 2021.3056092.

# Local time and seasonal variations in the D-region ionosphere: Does it reflect SSW effects?

Yuma Nozaki[1], Hiroyo Ohya[1], Fuminori Tsuchiya[2], Kenro Nozaki[3], Hiroyuki Nakata[1], and Kazuo Shiokawa[4]

[1] Graduate School of Science and Engineering, Chiba University, Japan
[2] PPARC, Tohoku University, Japan
[3] The University of Electro-Communications, Japan
[4] Institute for Space-Earth Environmental Research, Nagoya University, Japan

*Corresponding Author: yuuma201@chiba-u.jp

Daytime electron density in the D-region ionosphere varies depending on the solar zenith angle, which is a function of local time (LT) and season. In addition to the regular variation, D-region variations associated with various factors have been reported, for example, solar flares, geomagnetic storms, earthquakes, volcanic eruptions, and sudden stratospheric warming (SSW) [1, 2]. The detailed investigation of these factors is required to understand the D-region characteristics. In this study, we investigate seasonal and LT dependences of the D-region ionosphere using low frequency (LF) transmitter signals. The transmitter and receiver were JJY (60kHz, 33.47°N, 130.18°E) and RKB (Rikubetsu, Hokkaido, 43.45°N, 143.77°E), respectively. For removing effects of geomagnetic storms, we used international 5 quietest days (Q-days) for each month based on Kp index determined by GeoForschungsZentrum (GFZ) Potsdam. The daytime (or nighttime) mean value of amplitude for each day ($A_{\mathrm{mean}}$) was subtracted from the value of instantaneous amplitude ($A_i$) to determine the perturbations in amplitude ($\Delta A$), i.e., $\Delta A = A_i - A_{\mathrm{mean}}$. In daytime, both $\Delta A$ and $\Delta P$ were large during 09:00-15:00 JST. Variations in $\Delta A$ and $\Delta P$ were large in January. $\Delta A$ was large in summer and winter, while $\Delta P$ was large in spring and fall. Calculated $\Delta A$ based on wave-hop method was larger during sunrise and sunset than that around 09:00-15:00 LT, which is opposite to the observation. The change in $\Delta P$ between observed and calculated results was opposite during sunrise/sunset. The calculation results showed that the $\Delta P$ was large in summer. In observations, both $\Delta A$ and $\Delta P$ were larger in January than those in other months, although only $\Delta A$ was large in calculation. The increases in the $\Delta A$ and $\Delta P$ in January 2017 could be associated with sudden stratospheric warmingMean temperature at 10 hPa and the region where the latitude and longitude were >60°N and 110°E-170°E, respectively, based on JRA-55 dataset, and the LF amplitude had two similar periods of 5 and 21 days. In this presentation, we will discuss the differences between the observed and calculated $\Delta A$ and $\Delta P$, and cause of disturbances on the observed results for January, 2017.

## References

[1] S. Pal, Y. Hobara, S. K. Chakrabarti and P. W. Schnoor, "Effects of the major sudden stratospheric warming event of 2009 on the subionospheric very low frequency/low frequency radio signals," Journal of Geophysical Research: Space Physics, 122, pp. 7555-7566, 2017.
[2] J. Laštovička, "Forcing of the ionosphere by waves from below," Journal of Atmospheric and Solar-Terrestrial Physics, 68, pp. 479-497, 2006.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# On the Vlasov Simulation of VLF Chorus Containing Falling Tone Elements- Implications for Generation Region Location.

David Nunn[1*]

[1] School of Electronics and Computer Science,Southampton University, UK

*Corresponding Author: dn@ecs.soton.ac.uk

We present a quasi broadband Vlasov simulation code for the numerical modelling of VLF chorus with one spatial dimension, i.e. parallel propagating.[1,4] The legacy code has been parallelised using open MP software, which is based upon a shared memory formalism. All the valid do loops are parallelised, the maximum number of threads in parallel code sections being 40 on the Southampton University IRIDIS5 machine. The faster parallel code enables much longer simulations of chorus and or simulations with greater accuracy. [2]

We simulate long duration chorus over several seconds duration which has complex structure containing both rising and falling tones. The generation regions (GR) of both risers and fallers are identified, and it is found that the falling tone GRs are located in the negative inhomogeneity region S<0 downstream from the equator. Since the inhomoeneity factor S contains a term in df/dt, the faller GRs are located further downstream than the riser GRs. When the spectrograms in the simulations are viewed at the equator, we find risers are present but fallers absent as expected, since they are generated further downstream.

Previous simulations in joint research with Kyoto University have produced falling tones generated in the positive inhomogeneity region upstream from the equator S>0. [1,3]. This usually is in conditions of high linear growth rate which drives the wave amplitude profile upstream. It would thus appear that fallers may be generated either upstream or downstream of the equator depending upon growth rate conditions..

## References

[1] Nunn,D. and M.J. Rycroft, A parametric study of triggered VLF emissions and the control of radio emission frequency sweep rate, Annales Geophysicae, 23, 1-12, 2005.

[2] Nunn D., O. Santolik, M. Rycroft, and V. Trakhtengerts, On the numerical modelling of VLF chorus dynamical spectra , Ann. Geophys., 27, 1–19,2009

[3] Omura,Y. and D.Nunn,Triggering process of whistler mode chorus emissions in the magnetosphere, J. Geophys. Res., 116, A05205, doi:10.1029/2010JA016280, 2011.

[4] Nunn,D., The numerical simulation of the generation of lower-band VLF chorus using a quasi-broadband Vlasov Hybrid Simulation code Earth, Planets and Space 73:222 https://doi.org/10.1186/s40623-021-01549-3,2021.

# Variations in the D-region ionosphere associated with Tonga volcanic eruptions of 15 July 2022 using VLF/LF transmitter signals

Hiroyo Ohya[1*], Fuminori Tsuchiya[2], Masashi Kamogawa[3], Tomoyuki Suzuki[3], Tamio Takamura[1], and Jaroslav Chum[4]

[1] Chiba Univeristy, Japan
[2] Tohoku University, Japan
[3] Univeristy of Shizuoka, Japan
[4] Institute of Atmospheric Physics of the Czech Academy of Sciences, Czech Republic
*Corresponding Author: ohya@faculty.chiba-u.jp

