11th VERSIM Workshop

VLF and ELF Remote Sensing of the Ionosphere and Magnetosphere

Breckenridge, Colorado, USA

September 30 – October 4, 2024

FOREWORD

VERSIM is an international group of scientists that are interested in studying the behaviour of the magnetosphere and ionosphere by means of ELF and VLF radio waves, both naturally and artificially generated.

Since 2004, VERSIM workshops have been held every two years in different locations around the world. They are the occasion to present and discuss recent results, new techniques and encourage collaboration within the space physics community, specifically those studying the propagation of VLF and ELF radio waves, or using these waves to probe the ionosphere and magnetosphere.

The 11th VERSIM Workshop is held September 30 – October 4, 2024 at the Village at Breckenridge in beautiful Breckenridge, Colorado. Breckenridge is located in the Colorado mountains, but is less than two hours from the Denver International Airport. The early fall meeting period lines up with the peak of Colorado's changing fall colors.

SCIENTIFIC TOPICS

Talks at VERSIM 2024 were submitted under the following solicited scientific topics:

- Wave-particle interactions
- Wave-induced particle precipitation
- Wave propagation in the ionosphere and magnetosphere
- Results of recent space missions (e.g., Arase, MMS, RBSP)
- Simulations, Data assimilation, and machine learning applications
- Waves in other Magnetospheres
- Active Experiments

LOCAL ORGANIZING COMMITTEE

The VERSIM 2024 meeting was organized by:

- Robert Marshall (University of Colorado Boulder)
- Allison Jaynes (University of Iowa)
- Mark Golkowski (University of Colorado Denver)

Special thanks to Claudia Martinez-Calderon, Jyrki Manninen, and Craig Rodger for providing information about previous VERSIM meetings, as well as suggestions and resources that helped make the conference organization run smoothly.

SUPPORT

Financial support for VERSIM 2024 was provided by SCOSTEP, IAGA, and URSI.

VERSIM 2024 Website:

https://ccar.colorado.edu/versim2024/

1. Schedule at a Glance

All events, including meals, are held in the Elevations Ballroom at the Village at Breckenridge.

	Monday	Tuesday	Wednesday	Thursday	Friday
9:00 AM	Welcome	Chen	Manninen2	Santolik	Bortnik
9:25 AM	Blum	Kang (zoom)	Maxworth	Reddy	Z Li
9:50 AM	Gan	Albert	Marshall	Lichtenberger	Cannon
10:15 AM	Break	Break	Break	Break	Break
10:40 AM	Capannolo (zoom)	Shane	Golkowski1	Kolmosova	Ma2
11:05 AM	Daneshmand	Hartley	Wu	Khatun-E-Zannat	Vankawala
11:30 AM	Manninen1	Hanzelka	Business Meeting	Golkowski2	Ahmadi
12:00 PM	Lunch	Lunch	Lunch	Lunch	Lunch
1:00 PM	Anderson	Usanova		Nemec	Kalliokoski
1:25 PM	Burch	Jaynes		Bernhardt1	Rodger
1:50 PM	Ma1	Hendry		Martinez-Cal	
2:15 PM	George1	Black		Wold	
2:40 PM	Break	Break		Break	
3:05 PM	W Li	Bunting		Clilverd	
3:30 PM	George2	Gokani		Teysseyre	
3:55 PM	Artemyev	Min		Bernhardt2	
4:20 PM	Hua	Kurita		McLennan	
4:45 PM	Zhang	He		Discussion	
5:10 PM	Discussion	Discussion			

Legend:

- Break / Lunch / Other
- Wave Propagation in the Ionosphere
- Wave Propagation in the Magnetosphere
- Wave-particle interactions
- Active Experiments
- Results of Recent Space Missions
- Wave-induced Particle Precipitation
- Waves in Other Magnetospheres
- Sim / Data Assim / ML
- Other

2. Monday, September 30, 2024

7:30 AM: BREAKFAST
9:00 AM: WELCOME

9:25 AM: **Lauren Blum:** *The properties and drivers of bouncing electron microbursts in the inner and outer radiation belts*
9:50 AM: **Longzhi Gan:** *Effects of nonlinear interactions between electrons and whistler-mode chorus waves on precipitation of different timescales*

10:15 AM: BREAK

10:40 AM: **Luisa Capannolo:** *EMIC-Driven Relativistic Electron Precipitation: Properties, Energy Input and Atmospheric Ionization*
11:05 AM: **Lillian Daneshmand:** *Effects of Rising and Falling Tones in VLF Chorus Waves on Pulsating Aurora*
11:30 AM: **Jyrki Manninen:** *VLF bursty-patches at KAN and IST in 2020*

12:00 PM: LUNCH

1:00 PM: **Todd Anderson:** *Dependence of artificial field-aligned irregularities on HAARP heater frequency and beam pattern*
1:25 PM: **Harrison Burch:** *HF-heating modification of the lower ionosphere: A three-pronged approach*
1:50 PM: **Donglai Ma:** *Excitation of whistler waves by electron transverse anisotropy in a laboratory plasma*
2:15 PM: **Harriet George:** *Plasma wave survey from Parker Solar Probe observations during Venus gravity assists*