The Hunga Tonga-Hunga Ha'apai volcano in Tonga (in southern Pacific, 20.54°S, 175.38°W) explosively erupted during 04:10-04:30 UT on 15 January, 2022, and large pressure variations occurred from the volcano. Large and medium scale traveling ionospheric disturbances (LSTID and MSTID) due the eruptions were observed [1], which were caused by Lamb wave excited by the eruptions. Due to magnetic conjugate effect, the northern hemisphere TIDs appear three hours prior to the arrival of the Lamb wave [2]. Both direct and conjugate TIDs match with the theoretical dispersion relation of the atmospheric Lamb and gravity modes. However, D-region behavior for the Tonga eruptions has not been revealed yet. In this study, we investigate variations in VLF/LF transmitter signals and atmospheric electric field (or potential gradient) associated with Tonga volcanic eruptions of 15 January, 2022 to understand D-region ionosphere and atmosphere coupling. The VLF/LF transmitters used in this study were JJY(60 kHz, Japan), JJI(22.2 kHz, Japan), and BPC(68.5 kHz, China). The We used 0.1-s sampling amplitude data. Unfortunately, there were no phase data for all paths on that day. The minimum distances of the JJI-TNN, JJY60kHz-TNN, and BPC-TNN propagation paths from the Tonga volcano were 8167.7 km, 8311.6 km, and 8499.9 km, respectively. The atmospheric electric field has been observed in Chiba University (CHB), (35.63°N, 140.10°E), Seikei High School (SHS, Tokyo, 35.72°N, 139.57°E), Japan, and Studenec (STU), Czech Republic (50.26°N, 12.52°E). The distances of and STU from the Tonga volcano were 7789.5 km, 7830.4 km, and16634.7 km, respectively. The first variations in pressure data were seen around 10:57 UT and 19:03 UT on 15 January in CHB and STU, respectively. The propagation velocity was 310-320 m/s, which is typically propagation velocity of atmospheric Lamb waves. The VLF/LF amplitudes for all three paths showed the similar period around the first arrival time of the Lamb waves. Based on coherence analysis, the common periods for the three paths were 8.4, 11.2, 29.1, and 62.4 minutes. There were significant coherences (0.70-0.99) between atmospheric pressure at CHB and each LF amplitude. On the other hand, after arrival time of the Lamb wave, the atmospheric electric field at CHB showed similar variations with the pressure data at CHB. The periods of the variations were 40-50 and 80-100 minutes. The conductivity in the atmosphere might change due to Lamb wave. The amplitude of the variation in the atmospheric electric field at CHB and STU was similar after arrival time of the Lamb wave at each site. There were variations in atmospheric electric field with a period of 10-100 minutes at CHB at the first (direct) and second (rounding the Earth) arrival times of the Lamb waves. The conductivity in the atmosphere might change volcanic eruptions. In this presentation, we will report and discuss the phenomena in detail.

## References

[1] D. R. Themens, "Global Propagation of Ionospheric Disturbances Associated With the 2022 Tonga Volcanic Eruption," Geophysical Research Letters, https://doi.org/10.1029/2022GL098158, 2022.
[2] J. T. Lin et al., "Rapid conjugate appearance of the giant ionospheric Lamb wave signatures in the northern hemisphere after Hunga-Tonga volcano eruptions." Geophysical Research Letters, e2022GL098222, https://doi.org/10.1029/2022GL098222, 2022.

# Nonlinear Signatures of VLF Triggered Emissions

Yoshiharu Omura[1*] and Takeshi Nogi[1]

[1] Reserach Institute for Sustainable Humanosphere, Kyoto University, Uji, Kyoto 611-0011, Japan
*Corresponding Author: omura@rish.kyoto-u.ac.jp

We conduct a particle-in-cell simulation reproducing triggering process of whistler-mode rising-tone emissions by injecting a wave with a fixed frequency at the equator [1]. Rising-tone elements with multiple subpackets with monotonically increasing frequencies are generated from the triggering wave. Generation regions of the subpackets move upstream or downstream depending on the group velocities and resonance velocities for different frequencies. Because of the motion of a source region to the upstream, a long rising-tone subpacket is generated self-sustainingly through formation of an electron hole in velocity phase space stretched over the generation region. The upstream motion of the source region is a necessary condition for the absolute instability at the equator as assumed in the nonlinear wave growth theory [2]. The long rising-tone subpacket is modulated with increasing magnitude, splitting into smaller subpackets through propagation. The amplitude modulations in the subpacket arise from two different processes; resonant trapping oscillation of electrons at the equatorial region and enhancement of amplitude variations through convective wave growth with different group velocities in the downstream.

**References**

[1] T. Nogi, and Y. Omura (2022), Nonlinear signatures of VLF-triggered emissions: A simulation study, Journal of Geophysical Research: Space Physics, 127, e2021JA029826,
[2] Y. Omura (2021), Nonlinear wave growth theory of whistler-mode chorus and hiss emissions in the magnetosphere, Earth Planets Space 73, 95.

# Evolution of the Electron Zebra Stripes in the Earth's Inner Magnetosphere

Megha Pandya[1*], Yusuke Ebihara[1], and Takashi Tanaka[2]

[1]Research Institute for Sustainable Humanosphere, Kyoto University, Uji, Japan
[2]International Research Center for Space and Planetary Environmental Science, Kyoto University, Uji, Japan

*Corresponding Author: pandya.meghamahendra.3j@kyoto-u.ac.jp

The electrons with 10's-100's of keV energies exhibit repeated hills and valleys in the electron flux intensities in the Earth's inner magnetosphere. It appears like a banded structure in the energy versus L-value spectrogram that resembles the zebra patterns and hence named as "zebra stripes". We focused on the electron zebra stripes that appeared during an intense geomagnetic storm of September 8, 2017. We performed an advection simulation, under the time-dependent electric and magnetic fields provided by a global magnetohydrodynamics (MHD) simulation, and found that electron zebra stripes appeared. We back-traced the bounce-averaged trajectories of the electrons comprising of the hills and the valleys. The electrons comprising of the hills have experienced inward motion due to the westward electric field in the premidnight to postdawn region, whereas the electrons comprising of the valleys have not. The westward electric field arises from the presense of the Region 1 field aligned current (FAC) at the polar ionosphere. The electrical potential patterns are distorted due to the non-uniform ionospheric conductivity at the equatorward edge of the auroral oval. This alters the azimuthal electric fields at the high latitude ionosphere that penetrates deep into the lower latitudes, and skews toward dawn. Our study highlights the coupling of solar wind and inner magnetosphere for the formation of electron zebra stripes.

# A survey of Cluster Wideband measurements during Auroral Kilometric Radiation source crossings

D. Pisa[1*], U. Taubenschuss[1], G. Fischer[2], J. Souček[1], and O. Santolík[1, 3]

[1] Institute of Atmospheric Physics of Czech Academy of Sciences, Prague, Czechia
[2] Space Research Institute, Austrian Academy of Sciences, Graz, Austria
[3] School of Physics, Faculty of Mathematics and Physics, Charles University, Czechia
*Corresponding Author: dp@ufa.cas.cz

We survey measurements of Auroral Kilometric Radiation (AKR) from the four Cluster spacecraft. AKR is an intense radio emission propagating from the Earth's auroral regions in a frequency range from tens up to hundreds of kHz. This emission is generated by the cyclotron maser instability inside low-density cavities in the auroral acceleration regions [1]. Detailed analyses [2] show that AKR exhibits fine structures (e. g. pulsations and striations) similar to planetary radio emissions from Jupiter and Saturn. Several studies [3, 4] from the terrestrial auroral regions show the presence of electron solitary waves (ESW) and discuss their relations to the fine structure of the radio emissions. We present a detailed analysis of AKR emissions observed while the four Cluster spacecraft were within or very close to the AKR source region. For this study, we use high-resolution Wideband [5] snapshots of one component up to 577 kHz measured in translation bands of 125, 250, and 500 kHz.

**References**

[1] Yearby, K. H., & Pickett, J. S. (2022). A Review of Cluster Wideband Data multi-spacecraft observations of auroral kilometric radiation. Journal of Geophysical Research: Space Physics, 127, e2021JA029499. https://doi.org/10.1029/2021JA029499
[2] Fischer, G., Taubenschuss, U., and Píša, D.: Classification of spectral fine structures of Saturn kilometric radiation, Ann. Geophys., 40, 485–501, https://doi.org/10.5194/angeo-40-485-2022, 2022
[3] Pottelette, R., Berthomier, M., & Pickett, J. (2014). Radiation in the neighbourhood of a double layer. Annales Geophysicae, 32, 677–687. https://doi.org/10.5194/angeo-32-677-2014
[4] Treumann RA and Baumjohann W (2020) Auroral Kilometric Radiation and Electron Pairing. Front. Phys. 8:386. doi: 10.3389/fphy.2020.00386
[5] Gurnett, D. A., Huff, R. L., & Kirchner, D. L. (1997). The wide-band plasma wave investigation. Space Science Reviews, 79, 195– 208. https://doi.org/10.1023/A:1004966823678

# Examination of Radiation Belt Dynamics during Substorm Clusters: Magnetic Local Time Variation and Intensity of Precipitating Fluxes

Craig J. Rodger[1*], Mark A. Clilverd[2], Aaron T. Hendry[1], and Colin Forsyth[3]

[1] Department of Physics, University of Otago, Dunedin, New Zealand
[2] British Antarctic Survey (NERC), Cambridge, United Kingdom
[3] UCL Mullard Space Science Laboratory, Dorking, United Kingdom
*Corresponding Author: craig.rodger@otago.ac.nz

Substorms are short-lived but significant reconfigurations of the geomagnetic field during which energetic particles are injected into the inner magnetosphere close to magnetic midnight. There is currently a need to quantify substorm-driven energetic electron precipitation (EEP) to better understand its role in radiation belt dynamics and to quantify its impact on the atmosphere. As substorm injections trigger chorus waves, which have strong MLT, AE, and *L*-shell dependence, we investigate the dependence of EEP in terms of these variables.

We utilize many decades of low Earth orbit satellite observations to examine the typical statistical variability around substorm events identified by the Substorm Onsets and Phases from Indices of the Electrojet (SOPHIE) algorithm. In contrast to trapped flux enhancements, enhanced EEP is found to occur even for the quietest AE range of those considered (AE≤100 nT, 100 nT<AE≤300 nT, AE≥300 nT). The MLT-dependent analysis for all AE-ranges shows a well-defined variation in >30 keV EEP magnitude, with a maxima in the mid to late morning sector (6-12 MLT), and a distinct and deep minimum in the late afternoon sector (15-18 MLT). The patterns show similarities to previously published whistler-mode lower band chorus distributions with MLT.

Clusters of substorms reliably produce enhancements in electron precipitation for >30 keV and >300 keV, with steadily increasing peak precipitation magnitudes with increasing AE. The peak precipitation flux *L*-shell also moves inwards with increasing AE, in a similar way for the two energy ranges.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Geomagnetically Induced Currents and Harmonic Distortion: Contrasting Power Network Measurements and Wideband VLF

Craig J. Rodger[1*], Mark A. Clilverd[2], Malcolm Crack[1], Ian Martin[3], James B. Brundell[1], Daniel H. Mac Manus[1], and Michael Dalzell[3]

[1] Department of Physics, University of Otago, Dunedin, New Zealand
[2] British Antarctic Survey (NERC), Cambridge, United Kingdom
[3] Transpower New Zealand Limited, Wellington, New Zealand
*Corresponding Author: craig.rodger@otago.ac.nz

During Space Weather events, geomagnetically induced currents (GICs) can be induced in high-voltage transmission networks. High GIC levels can damage transformers within substations, potentially resulting in them becoming non-operational and disrupting electrical supply to customers. Damage and disruption has occurred during some "large" geomagnetic disturbances over the last ~25 years; significantly more impact is expected during a future "extreme" geomagnetic disturbance.

In much of the world research in this area has been hampered by a lack of GIC observations. Previous studies have noted that New Zealand is unusually fortunate in having a comparatively dense, high quality, set of GIC measurements, spanning >70 transformers in >20 substations. However, due to operational reasons these observations are clustered in the mid and lower South Island, giving a limited spatial sampling. GICs lead to half cycle transformer saturation and those currents are one of the few ways in which even harmonics are produced in a well run power transmission network. Hence even-order harmonic distortions are an alternative way to monitor the influence of GIC on transformers and identify "stressed" transformers. We have previously undertaken a case study for 7-8 September 2017 showing how GIC effects can be monitored by using even harmonic distortion in locations where no GIC measurements are present (for example, the most of New Zealand's North Island) [1].

Near Dunedin at the Halfway Bush substation we have data coverage from a unique combination of instrumentation: measurements of GIC on both the single phase transformer T4 and 3-phase transformer T6 located within the substation, nearby magnetic field perturbation measurements, very low frequency (VLF) wideband measurements detecting the presence of power system harmonics with high time resolution, and low time resolution power network high-voltage harmonic distortion measurements [2]. This combination means we can analyse high time resolution (1-5 s) magnetometer, geomagnetically induced current (GIC), and mains harmonic distortion data from the Halfway Bush substation, with VLF radio wave data are used to provide high resolution measurements of mains harmonic distortion levels within the substation.

In this talk we will discuss an approach to use the very noisy wideband VLF observations made very near the substation to detect GIC-produced harmonics, and the impact of changing transformer core configurations in the Halfway Bush substation (and in other parts of NZ) on the production of harmonics.

The presentation is based on work undertaken inside the New Zealand Solar Tsunamis research programme.

**References**

[1] Rodger C. J., et al., Geomagnetically Induced Currents and Harmonic Distortion: Storm-time Observations from New Zealand. Space Weather, 18, e2019SW002387, 2020, https://doi.org/10.1029/2019SW002387
[2] Clilverd, M.A., et al., Long-Lasting Geomagnetically Induced Currents and Harmonic Distortion observed in New Zealand during the 07-08 September 2017 Disturbed Period, Space Weather, 16, 2018, pp. 704-717, doi:10.1002/2018SW001822.

# Some recent advances in VERSIM science

Michael J. Rycroft[1*]

[1] CAESAR Consultancy, 35 Millington Road, Cambridge CB3 9HW, U.K.

*Corresponding Author: michaelrycroft@btinternet.com

Since the first VERSIM Workshop held in Sodankyla in 2004, there have been many significant results in the scientific arenas investigated using ELF and VLF radio waves recorded on the ground and aboard satellites. Here particular attention is paid to recent advances which can be classified as being centred on either (a) the physical processes which generate the radio signals observed or (b) propagation effects.

The main sources of natural ELF and VLF radio waves in the Earth's environment are (i) lightning discharges and (ii) magnetospheric plasma instabilities. Concerning generation mechanisms, highlights include observations of lightning discharges having large peak currents which generate sprites [1] and elves [2]. Attention has been paid to improving numerical models of cyclotron resonance mechanisms for generating chorus occurring on a particular L-shell at less than half the equatorial electron gyro frequency [3, 4, 5]. Unusual VLF emissions observed near Sodankyla, Finland, at more than half the equatorial electron gyro frequency have been reported [6]. Numerous lightning flashes (~ 90 $s^{-1}$) associated with the Hunga (Tonga) volcano explosion at 04.15 UT on 15 January 2022 caused a four-fold increase in the intensity of Schumann resonance signals world-wide which lasted for about an hour and a half [7].

Propagation effects, e.g., frequency-dependent time delays, result from (i) propagation in the Earth-ionosphere waveguide from source to receiver or (ii) ducted or unducted propagation in the whistler mode through the magnetosphere and down through the ionosphere. There is a need to study the cut-off frequency of "tweeks" before and after large earthquakes to find out if the D-region ionosphere is lowered at the time of a large earthquake. The source of whistlers observed at a certain ground station has been shown to be middle latitude thunderstorms, typically within 2000 km of the station's magnetic conjugate point [8].