2:40 PM: BREAK

3:05 PM: **Wen Li:** *Unraveling Whistler-mode Waves and Their Impact on Energetic Electron Dynamics at Jupiter*
3:30 PM: **Harriet George:** *Mapping lightning-generated whistler waves through near-Uranus space*
3:55 PM: **Anton Artemyev:** *Wave-Particle Resonant Interactions in Plasma Injections: View from Low Altitudes*
4:20 PM: **Man Hua:** *Upper Limit of Outer Belt Electron Acceleration and Their Controlling Geomagnetic Conditions*
4:45 PM: **Xiaojia Zhang:** *Precipitation of Relativistic Electrons from the Earth's Plasma Sheet: Wave-Particle Resonant Interactions versus Curvature Scattering*

5:10 PM: DISCUSSION

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The properties and drivers of bouncing electron microbursts in the inner and outer radiation belts

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The radiation belts are a highly dynamic region of the Earth's magnetosphere, with often-unpredictable variations in intensity and spatial extent. Characterization of this variable radiation environment is critical to mitigating spacecraft anomalies often caused by energetic particles. The physical processes controlling the acceleration and loss of trapped relativistic electrons in the radiation belts are complex and there are a number of competing processes that can combine to produce net enhancements or depletions of the belts. Precipitation into the atmosphere has been shown to be an important loss process for energetic particles in Earth's magnetosphere, but when, where, and how much precipitation contributes remain open questions. While radiation belt diffusion models can now reproduce observed acceleration events quite accurately, radiation belt depletion events are often less well-captured. Quantification of precipitation loss, as well as understanding of the physical mechanisms producing it, is thus critical to our understanding of the dynamics of the outer radiation belt.

Through high time resolution MeV electron measurements, here we explore the nature and extent of electron loss to the atmosphere as well as what electromagnetic wave modes may be causing it. In particular, we examine the detailed properties of rapid sub-second precipitation, termed microbursts. Microburst precipitation from the outer radiation belt has long been associated with whistler mode chorus wave activity, due to their similar global distributions and sub-second structure. More recently, such microbursts have also been observed from the inner radiation belt and attributed to interaction with lightning-generated whistler waves. However, despite decades of observations, large gaps remain in our understanding of how, where, and when whistler mode waves produce relativistic electron microbursts.

Using 20ms measurements of >1 MeV electrons from SAMPEX/HILT, we examine the detailed properties of energetic electron microburst precipitation observed in both the inner and outer radiation belts. In particular, we characterize the repetition periods of energetic electron microbursts and identify events termed "bouncing microburst packets," which exhibit a repetition period equal to that of the electron bounce period at their given location. We present the global distributions of such events, observed from both the outer and inner radiation belts, to better determine their properties and drivers. These results improve our understanding of the interaction between MeV electrons and whistler mode waves, including both chorus waves in the outer belt as well as lightning-generated whistlers in the inner.

Effects of nonlinear interactions between electrons and whistler-mode chorus waves on precipitation of different timescales

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Nonlinear interactions between energetic electrons and whistler-mode chorus waves play a crucial role in driving electron precipitation. Phase bunching scatters electrons far from the loss cone into it, creating an additional source of precipitation. Meanwhile, anomalous scattering, which includes anomalous trapping and positive bunching, scatters electrons away from the loss cone, thereby reducing the source of precipitation that originates close to the loss cone. This source is the only one considered in quasilinear theory. This presentation studies the effects of nonlinear interactions between electrons and chorus waves on precipitation on two typical timescales. The shorter timescale ranges from 1 to 2 electron bounce periods, representing the typical timescale of microbursts. The other timescale exceeds tens of electron bounce periods, reaching a quasi-equilibrium state. Test particle simulations and theoretical analyses evaluate both timescales, indicating that nonlinear effects on precipitation are more significant at lower energies in the range of tens of keV. Furthermore, we demonstrate that realistic wave spectra and waveforms diminish the effects of nonlinear interactions close to the loss-cone, leading to simultaneous quasilinear and nonlinear precipitation. Additionally, we discuss the implications of these results on Low-Earth-Orbit (LEO) and stratospheric observations, such as the Balloon Array for Radiation Belt Relativistic Electron Losses (BARREL).

EMIC-Driven Relativistic Electron Precipitation: Properties, Energy Input and Atmospheric Ionization

Luisa Capannolo[1*], Wen Li[1], Robert Marshall[2], Vassilis Angelopoulos[3], Qianli Ma[1,3], Grant Berland[4], Katharine Duderstadt[5], Drew Turner[4], Xiao-Jia Zhang[6], Anton Artemyev[3], Nithin Sivadas[7,8], Murong Qin[1], Xiao-Chen Shen[1], and Miroslav Hanzelka[9]

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Electromagnetic Ion Cyclotron (EMIC) waves frequently occur in the magnetosphere and represent a key player in the loss of energetic electrons from the radiation belts into Earth's atmosphere. EMIC-driven loss is often significant enough to deplete the outer belt electron population on localized radial (L shell) scales. The resulting EMIC-driven precipitation is typically observed for ~MeV electrons, but is also accompanied by sub-MeV precipitation extending down to a few hundred keV.