**References**

[1] Pizzuti, A., Wilkinson, J. M., Soula, S., Mlynarczyk, J., Kolmašová , I., et al. (2021). Signatures of large peak current lightning strokes during an unusually intense sprite-producing thunderstorm in southern England, Atmospheric Research, **249**, 105357

[2] Kolmašová, I., Santolík, O., Kašpar, P., Popek, M., Pizzuti, A., Spurný, P., et al. (2021). First observations of elves and their causative very strong lightning discharges in an unusual small-scale continental spring-time thunderstorm. J. Geophys. Res., Atmospheres, **126**, e2020JD032825

[3] D. Mourenas, D., Zhang, X.-J., Nunn, D., Artemyev, A. V., Angelopoulos, V., Tsai, E., and Wilkins, C. (2022). Short chorus wave packets: Generation within chorus elements, statistics, and consequences on energetic electron precipitation. J. Geophys. Res., Space Physics, **127**, e2022JA030310.

[4] Nunn, D., Zhang, X.-J., Mourenas, D., and Artemyev, A. V. (2021). Generation of realistic short chorus wave packets. Geophysical Research Letters, **48**, e92178

[5] Omura, Y. (2021). Nonlinear wave growth theory of whistler-mode chorus and hiss emissions in the magnetosphere. Earth Planets and Space, **73**, 95

[6] Manninen, J., Kleimenova, N., Turunen, T., Nikitenko, A., Gromova, L. Fedorenko, Y. (2021). New type of short high-frequency VLF patches ("VLF birds") above 4–5 kHz. J. Geophys. Res., Space Physics, **126**, e2020JA028601

[7] Nickolaenko, A. P., Schekotov, A.Y., Hayakawa, M., Romero, R. and Izutsu, J. (2022). Electromagnetic manifestations of Tonga eruption in Schumann resonance band. J. Atmos. Sol.-Terr. Phys, **237**, 105897

[8] Koronczay, D., Lichtenberger, J., Clilverd, M. A., Rodger, C. J., Lotz, S.I., Sannikov, D. V., et al. (2019). The source regions of whistlers. J. Geophys. Res., Space Physics, **124**, 2019JA026559

# Multipoint observations of whistler-mode waves in plasmaspheric plumes

O. Santolík[1,2*], I. Kolmašová[1, 2], F. Darrouzet[3], J. S. Pickett[4], N. Cornilleau-Wehrlin[5,6]

[1] Department of Space Physics, Institute of Atmospheric Physics, Czech Academy of Sciences, Czechia

[2] Faculty of Mathematics and Physics, Charles University, Czechia

[3] Royal Belgian Institute for Space Aeronomy (IASB-BIRA), Brussels, Belgium

[4] Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA

[5] Laboratoire de Physique des Plasmas, Ecole Polytechnique, CNRS, Palaiseau, France

[6] LESIA, Observatoire de Meudon, Meudon, France

*Corresponding Author: os@ufa.cas.cz

The fleet of four Cluster spacecraft has provided us with multi-point measurements of VLF and ELF waves in the magnetosphere and in the solar wind for almost 22 years, and the operations of this space mission are still ongoing. Complemetary measurements of the Wide band data (WBD) and Spatio-temporal analysis of field flustuations (STAFF-SA) instruments are used in this study to investigate whistler mode emissions in the plasmaspheric plumes.

These natural emissions of whistler-mode electromagnetic waves, especially chorus and hiss can influence the dynamics of the Van Allen radiation belts through quasi-linear or nonlinear wave particle interactions. Therefore, these waves play a role in complex processes of coupling between different electron populations in this region but also in losses of energetic particles by their precipitation into the atmosphere.

The high density regions of plasmaspheric plumes can serve as a natural waveguide for the whistler mode waves which can thus propagate from outer regions into the plasmasphere. We have selected a case in which the Cluster spacefleet observed both whistler mode hiss and discrete nonlinear wave packets of chorus in plasmaspheric plumes. The integrated amplitudes reached up to 200 pT, with median values of 2-40 pT. Our measurements show that these mostly quasi-parallel propagating whistler-mode waves are often generated at low latitudes. Discrete emissions were found in more then one-half of the observed plume intervals. Their amplitudes are significantly higher than amplitudes of hiss.

Detailed analysis of the structures of discrete emissions shows that their intensities and wave vector angles exhibit large-scale spatial variations which are scanned by the orbital motion of the Cluster spacecraft while the onset of discrete emissions is observed by different spacecraft at the same time.

# The Impact of Sudden Stratospheric Warmings and Elevated Stratopause Events on the VLF signal in high latitudes

H. Schneider[1*], V. Matthias[1], D. Banys[1], M. Hansen[1], M. Clilverd[2]

[1] Institute for Solar Terrestrial Physics, German Aerospace Center, Neustrelitz, Germany
[2] British Antarctic Survey, UKRI_NERC,Cambridge, UK

*Corresponding Author: helen.schneider@dlr.de

Sudden Stratospheric Warmings (SSW) and Elevated Stratopause (ES) events are atmospheric wave driven winter phenomena, which lead to significant changes in atmospheric dynamics and temperatures. SSWs are characterized by a sudden warming in the stratosphere by up to 90K and a mesospheric cooling by up to 30K. At the same time the background wind decelerates and can even revers which modifies the vertical mass transport. Occasionally SSW are followed by an ES where the stratopause at 50-60 km vanishes and subsequently reforms in elevated altitude ranges of 70-85 km. This leads to an temperature increase of up to 50 K in mesospheric heights. The temperature changes during a SSW and ES event can have an impact on the VLF signal absorption. In theory a decrease/ increase in temperature can lead to an decreased/enhanced VLF signal aborption due to a decreased/increased collision frequency. Here we want to investigate the impact of a SSW and ES on VLF signals using the VLF signals of three transmitter and receiver combinations, with reflections points located in high latitudes. For the winter 2008/2009 we found an anticorrelation between VLF amplitude pertubations and the temperature at 70 km at midpoint location confirming the theory. We aim to discuss possible mechanisms leading to those observed pertubations in the VLF signals during SSW and ES event.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# GLD360 to RBSP: Mapping the Energy Input of Lightning Generated Whistlers into the Magnetosphere

Alexander D. Shane[1,*], Robert A. Marshall[1], and Alexandra Wold[1]

[1] University of Colorado Boulder, Department of Aerospace Engineering Sciences, USA

*Corresponding Author: alsh7949@colorado.edu

Lightning generated whistlers (LGWs) are VLF waves that can have a significant impact on radiation belt electrons through pitch angle scattering and energization due to resonant wave-particle interactions. The goal of this study is to produce a data-driven map of the electromagnetic energy input into the magnetosphere from lightning in the Earth's atmosphere. From this, the global effect of LGWs on radiation belt electron precipitation can be quantified.

Dechirping [1,2] is a method of detecting LGWs and correcting for the phase dispersion they experience as they travel through the magnetosphere. This automated algorithm can be used to identify the time at which the LGW was generated by a lightning strike. We apply this dechirping algorithm to a list of RBSP burst intervals that contain LGWS. Lightning data from the GLD360 database [3] is used to pair each identified whistler with a lightning strike, using the spacecraft footpoint as a reference for where to search for lightning. The GLD360 data contains the peak current and from this, the energy leaving the ionosphere can be calculated using an illumination model [4] and estimating the ionospheric absorption [5]. We can then compare this to the energy observed at RBSP. Ray tracing of selected case studies will be performed to validate this mapping procedure before extrapolating our results to the entire GLD360 dataset.