We have collected a dataset of 144 EMIC-driven electron precipitation events as observed by the ELFIN (Electron Losses and Fields InvestigatioN) CubeSats and analyzed their properties (i.e., location, pitch angle distribution, precipitation efficiency, etc.). These events were selected by leveraging the POES/MetOp observations of nearby 10s–100s keV proton precipitation, which we use as a proxy for EMIC waves. We found that EMIC-driven precipitation is primarily located in the heart of the outer belt (5–8 L shells), from late afternoon through midnight. Precipitation was confined to narrow radial scales (~0.3 L) and its efficiency was weaker at 100–200 keV and progressively stronger up to ~2 MeV.

When precipitating energetic electrons penetrate into Earth's atmosphere, they interact with the ambient molecules and deposit energy in the system. The higher the electron energy, the deeper in the atmosphere the electron deposits its energy. Ionization of the atmosphere is enhanced during electron precipitation, leading to variabilities in ionospheric density and conductivity as well as changes in atmospheric chemistry (i.e., NO_x and HO_x), which may contribute to ozone destruction. We estimate the energy input resulting from EMIC-driven precipitation and we use a comprehensive ionization model known as the Boulder Electron Radiation to Ionization (BERI) model to quantify the ionization rates. EMIC-driven precipitating electrons primarily impact the mesosphere (50–70 km of altitude), with ~70% of the precipitating flux ionizing the atmosphere, while the rest is backscattered.

Our findings are critical to advancing our understanding of the impact of EMIC waves, from delineating the typical properties of the precipitation they drive (i.e., location, intensity, energy input) to quantifying the resulting ionization effects in the atmosphere. This information is essential to account for wave-driven electron precipitation into atmospheric models and ultimately to quantify the impact of EMIC waves on the entire atmospheric system.

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Effects of Rising and Falling Tones in VLF Chorus Waves on Pulsating Aurora

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Previous studies have demonstrated the link between whistler mode chorus waves originating in the equatorial magnetosphere and pulsating aurora. It is understood that lower-band chorus waves serve as a main driver for pulsating aurora through pitch angle scattering of electrons with energies of tens of keV into the loss cone. This work aims to further illuminate the extent of the relationship between VLF chorus and pulsating aurora by investigating the potential impact of sub-second rising and falling tones present in chorus waves on pulsating aurora as well as the processes through which chorus waves are modulated. One theory posits that chorus wave modulation may be due to interactions between ULF waves and the background plasma through mechanisms such as density modulation. This work uses in situ wave and particle data from the Van Allen Probes to study the relationship between these ULF waves and the modulated chorus. Furthermore, this study will connect the wave-particle interactions with concurrent observations of pulsating aurora from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) all-sky imagers in order to provide a clearer picture of the process by which chorus waves are generated and modulated in the magnetosphere as well as how their modulation affects pulsating aurora observed on the ground.

VLF bursty-patches at KAN and IST in 2020

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In October 2023, we decided to study VLF events that occurred during a single year in selected PWING VLF receivers. The best coverage for a statistical study seemed to be in 2020. We therefore selected Istok (IST), Athabasca (ATH), Gakona (GAK), Kapuskasing (KAP), and Maimaga (MAM) for a more in-depth analysis. We use Kannuslehto (KAN) data as a reference.

In this presentation we will compare observed VLF bursty-pacthes at KAN and IST. These are whistler-mode VLF waves detected at frequencies higher than half the local equatorial electron gyrofrequency at the L-shell of the ground station where they are detected. We chose these two stations for an initial analysis as they are the closest in L-shell, with KAN at 5.5 and IST at 6.2 for the year in question. Several very interesting events will be shown.

Dependence of artificial field-aligned irregularities on HAARP heater frequency and beam pattern

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Field-aligned irregularities (FAIs) are plasma density gradient structures in the mid- and high-latitude ionosphere that occur as a consequence of natural plasma turbulence. FAIs may also be generated artificially using an ionospheric heater facility, such as HAARP in Gakona, Alaska. In this case, FAIs are generated by mode conversion of the electromagnetic heater wave into plasma waves when the upper-hybrid resonance is met, heating the ionospheric plasma; the heated plasma then rapidly diffuses away from the heating region along magnetic field lines. In the F-region, this process results in plasma density depletions in field-aligned resonant cavities. When the plasma expelled from the heated region is injected into the plasmasphere, it produces field-aligned plasma density enhancements, commonly referred to as magnetospheric ducts. Ducts, both natural and artificial, may guide VLF whistler waves along field lines in the magnetosphere. Mid- and high-latitude HF heater facilities like HAARP may then be used to generate magnetospheric ducts, enabling precise studies of ducted VLF propagation.

Previous experiments at HAARP have found that heating near the F-region critical frequency (foF2) in the magnetic zenith direction produces the strongest ducting effects, as characterized by SuperDARN backscatter from FAIs and spacecraft measurements of plasma enhancements. However, much of the HAARP heater parameter space remains unexplored in the context of FAI generation.

We conducted several experiments at HAARP with the goal of determining the heater conditions that would result in the strongest SuperDARN backscatter, over the largest geographic region. We used the Kodiak Island SuperDARN radar as the primary means of characterizing FAI intensity and the size of the FAI region. Additionally, a wideband HF receiver was used to capture stimulated electromagnetic emissions (SEE) from the heated region. The ionosphere state was characterized using the ionosondes at Gakona and Eielson, Alaska, as well as the Poker Flat Incoherent Scatter Radar (PFISR).