**References**

[1] Jacobson, A. R. et al., (2011) Study of oblique whistlers in the low-latitude ionosphere, jointly with the C/NOFS satellite and the World-Wide Lightning Location Network, *Ann. Geophys*

[2] Zheng, H. et al., (2016), A statistical study of whistler waves observed by Van Allen Probes (RBSP) and lightning detected by WWLLN, *J. Geophys. Res. Space Physics*

[3] Said, R. K. et al., (2013), Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations, *J. Geophys. Res. Atmos*

[4] Bortnik J. (2005) Precipitation of radiation belt electrons by lightning-generated magnetospherically reflecting whistlers. *Doctoral dissertation, Stanford University*

[5] Graf K. L. et al., (2013) Analysis of experimentally validated trans-ionospheric attenuation estimates of VLF signals. *J. Geophys. Res. Space Physics*

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Recent results on ionospheric disturbances and EMIC/ELF/VLF waves obtained by ground and satellite measurements by the PWING project

Kazuo Shiokawa[1*], Claudia Martinez-Calderon[1], Yuichi Otsuka[1], Mitsunori Ozaki[2], and the PWING Team[3]

[1] Institute for Space-Earth Environmental Research, Nagoya University, Japan
[2] Kanazawa University, Japan
[3] http://www.isee.nagoya-u.ac.jp/dimr/PWING/en/

*Corresponding Author: shiokawa@nagoya-u.jp

The PWING project (study of dynamical variation of Particles and Waves in the INner magnetosphere using Ground-based network observations) has been conducted since 2016. This project operates induction magnetometers, ELF/VLF wave receivers, all-sky airglow/aurora camera, and riometers at eight stations around the north geomagnetic pole at magnetic latitudes of 60 degrees. PWING's purpose is to elucidate longitudinal development of plasma structures and waves at subauroral latitudes. These ground-based observations have been coordinated with the Arase (ERG) satellite mission to make ground-satellite conjugate measurements of phenomena in the inner magnetosphere. More than 200 publications have been issued by members of the PWING project since 2016. In this presentation, we review results obtained by the PWING network in 2021-2022, particularly for ground-satellite conjugate measurements of ionospheric disturbances and electromagnetic ion cyclotron (EMIC) and electron cyclotron (ELF/VLF) waves.

# Exploration of Earth's Upper Atmosphere by Ground Based Observation of Very Low Frequency (VLF) Waves: Indian Scenario

A. K. Singh[1*]

[1] Department of Physics, University of Lucknow, Lucknow-226007, India

[*]Corresponding Author: aksphys@gmail.com

Ground based observations and research of Very Low Frequency (VLF) waves is being carried out in India since mid of 1960s. Probing potentiality of VLF waves have been used successfully to investigate the Earth's ionosphere and the magnetosphere. As we all know that the radio waves play dual role in the ionosphere because they can impact ionosphere dynamics directly and are also used for monitoring purposes, namely, Inferring medium propagation conditions and characterization. The purpose of this paper is to review briefly some research done on tweeks, whistlers, emissions etc. especially with Indian prospective. The propagation of lightening generated ELF/VLF waves in the ionosphere and magnetosphere provide us with valuable information regarding the physical structure of these regions. Waves propagating through different regions of space carry information about the medium through which they travel. By analyzing the received wave features, it is possible to derive information about the medium such as the electron and proton density, temperature and electric and magnetic field distributions in the medium. The associations of VLF wave with some space weather parameter will also be discussed.

# Role of Mesoscale Convective System (MCS generated Gravity Waves (GWs in Atmosphere-ionosphere coupling

Rajesh Singh[1*]

[1] Dr. KSK Geomagnetic Research Laboratory, IIG, Prayagraj, 221505 India

*Corresponding Author: rajeshsing03@gmail.com

Being involved in the energy and momentum transfer, the Gravity waves (GWs) associated with thunderstorms/lightning discharges during Mesoscale Convective System (MCS) are the important dynamical drivers of the coupling of atmosphere-ionosphere system. Observations suggest that GWs from thunderstorm/MCS convection can reach to the lower ionosphere and upper ionosphere, and hence their simultaneous observations in D-, E- and F- regions during a MCS with multiple instruments at a given location is valuable. In this study, we use simultaneous data from imaging observations of sprites and GWs using a TLE camera, VLF receiver, all-sky airglow imager and GPS receiver located at Prayagraj (25.5° N, 81.9° E), India. We investigated the GWs and associated physical coupling of the D-, E- and F- regions during MCS events and deep depressions during tropical cyclones which occurred during last one decade in North Indian Ocean region. The investigation showed generations of GWs from MCS region in atmosphere, and its subsequent coupling and perturbations in D-, E-, and F-region ionosphere. The D-region shows the presence of GWs with period ~20 mins, in E-region ~15 mins, and in F-region GWs with period ~18 mins are observed during MCS events. The results presented here are important to understand the physical coupling of the troposphere with the lower and upper ionosphere through GWs.

# ULF modulation of energetic electron precipitation in the D-region ionosphere in magnetically quiet time using OCTAVE VLF/LF observations

Kentaro Tanaka[1*], Hiroyo Ohya[1], Fuminori Tsuchiya[2], Kazuo Shiokawa[3], Yoshizumi Miyoshi[3], Mariko Teramoto[4], Kenro. Nozaki[5], Martin Connors[6], and Hiroyuki Nakata[1]

[1]Graduate School of Engineering, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
[2]Tohoku University, Japan
[3]ISEE, Nagoya University, Japan
[4]Kyushu Institute of Technology, Japan
[5]The University of Electro-Communications, Japan
[6]Athbasca University, Canada

[*]Corresponding Author: kentaro.t0905@chiba-u.jp

Energetic electron precipitation (EEPs, >100 keV) from radiation belts to the D-region ionosphere during substorms has been studied since the 1960's using very-low frequency (VLF, 3-30 kHz)/low frequency (LF, 30-300 kHz) transmitter signals and riometers [1]. Modulation of D-region due to EEP by ultra-low frequency (ULF) waves during a substorm was reported [2]. However, there was only one report for the EEP associated with ULF modulation using VLF/LF transmitter signals. In this study, we investigate the EEP event associated with the ULF modulation that occurred on 11:15-11:40 UT on October 9, 2017 (magnetically quiet time), using VLF/LF transmitter signals of "Observation of CondiTion of ionized Atmosphere by VLF Experiment (OCTAVE)" network. The VLF/LF transmitter signals from four transmitters (NLK, NDK, WWVB and NAA, USA) were received at Athabasca (ATH), Canada. We found oscillations in intensities on the NDK-ATH and NLK-ATH paths with a period of 200-300 s during magnetically quiet time in 11:00-12:00 UT on 9 October, 2017. However, the VLF/LF oscillations were not seen on the WWVB-ATHpath.Thecalculationresultsbasedon wave-hop method showed that even if the height decreases due to the EEPs, the electric field strength of WWVB-ATHpathwouldoscillate.Because of the characteristics of the WWVB-ATHpath,weconsideredthatthere were no variations in the WWVB-ATH amplitude during the EEPs. H-component of magnetic field variations (ΔB_H) at ATH and the low latitudes in the wide longitudes also oscillated with the same periods of 200-300 s. The VLF waves and magnetic data were almost in-phase. It is reported that when the solar wind speed is less than 300 km/s, Pi2 pulsations with a long period (> 200 s) is generated by the cavity mode of the magnetosphere [3]. We concluded that the VLF oscillations showed EEPs modulated by Pi2 ULF magnetic pulsation. In this presentation, we will discuss the cause of the VLF/LF oscillations in detail.