Here, we present results from experiments undertaken at the HAARP Polar Aeronomy and Radio Science (PARS) summer school in August 2023. We compare FAI region size and intensity generated with different heater beam widths and frequencies relative to the foF2. We also present preliminary findings from recent experiments at PARS in August 2024.

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HF-heating modification of the lower ionosphere: A three-pronged approach

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The propagation of HF radio waves through the lower ionosphere has significant impact on a wide range of human activities from scientific observations such as remote sounding of the ionosphere and VLF wave generation to communications and ranging systems such as over-the-horizon radar. The D-region ionosphere is thought to be responsible for the vast majority of signal absorption for HF waves propagating through the lower ionosphere due to the collisional nature of D-region physics, but other effects such as polar mesospheric summer echoes in HF and VHF radars and anomalous absorption from HF cross-modulation observations highlight the complexity of interactions that are present in the lower ionosphere. Here we present observations from a HAARP HF-heating campaign, which ran from Feb 29 to Mar 03 2024, in which we performed a variety of transmissions with the goal of more thoroughly understanding the nature of HF propagation through the lower ionosphere. These experiments include HF cross-modulation, HF partial reflections from the lower ionosphere, and VLF scattering. More specifically, we will present the reproduction of salient cross-modulation observations made by Langston and Moore 2013 using a new more efficient transmitter programming method, observations of HF partial reflections from the lower ionosphere in the presence of HF heating, and preliminary results of VLF scattering produced by HF heating. If time permits, preliminary observations from the recently completed PARS 2024 HAARP campaigns will also be shown.

Excitation of whistler waves by electron transverse anisotropy in a laboratory plasma

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Whistler-mode waves that are known to play a fundamental role in driving radiation-belt dynamics are excited on the Large Plasma Device (LAPD) by the electron transverse anisotropy for the first time. A trapped electron population with large perpendicular energy is generated in the mirror section by X-mode high power microwave pulses. Whistler waves generated by such sufficient temperature anisotropy are then observed on the LAPD. It is shown that the whistler wave strength is affected by the microwave heating efficiency and can be modulated by the drift hot electrons. Other typical behavior of whistler wave in the inner magnetosphere like frequency chirping and two-band structures are also observed. Further Particle-in-cell (PIC) simulation is performed and such excitation mechanism of whistler wave is confirmed.

The experiment allows us for the first time to study whistler wave excitation by temperature anisotropy which is the most common mechanism for whistler wave excitation in the earth's inner magnetosphere. Further experiments will focus on the controlling factor of these whistler behaviors that similar within the earth’s magnetosphere.

Plasma wave survey from Parker Solar Probe observations during Venus gravity assists

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Parker Solar Probe (PSP) performs Venus gravity assists (VGAs) in order to lower its perihelion. PSP takes high-cadence electric and magnetic field observations during these VGAs, providing the opportunity to study plasma waves in Venus's induced magnetosphere.

This study analyzes plasma wave activity detected by the FIELDS instrument suite throughout the first five VGAs. We summarize the plasma environment during these VGAs, including the regions of near-Venus space that PSP traversed and the key boundary crossings. We comprehensively identify Langmuir, ion acoustic, whistler-mode and ion cyclotron waves during these VGAs and map the location of these waves throughout near-Venus space. We compare the FIELDS instrumentation capabilities to the capabilities of the plasma wave instruments onboard the Pioneer Venus Orbiter (PVO) and the Venus Express (VEX).

We find that the PVO electric field instrument was well suited to observe Langmuir waves, especially near the bow shock and in the foreshock. However, evaluation of the other plasma waves detected by PSP FIELDS revealed that PVO and VEX would have often been unable to observe key features of these waves modes, including maximum power, bandwidth and propagation direction. These wave characteristics provide critical information on the wave generation mechanisms and wave-particle interactions, so provide fundamental information on the nature of Venus's induced magnetosphere. These results highlight the advances in plasma wave instrumentation capabilities that have been made in the decades since the PVO and VEX eras, and illustrate the value of a plasma wave instrument on a new Venus mission.

Unraveling Whistler-mode Waves and Their Impact on Energetic Electron Dynamics at Jupiter

Wen Li[1*], Qianli Ma[1,2], Xiao-Chen Shen[1], and Juno team

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Wave-particle interactions in planetary magnetospheres are crucial for shaping the dynamics of energetic particles. Whistler-mode waves are known for their dual role: they can accelerate energetic electrons to relativistic energies and induce their precipitation into the upper atmosphere. While the influence of whistler-mode waves in Earth's magnetosphere has been extensively studied, their precise impact on energetic electron dynamics in Jupiter's magnetosphere remains elusive.

The Juno mission presents an exceptional opportunity to explore the effects of diverse whistler-mode waves on the dynamics of energetic electrons in Jupiter's magnetosphere. In contrast to Earth, where whistler-mode chorus waves typically occur outside the plasmasphere and hiss waves are predominantly present within it, the Jovian magnetosphere often exhibits the simultaneous occurrence of chorus and hiss waves. In this study, we conduct a comprehensive survey of whistler-mode waves (e.g., chorus, hiss, etc.) in Jupiter's magnetosphere using Juno data. Employing a physics-based modeling approach informed by observed wave and plasma parameters, we quantify the individual and combined effects of chorus and hiss waves on energetic electron dynamics. Our findings are significant as they unveil the typical properties of whistler-mode waves and their influence on energetic electron dynamics, not only on Jupiter but also on other magnetized celestial bodies.

Mapping lightning-generated whistler waves through near-Uranus space

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The presence and occurrence rate of lightning can reveal fundamentally important information about the planetary environment. In order for lightning to occur, atmospheric convection must take place and there must be significant separation of charged particles within the atmosphere. Therefore, lightning provides critical insight to the convection patterns and constituents of planetary atmospheres.

When lightning strikes occur, they generate very low frequency plasma waves called ‘whistlers’ that propagate through the surrounding space environment. These whistlers travel along the magnetic field lines and can be detected by spacecraft with plasma wave instrumentation. The location and properties of these whistler waves can be used to evaluate both the location and intensity of the lightning strikes that generated the waves, and evaluate the magnetospheric plasma environment that the waves travelled through. Detection of lightning-generated whistlers at Uranus can therefore address multiple key science questions listed in the 2023 planetary decadal for the Uranus Orbiter and Probe.

We evaluate the propagation of potential lightning generated whistler waves through the Uranian magnetosphere. We use a simplified two dimensional simulation of Uranus’s magnetosphere and cold plasma environment, and perform ray tracing to evaluate the propagation of whistlers through near-Uranus space. The starting position of these waves is set at the location of the brightest storm ever observed at Uranus, and they propagate through a low-density plasma and a tilted dipole magnetic field. We map these whistlers throughout near-Uranus space and evaluate the probability of in-situ observation of lightning generated whistlers with a plasma wave instrument onboard a Uranus Orbiter.

Wave-Particle Resonant Interactions in Plasma Injections: View from Low Altitudes

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Precipitation of relativistic electrons into the Earth's atmosphere regulates the outer radiation belt fluxes and contributes to magnetosphere-atmosphere coupling. One of the main drivers of such precipitation is electron scattering by whistler-mode waves. Such waves typically originate at the equator, where they can resonate with and scatter sub-relativistic (tens to a few hundred keV) electrons. However, they can occasionally propagate far away from the equator along field lines, reaching middle latitudes, where they can resonate with and scatter relativistic (>500 keV) electrons. Such a propagation is typical for the dayside, but statistically has not been found on the nightside where the waves are quickly damped along their propagation due to Landau damping. In this presentation we explore relativistic electron precipitation from low-altitude observations on the nightside. Combining measurements of whistler-mode waves from ground observatories, relativistic electron precipitation from low-altitude satellites, total electron content maps from GPS receivers, and magnetic field and electron flux from equatorial satellites, we show that plasma sheet injections in the night-side may drive relativistic electron losses. We discuss that wave ducting by plasma density gradients is the possible channel that allows the waves to reach middle latitudes and scatter relativistic electrons. We suggest that both whistler-mode wave generation and ducting can be driven by equatorial mesoscale (with spatial scales of about one Earth radius) transient structures during plasma injections. We suggest that shown results demonstrate the potential importance of mesoscale plasma injections in relativistic electron precipitation. We also compare efficiency of such whistler-driven electron precipitations from the plasma injections with relativistic electron losses due to current sheet scattering and scattering by electromagnetic ion cyclotron waves in the night-side.

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Upper Limit of Outer Belt Electron Acceleration and Their Controlling Geomagnetic Conditions

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The Earth's outer belt electrons with high energies, also known as "killer" electrons due to their deleterious effects on satellites, can be quickly accelerated with fluxes varying up to several orders of magnitude. Historically, these electron dynamics are associated with geomagnetic storms. It remains unclear what is the critical geomagnetic condition that governs the electron acceleration during non/weak storm time. Our study provides the first statistical analysis of electron acceleration events over a wide energy range (300 keV to ~10 MeV) regardless of storm events using 6-years observations from Van Allen Probes. The statistical properties of acceleration events strongly depend on L-shell and energy, which are consistent with the characteristic energies of combined local acceleration by chorus waves and inward radial diffusion. By performing a superposed epoch analysis of acceleration events during storm and non/weak storm events and comparing their geomagnetic conditions, we reveal the strong correlation between accumulated impacts of substorms as indicated by time-integrated AL index (Int(AL)) and the upper limit of electron acceleration. While intense storms can provide favorable conditions for efficient acceleration, they are not necessarily required to produce large maximum fluxes.