## References

1. R. M. Thorne and T. R. Larsen, "An Investigation of Relativistic Electron Precipitation Events and Their Association With Magnetospheric Substorm Activity," *Journal of Geophysical Research: Space Physics*, **81**, pp. 5501-5506, 1976.
2. T. Miyashita, H. Ohya, F. Tsuchiya, A. Hirai, M. Ozaki, K. Shiokawa, Y. Miyoshi, N. Nishitani, M. Teramoto,
M. Connors, S. G. Shepherd, Y. Kasahara, A. Kumamoto, M. Shoji, I. Shinohara, H. Nakata and T. Takano, "ULF Modulation of Energetic Electron Precipitation Observed by VLF/LF Radio Propagation," *The Radio Science Bulletin*, **372**, pp. 29-40, 2020.
3. H.-J. Kwon, K.-H. Kim, C.-W.Jun,K.Takahashi,D.-H. Lee, E. Lee, H. Jin, J. Seon, Y.-D. Park and J. Hwang, "Low-latitude Pi2 pulsations during intervals of quiet geomagnetic conditions (Kp≤1)," *Journal of Geophysical Research: Space Physics*, **118**, pp. 6145–6153, 2013.

# Combined VLF and magnetic observations for improved space situatinal awareness

E.I. Tanskanen[1*]

[1] Sodankylä Geophysical Observatory, Finland

*Corresponding Author: Eija.Tanskanen@oulu.fi

The near-Earth environment is continuously changing by disturbances from external and internal sources. New national infrastructure Earth-Space Research Ecosystem (E2S) will combine measurements from atmosphere to near-Earth and distant space. This combined infrastructure will enable resolving how the Arctic environment change over the seasons, years, decades and centuries. We target our joint efforts to improve the situational awareness in the near-Earth and space environments, and in the Arctic for enhancing safety on ground and in space. This presentation will give details on the Sodankylä geophysical observatory together with large-scale Earth-space infrastructures and research ecosystems, and will give examples on how they can improve the situational awareness in polar regions and improve knowledge on the coupling of the upper and lower atmospheric processed such as lightning and its drivers. Joint VLF campaigns together with continuous observatory-quality magnetic observations make it possible for targeting for the different aspects of the space weather. New magnetic and VLF observations of Earth-Space Research Ecosystem (E2S) at Finnish infrastructure road map enable better coverage of observations in the polar regions. Combined quick-look plots e.g. on auroral substorms, geomagnetic pulsations and VLF emissions enable rapid evaluation of the state of the near-Earth space environment.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Statistical Survey of Arase Satellite Data Sets in Conjunction With The Finnish Riometer Network

Neethal Thomas[1*], Antti Kero[1], Yoshizumi Miyoshi[2], Kazuo Shiokawa[2], Miikka Hyötylä[1], Tero Raita[1] , Yoshiya Kasahara[3] , Iku Shinohara[4] , Shoya Matsuda[3] , Satoko Nakamura[2] , Satoshi Kasahara[5] , Shoichiro Yokota[6] , Kunihiro Keika[5] , Tomoaki Hori[2] , Takefumi Mitani[4] , Takeshi Takashima[4], Kazushi Asamura[4] , Yoichi Kazama[7] , Shiang-Yu Wang[7] , C.-W. Jun[2] , and Nana Higashio[8]

[1]Sodankylä Geophysical Observatory, University of Oulu, Finland,
[2]Institute for Space-Earth Environmental Research, Nagoya University, Japan,
[3]Kanazawa University, Kanazawa, Japan,
[4]ISAS/JAXA, Sagamihara, Japan,
[5]The University of Tokyo, Tokyo, Japan,
[6]Osaka University, Osaka, Japan,
[7]Academia Sinica Institute of Astronomy and Astrophysics, Taipei, Taiwan,
[8]Research and Development Directorate, JAXA, Tsukuba, Japan

*Corresponding Author: neethal.thomas@oulu.fi

During disturbed geomagnetic conditions, the energetic particles in the inner magnetosphere are known to undergo precipitation loss due to interaction with various plasma waves. This study, investigates the energetic particle precipitation events statistically using coordinate observations from the ground riometer network and the inner-magnetospheric satellite mission, Arase. We have compared cosmic noise absorption (CNA) data obtained from the Finnish ground riometer network located in the auroral/sub-auroral latitudes with the comprehensive data set of omnidirectional electron/proton flux and plasma waves in ELF/VLF frequency range from the Arase satellite during the overpass intervals. The study period includes one and a half years of data between March 2017 and September 2018 covering Arase conjunctions with the riometer stations from all magnetic local time sectors. The relation between the plasma flux/waves observed at the satellite with the riometer absorptions are investigated statistically for CNA (absorption >0.5 dB) and non-CNA (absorption<0.5 dB) cases separately. During CNA events, Arase observed elevated electron flux in the medium energy range (2–100 keV), and plasma wave activity in the whistler-mode frequency range (0.5–3 kHz) of the spectra. The study provides an estimate of the statistical dependence of the electron flux and plasma wave observations at Arase with the ground reality of actual precipitation.

# New Perspectives on Wave-Induced Electron Precipitation from Earth's Radiation Belt using Van Allen Probes, MMS, and ELFIN Observations: Insights on Loss Rates and Energy Inputs to Earth's Ionosphere and Atmosphere

Drew L. Turner[1*], Vassilis Angelopoulos[2], and the ELFIN mission team

[1] Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA
[2] University of California, Los Angeles, CA, USA
*Corresponding Author: drew.turner@jhuapl.edu

ELFIN[1] is a satellite mission launched in 2018 consisting of two, identical 3U CubeSats in circular, polar low-Earth orbit (LEO) at altitudes ~450 km. Onboard each spacecraft, the ELFIN prime payloads consist of energetic particle telescopes and boom-deployed fluxgate magnetometers. Each orbit, ELFIN observes energetic electrons ranging from 50 keV to 7 MeV precipitating from Earth's radiation belts and plasma sheet. ELFIN offers the opportunity to study radiation belt and relativistic electron precipitation losses with unprecedented energy resolution and multipoint observations that enable some disambiguation of spatiotemporal evolution. Furthermore, the ELFIN spacecraft are spinners, revealing for the first time details of electron pitch angle distributions within the atmospheric loss cones. In this talk, we will present new results from ELFIN highlighting several enlightening features of relativistic electron precipitation. With simultaneous, multipoint observations from the two ELFINs plus the two Van Allen Probes (RBSP) and Magnetospheric Multiscale (MMS) during the last months of the RBSP mission in 2019, we quantify quiet-time and storm-time losses of Earth's radiation belt electrons due to atmospheric precipitation. We highlight evidence of nonlinear scattering resulting in intense yet stochastic microburst precipitation and evidence of MeV electron losses from interactions with electromagnetic ion cyclotron waves. With the combination of RBSP and MMS in the near-equatorial region and ELFIN observing losses at LEO, we estimate the relative contribution of atmospheric losses as a function of L-shell during quiet and stormy magnetospheric conditions. Furthermore, for those events and others using a combination of ELFIN and MMS only, we employ the excellent energy and pitch angle coverage of the ELFIN data to quantify energy input as a function of altitude from relativistic electrons precipitating into Earth's ionosphere and neutral atmosphere. These cases highlight how relativistic electron precipitation penetrate deep into the ionosphere (D-layer) and further into the neutral atmosphere, with direct energy deposits down to < 40 km altitude and that these energy deposits can far exceed those from auroral precipitation at higher altitudes (E-region ionosphere and thermosphere, ~100 km), during both active and quiet times depending on the current state of the radiation belts. We stress that relativistic electron precipitation must be considered for ionospheric D-region activation and stratospheric and mesospheric chemistry and energy budgets.