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Precipitation of Relativistic Electrons from the Earth's Plasma Sheet: Wave-Particle Resonant Interactions versus Curvature Scattering

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During geomagnetic substorms, energetic electrons in the Earth's plasma sheet, a region in the nightside magnetosphere filled with hot plasma, precipitate to the ionosphere. These energetic electron precipitation (EEP) can affect the density, temperature, and composition of the ionosphere. However, the precise mechanism behind this precipitation remains poorly understood, primarily due to observational constraints. The main challenge lies in simultaneously measuring EEP properties in the ionosphere and the characteristics of plasma and waves in the plasma sheet. Currently, two primary mechanisms have been proposed: whistler-mode wave scattering, which dominates at low latitudes (mapping to the inner magnetosphere), and magnetic field-line curvature scattering, which prevails further towards the poles. In this presentation, we will present several substorm events observed by ELFIN at low altitudes, exhibiting various EEP patterns (including localized precipitation bursts or broad-band precipitation) and different upper energy limits (reaching up to several MeV). Using high-energy-resolution data from ELFIN, we compare the relative importance of energetic electron (50-1000 keV) precipitation caused by whistler-mode wave scattering versus precipitation caused by strongly curved magnetic field lines in the plasma sheet. Furthermore, using data from Swarm, DMSP, and ELFIN, we can pinpoint the location of EEP with energies up to ~ 1MeV, which extends from the plasmapause to the near-Earth plasma sheet. This multi-spacecraft analysis provides valuable insights into the dynamics of these energetic electron precipitation during substorms.

3. Tuesday, October 1, 2024

7:30 AM: BREAKFAST

9:00 AM: **Lunjin Chen:** *Electron microbursts induced by chorus waves*
9:25 AM: **Ning Kang:** *The principal role of chorus ducting for night-side relativistic electron precipitation*
9:50 AM: **Jay Albert:** *Recent developments in QL and NL theories of w-p interactions*

10:15 AM: BREAK

10:40 AM: **Alexander Shane:** *Lightning Generated Whistlers: Variability of Frequency and Wave Normal Angle Distributions*
11:05 AM: **David Hartley:** *Whistler-Mode Waves in Plasmasphere-Plasmatrough Transition Regions and Sheath Effects on Electric Field Observations*
11:30 AM: **Miroslav Hanzelka:** *Acceleration and Losses of Radiation Belt Electrons Driven by Intense Chorus Wave Packets: Comparison of Nonlinear and Quasilinear Paradigms*

12:00 PM: LUNCH

1:00 PM: **Maria Usanova:** *Van Allen Probes observations of EMIC waves in the inner magnetosphere*
1:25 PM: **Allison Jaynes:** *The influence of cold plasma density on radiation belt enhancements*
1:50 PM: **Aaron Hendry:** *Advances in modeling high-L* and midlatitude radiation belt dynamics*
2:15 PM: **Rachel Black:** *Investigating the variability of chorus waves in the Van Allen probes 'burst-mode' data for improved understanding of nonlinear interactions*

2:40 PM: BREAK

3:05 PM: **Kaine Bunting:** *New Chorus Diffusion Coefficients at Geosynchronous Orbit and Beyond*
3:30 PM: **Sneha Gokani:** *Revisiting the geomagnetic storm occurred on 1st March 2024: Excess heating of the thermosphere*
3:55 PM: **Kyungguk Min:** *Can a Parallel Electron Plateau Distribution Generate Chorus Band Gap? Parametric Analysis Using 1D PIC Simulations*
4:20 PM: **Satoshi Kurita:** *Rapid deformation of electron distribution function by whistler mode chorus observed by the Arase satellite: Implications for nonlinear wave-particle interaction*
4:45 PM: **Jiabei He:** *Statistical Analysis of Subpacket Structure in Isolated and Overlapping Chorus Elements*

5:10 PM: DISCUSSION

Electron microbursts induced by chorus waves

Lunjin Chen[1*]

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During magnetospheric storms, radiation belt electrons are produced and then removed on varying timescales. An efficient loss process is microbursts, strong, transient precipitation of electrons into the lower atmosphere over a wide energy range, from tens of keV to sub-relativistic and relativistic energies (100s keV and above). However, the detailed generation mechanism of microbursts, especially over sub-relativistic and relativistic energies, remains unknown. Here, it is showed that these energetic electron microbursts may be caused by ducted whistler-mode lower-band chorus waves. Using combined observations of equatorial chorus waves from Van Allen Probes and electron precipitation from low-altitude ELFIN, the data-driven simulations demonstrate that the observed microbursts are the result of resonant interaction of electrons with ducted chorus waves rather than nonducted ones. Revealing the physical mechanism behind the microbursts advances our understanding of radiation belt dynamics and its impact on the lower atmosphere and space weather.

The principal role of chorus ducting for night-side relativistic electron precipitation

Ning Kang[1*], Anton V. Artemyev[2], Jacob Bortnik[1], Xiao-Jia Zhang[3,2], and Vassilis Angelopoulos[2]

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Night-side chorus waves are often observed during plasma sheet injections, typically confined around the equator and thus potentially responsible for precipitation of <100 keV electrons. However, recent low-altitude observations have revealed the critical role of chorus waves in scattering relativistic electrons on the night-side. This study presents a night-side relativistic electron precipitation event induced by chorus waves at the strong diffusion regime, as observed by the ELFIN CubeSats. Through event-based modeling of wave propagation under ducted or unducted regimes, we show that a density duct is essential for guiding chorus waves to high latitudes with minimal damping, thus enabling the strong night-side relativistic electron precipitation. These findings underline both the existence and the important role of density ducts in facilitating night-side relativistic electron precipitation.