**References**

[1] V. Angelopoulos et al., "The ELFIN Mission", *Space Science Reviews*, **216**:103, 30 July 2020, doi:10.1007/s11214-020-00721-7.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Temporal variability of waves and wave-particle interactions in Earth's magnetosphere

Clare E. J. Watt[1*], Hayley J. Allison[2], Sarah N. Bentley[1], R. L. Thompson[3], I. Jonathan Rae[1], Oliver Allanson[4], Nigel P. Meredith[5], Sarah A. Glauert[5], John P. J. Ross[5], R. B. Horne[5], Shuai Zhang[6]

[1] Northumbria University, UK
[2] GFZ German Research Centre for Geosciences, Germany
[3] University of Reading, UK
[4] University of Exeter, UK
[5] British Antarctic Survey, UK
[6] Southern University of Science and Technology, China

*Corresponding Author: clare.watt@northumbria.ac.uk

Kinetic wave-particle interactions in Earth's outer radiation belt energize and scatter high-energy electrons, playing an important role in the dynamic variation of the extent and intensity of the outer belt. It is possible to model the effects of wave-particle interactions across long length and time scales using quasilinear theory, leading to a Fokker-Planck equation to describe the effects of the waves on the high energy electrons. This powerful theory renders the efficacy of the wave-particle interaction in a diffusion coefficient that varies with energy or momentum and pitch angle.

In this presentation we explore the temporal variability of wave-particle interactions in Earth's magnetosphere, focusing on whistler-mode chorus and hiss. Guided by observations from the NASA Van Allen Probes and a range of other missions, we first compile evidence for how whistler-mode waves vary in time and space, and describe new probabilistic models of that variability. Given new interest in event-specific models of wave-particle interactions [1,2], in contrast to statistical models of diffusion coefficients [3], we discuss methodologies for constructing diffusion coefficients from long-term datasets of wave and plasma data [4]. We then explore how the temporal variability of diffusion coefficients on different timescales affects the solutions of the Fokker-Planck equation [5]. Since quasilinear theory involves averaging wave processes in time and space, we discuss how and where we might usefully average observations, and the diffusion coefficients derived from them, in a way that minimizes the uncertainty in solutions of the Fokker-Planck equation.

**References**

[1] Ripoll, J.-F., Santolik, o., Reeves, G., Kurth, W. S., Denton, M. H., Loridan, V., et al. (2017). Effects of Whistler Mode Hiss Waves in March 2013. J. Geophys. Res. Space Phys. 122, 7433——7462. doi:10.1002/2017JA024139
[2] Millan, R., Ripoll, J.-F., Santolik, O. and Kurth, W. S. (2021), "Early-Time Non-Equilibrium Pitch Angle Diffusion of Electrons by Whistler-Mode Hiss in a Plasmaspheric Plume Associated with BARREL Precipitation", Frontiers in Astronomy and Space Sciences, 8, 10.3389/fspas.2021.776992
[3] Horne, R. B., Kersten, T., Glauert, S. A., Meredith, N. P., Boscher, D., Sicard-Piet, A., Thorne, R. M., and Li, W. (2013), A new diffusion matrix for whistler mode chorus waves, J. Geophys. Res. Space Physics, 118, 6302– 6318, doi:10.1002/jgra.50594.
[4] Watt, C. E. J., Allison, H. J., Meredith, N. P., Thompson, R. L., Bentley, S. N., Rae, I. J., et al. (2019). Variability of quasilinear diffusion coefficients for plasmaspheric hiss. Journal of Geophysical Research: Space Physics, 124, 8488– 8506. https://doi.org/10.1029/2018JA026401
[5] C. E. J. Watt, H. J. Allison, R. L. Thompson, S. N. Bentley, N. P. Meredith, S. A. Glauert, R. B. Horne, I. J. Rae, The Implications of Temporal Variability in Wave-Particle Interactions in Earth's Radiation Belts, Geophysical Research Letters, 10.1029/2020GL089962, 48, 1, (2021).

# Lightning generated whistler wave ducting assessment with the Van Allen Probes

Alexandra M. Wold[1*], Robert A. Marshall[1], David M. Malaspina[1, 2], Riley Reid[1] , Grant Berland[1]

[1] University of Colorado Boulder, USA

[2] Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, USA

*Corresponding Author: alexandra.wold@colorado.edu

Lightning generated whistlers (LGWs) are very-low-frequency waves produced when lightning sferics excite whistler mode waves through the ionosphere and into the magnetosphere. LGWs incite pitch-angle scattering and precipitation of trapped energetic electrons, affecting atmospheric chemistry and contributing to the slot region between the radiation belts [1]. Field-aligned plasma density irregularities, or ducts, affect the propagation of LGWs. Ducting can determine where wave energy travels, how long it persists, and which energetic particle populations are exchange energy with a given wave. This project assesses the prevalence of ducted and non-ducted whistler propagation using data from the Van Allen Probes mission.

We utilize burst-mode plasma wave data from the Electric Field and Waves instrument (EFW) and identify all bursts containing LGWs [2]. We apply a filter to isolate the LGW signals. We implement a clustering method to group whistlers with potentially matching lightning sources and further remove noise [3]. We calculate the average wave normal angle (WNA), as well as other wave parameters, of each whistler group using spectral analysis [4].

We use the mean WNA to indicate whether a wave is propagating in a ducted or non-ducted mode. LGWs enter the magnetosphere with low WNAs, close to field aligned. As non-ducted LGWs propagate, the WNA quickly increases as k becomes perpendicular to the background B-field. In the ducted mode, k remains near parallel with the B-field, so the WNA remains small. Supported by ray tracing analysis, we apply a L-shell dependent WNA threshold to identify potentially ducted LGW groups [5]. For selected ducted events, we evaluate local plasma density structures.

Preliminary results show that LGWs favor lower L-shells (within the plasmasphere), and ~20% of EFW bursts at $L < 3$ contain LGWs. Of the bursts containing LGWs, 0.55-15.0% of LGW clusters may be ducted, based on their average WNA and the method for selecting the ducted WNA threshold. We further investigate the dependence of ducting on L-shell, MLT, season, and other geomagnetic parameters.

## References

[1] Xu, W., Marshall, R. A., Kero, A., & Sousa, A. (2021). Chemical response of the upper atmosphere due to lightning-induced electron precipitation. Journal of Geophysical Research: Atmospheres, 126, e2021JD034914. https://doi.org/10.1029/2021JD034914

[2] Wygant J.R. et al. (2013) The Electric Field and Waves Instruments on the Radiation Belt Storm Probes Mission. In: Fox N., Burch J.L. (eds) The Van Allen Probes Mission. Springer, Boston, MA. https://doi.org/10.1007/978-1-4899-7433-4_6

[3] Scikit-learn: Machine Learning in Python, Pedregosa et al., JMLR 12, pp. 2825-2830, 2011.

[4] Santolík, O., Parrot, M., and Lefeuvre, F. (2003), Singular value decomposition methods for wave propaga- tion analysis, Radio Sci., 38, 1010, doi:10.1029/2000RS002523, 1.

[5] Inan, U. S., and Bell, T. F. (1977), The plasmapause as a VLF wave guide, J. Geophys. Res., 82(19), 2819– 2827, doi:10.1029/JA082i019p02819.