Recent developments in QL and NL theories of w-p interactions

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Quasi-linear theory has long been the standard approach to evaluating the effects of waves on particles throughout the magnetosphere, but it is increasingly acknowledged that this may be inappropriate for large amplitude waves. Standard nonlinear theory involves phase bunching and phase trapping, but in recently this has been supplemented by "positive phase bunching," "anomalous phase trapping," and related particle behavior, especially associated with low pitch angle, e.g. near the loss cone. Analysis of the Hamiltonian for interaction with a single coherent wave can be extended to include these phenomena, though analytical results are still incomplete. Even quasi-linear theory is now being reexamined, due to claims of long-standing "errors" in its implementation.

I will survey recent theoretical developments, which apply to modeling spanning the range from the radiation belts to the aurora to, arguably, atmospheric chemistry.

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Lightning Generated Whistlers: Variability of Frequency and Wave Normal Angle Distributions

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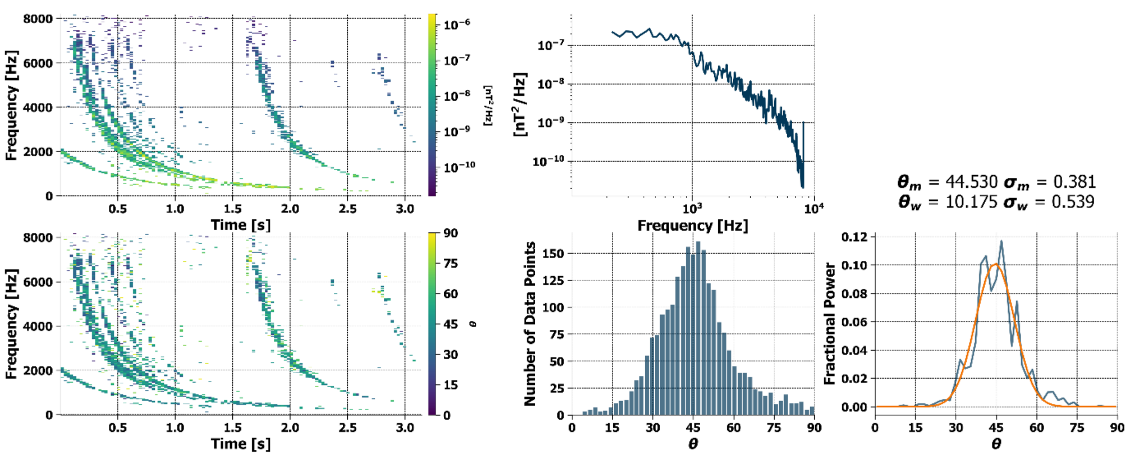
When a lightning strike occurs, very low frequency (VLF) waves emanate from the source region. The majority of the wave energy is trapped in the Earth-ionosphere wave guide, but a non-negligible amount of energy is released into the magnetosphere after ionospheric attenuation. The waves that reach the inner magnetosphere are called lightning-generated whistlers (LGWs). LGWs are important for radiation belt dynamics as they resonantly interact with high energy electrons leading to electron precipitation. LGWs have a major role in the formation and maintenance of the slot region.

Previous calculations of LGW quasi-linear diffusion coefficients are done the traditional way: averaging all the inputs (background magnetic field strength, background thermal electron density, wave frequency distribution, wave normal angle distribution, and wave amplitude) from years of spacecraft measurements. There are severe shortcomings when calculating diffusion coefficients in this manner and the inherent variability of the wave-particle interaction is not captured. In this study, we have analyzed ~83,000 individual LGW events observed by the Van Allen Probes to better understand the variability of LGW wave properties. Preliminary results show that the wave normal angle power distributions are well described by a Gaussian distribution (a common assumption when calculating diffusion coefficients). However, our results show that the width of these Gaussian distributions (per event) is narrow, while previous diffusion coefficient calculations include the entire range of possible values. The frequency power distributions of LGW events are not that variable with about one order of magnitude difference between 25th and 75th percentiles.



<u>Example LGW event</u>: (Top left) Filtered power spectral density. (Bottom left) Filtered wave normal angle. (Top middle) Averaged frequency power distribution. (Bottom middle) Wave normal angle distribution occurrence rate. (Bottom right) Wave normal angle power distribution with Gaussian fit. Fit parameters and associated errors are given in degrees.

Whistler-Mode Waves in Plasmasphere-Plasmatrough Transition Regions and Sheath Effects on Electric Field Observations

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Whistler-mode waves are generally characterized by spatial location and geomagnetic activity. However, the cold plasma density plays a critical role in the observed wave properties and their propagation characteristics. Furthermore, the plasma density is often used as a metric for separating different whistler-mode wave types. Statistical studies, whose results are directly used by the radiation belt modeling community, often make the assumption that all hiss occurs inside of the plasmasphere and all chorus occurs outside of the plasmapause boundary. There is an issue with this assumption: the plasmapause boundary is often (~50% of cases) ill-defined, with weak density gradients that can span large radial distances. When this occurs, chorus and hiss may exist simultaneously. Statistical studies often exclude these data, resulting in whistler-mode wave property databases built only from time periods when the plasmapause is a sharp, well-defined density gradient. Basing predictive models on these cases may introduce a bias towards more elevated geomagnetic activity, and therefore more extreme particle scattering, acceleration, and precipitation. Here, we contrast whistler-mode wave characteristics observed in the case of sharp plasmapause boundaries, with wave properties during the case where a broad transition region exists between the plasmasphere and the plasmatrough.