VLF • ELF Remote Sensing of Ionospheres and Magnetospheres
10th VERSIM Workshop
Sodankylä, 07 – 11 November 2022

# Lower ionosphere Electron Density and Effective Recombination Coefficients from Multi instrument Satellite Observation s and Ground VLF Measurements during Solar Flares

Vida Žigman[1]*, Marie Dominique[2], Davorka Grubor[3], Craig J. Rodger[4], and Mark A. Clilverd[5]

[1] University of Nova Gorica, Nova Gorica, Slovenia
[2] Royal Observatory of Belgium, Brussels, Belgium
[3] University of Belgrade, Faculty of Mining and Geology, Phys. Cathedra, Belgrade, Serbia
[4] Department of Physics, University of Otago, Dunedin, New Zealand
[5] British Antarctic Survey (UKRI-NERC) Cambridge, UK

*Corresponding Author: vida.zigman@ung.si

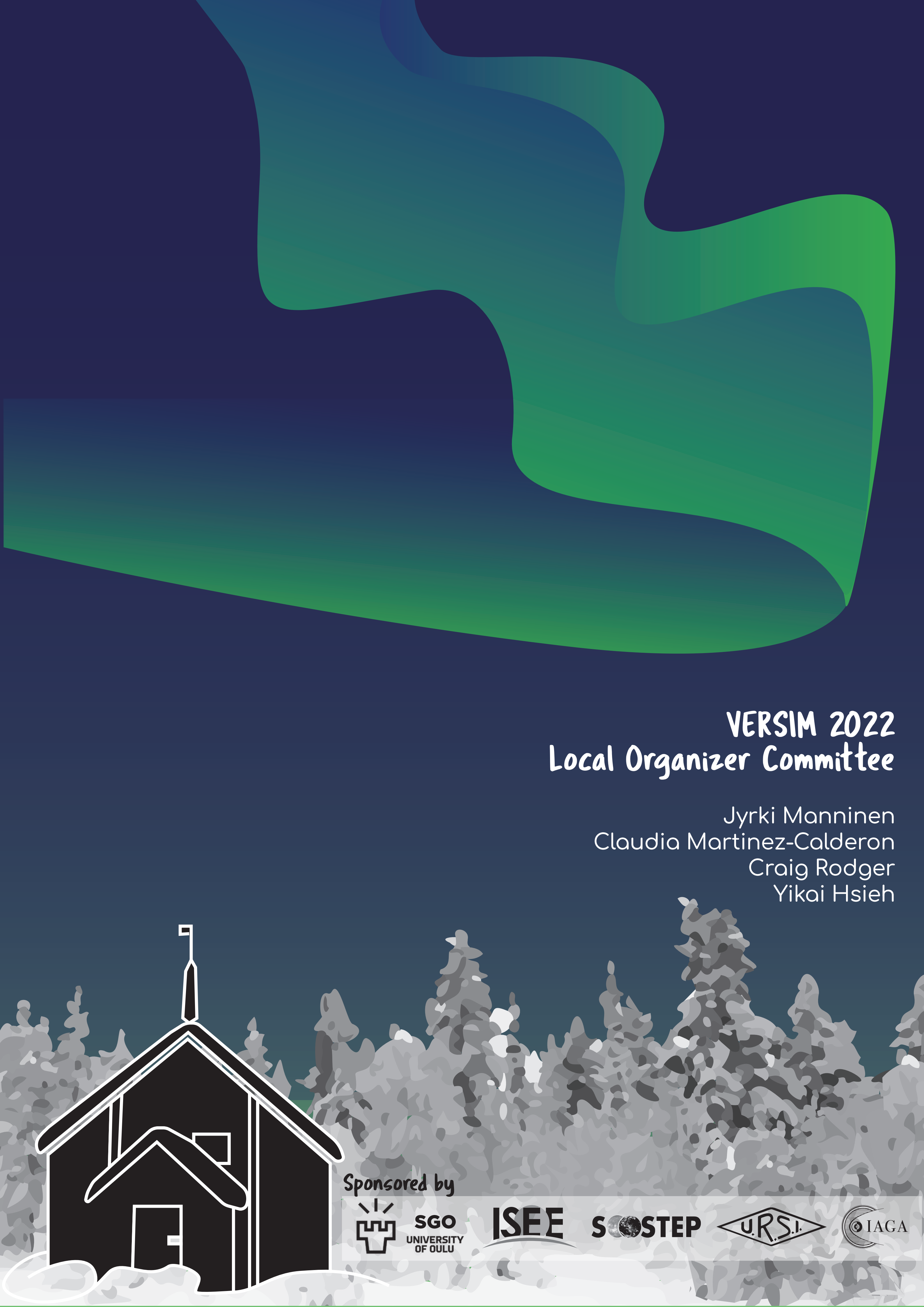
A new model to predict effective recombination coefficients and electron density enhancements during solar flares is put forward. The model relies on space-borne solar irradiance measurements in coincidence with ground recorded man-made Very Low Frequency (VLF), (< 30 kHz) signals. The model computation is based on the coupling of the continuity equation and the Appleton relation [1] and uses the concept of time delay – the time lag of the extreme VLF amplitude and/or phase variation following the flare irradiance maximum. Use is made of irradiance measured by broad-band radiometers on board the satellites GOES, SDO, and PROBA2 over succeeding and partly overlapping wavelength intervals of the instrument bandpasses, altogether covering the wavelengths 0.1-20 nm. At the same time ground-based measurements are taken of the amplitude and phase of VLF signals propagating subionospherically along great circle paths, utilizing four transmitters and two receiving sites.

The aim is to determine the effectiveness of the particular wavelength range, as presented by the instrument bandpass (X-ray and EUV domain), in producing ionization changes in the lower ionosphere (D- region) during solar flares. To obtain a realistic estimate of the ionization efficiency, this is evaluated using the solar spectral irradiance as modelled by the XUV Photometer System Level 4 Algorithm [2] for each flare separately and for each particular bandpass of the three selected instruments.

The solution of the continuity equation predicts the electron density time - height profile in the range 55 -100 km. The analysis of M to X class flares shows that the flare-enhanced electron densities due to a particular ionizing wavelength domain are in good agreement in both the cases: (1) the irradiances are taken over the bandpass of either GOES (0.1-0.8 nm) or SDO/ESP (0.1-7 nm) when the range of heights up to 90 km is considered; (2) either SDO/ESP or PROBA2/LYRA (1-2 +6-20 nm) concerning heights above 90 km. The results agree within 22% in the height range up to 90 km, and differ by at most a factor of 2 above 90 km. Remarkable agreement is shown between measured and evaluated time delay, discrepancies generally amounting to less than 8%. The effective recombination coefficient is deduced from the model itself and is found to be consistent with other independent estimates. These results indicate that our model is a reliable tool in predicting electron density and effective recombination coefficients of the lower ionosphere under flare conditions.

## References

[1] Appleton, E.V., 1953. A note on sluggishness of ionosphere. Journal of Atmospheric and Terrestrial Physics 3(5), 282–284, doi: 10.1016/0021-9169(53)90129-9.
[2] Woods, Thomas N., Chamberlin, Phillip C., Peterson, W. K., et al., 2008. XUV Photometer System (XPS): Improved Solar Irradiance Algorithm Using CHIANTI Spectral Models. Solar Physics, Volume 250, Issue 2, pp.235-267, doi: 10.1007/s11207-008-9196-6.


VERSIM 2022
Local Organizer Committee
Jyrki Manninen
Claudia Martinez-Calderon
Craig Rodger
Yikai Hsieh
Sponsored by
SGO
UNIVERSITY OF OULU
ISEE
SCOSTEP
U.R.S.I.
IAGA