In addition, a significantly refined approach for the on-orbit quantification of antenna sheath impedance effects will be presented. The antenna sheath impedance and shorting factor for the Van Allen Probes mission have recently been investigated and quantified, however these calculations were somewhat limited in scope due to the requirement for simplifying wave, antenna, and magnetic field geometry. Here, we present a methodology which removes these limitations, offering a more general solution. We present the results of applying this technique to observations of whistler-mode waves made by the MMS mission, conduct comparisons with previous work, and discuss how this methodology could be applied to quantify sheath impedance effects on-orbit during future spacecraft missions.

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Acceleration and Losses of Radiation Belt Electrons Driven by Intense Chorus Wave Packets: Comparison of Nonlinear and Quasilinear Paradigms

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The dynamic evolution of Earth’s outer radiation belt is driven mainly by radial electron diffusion and local scattering by plasma waves. Whistler-mode waves play a dominant role in acceleration of electrons from energies around 10 keV up to 1 MeV and higher. A special type of whistler-mode waves is the lower-band chorus emission, which often displays coherent rising-tone elements with high amplitudes, especially during substorms. Such strong waves can cause large perturbations to particle trajectories and transport them far across the pitch-angle–energy space during a single resonant interaction.

Long-term simulations of the outer radiation belt electron population often rely on the Fokker-Planck equation with bounce-averaged diffusive terms derived from the small perturbation described by the quasilinear theory. Yet, test-particle simulations show a distinctly non-diffusive behavior on short time scales of a few bounce periods (a few seconds for the energetic particles). While it is well known that the bounce-averaged diffusive formalism cannot describe transient phenomena such as microbursts, it is yet to be determined whether the nonlinear behavior on short scales has any impact on the long-term behavior, or if it simply averages out.

To simulate nonlinear scattering of electrons on the scales of minutes to hours, we use backward-in-time test-particle tracing in 4D (energy, pitch-angle, gyrophase, and latitude) and construct phase space density (PSD) maps capturing the nonlinear evolution driven by interaction with a rising-tone chorus element. Repeated application of precalculated maps allows us to simulate the interactions with a long train of heterogeneous chorus elements. The individual elements are described by their duration, frequency range, chirp rate, amplitude, and, importantly, also by their bandwidth and wave normal distribution, which define their subpacket structure. The presence of subpackets and chirp represents the main difference between the models used in particle simulations and the quasilinear simulations, which use an averaged spectrum.

Electron PSD from 2D Fokker-Planck simulations (bounce-averaged equatorial distribution in energy and pitch angle on a single field line) is compared with the test-particle mapping. We show that nonlinear trapping effects drive faster acceleration than predicted by the quasilinear simulations. The bandwidth and WNA distribution affect the pitch angle range of accelerated electrons, and the associated amplitude modulations can increase the trapping probability and subsequently the net acceleration at higher latitudes. Increased acceleration can maintain higher fluxes in the trapped population of 100s keV electrons, leading to higher precipitating fluxes as the strong chorus waves completely fill the loss cone.

Our numerical simulations suggest that the quasilinear theory needs to be modified to properly capture the electron acceleration when intense chorus emissions occur. Rescaling the diffusion coefficients or including weak advective terms are some possible ways to improve the current radiation belt models.

Van Allen Probes observations of EMIC waves in the inner magnetosphere

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Electromagnetic ion cyclotron (EMIC) waves are believed to play an important role in the dynamics of the inner magnetosphere, including the ring current, the radiation belts and potentially, the cold plasma. In this work, we investigate their occurrence in the magnetosphere and the geomagnetic and solar wind conditions which lead to their excitation. We use an automated detection algorithm of EMIC waves observed by Van Allen Probes over the entire mission duration between 2012 and 2019. Consistent with earlier studies, we find that the H^+ band occurrence maximizes in the dayside magnetosphere during enhancements of solar wind dynamic pressure. Both the H^+ and He^+ band are also generated along the duskside magnetosphere during disturbed geomagnetic conditions. In addition, to H^+ and He^+ bands commonly surveyed, we investigate the occurrence of H^+ waves above and below 0.5 H^+ gyrofrequency, as well as wave occurrence in the N^+ and O^{++} bands. Most H^+ waves are observed in the band below $0.5f_{H+}$. We find several events in the N^+ band, indicative of their very low occurrence. The O^{++} band is observed during disturbed geomagnetic conditions at low L-shells. Its radial localization coincides with the O^{++} torus. This study provides a comprehensive picture of EMIC wave distribution and insight into ion composition in the inner magnetosphere during variable geomagnetic conditions.

The influence of cold plasma density on radiation belt enhancements

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The background plasma density in the magnetosphere determines the behavior of wave growth and wave-particle interactions the shape the warm and hot plasma including the ring current and radiation belts. Specifically, the ratio between the cyclotron frequency and the plasma frequency is a critical number that controls these interactions. To assess the potential role of cold plasma density in the formation of radiation belt enhancements, we analyze this ratio over the entirely of the seven-year Van Allen Probes mission to look for statistical patterns in cold plasma density values. We also conduct diffusion simulations to examine how low densities in particular areas of the inner magnetosphere might affect acceleration of radiation belt energy particles, particularly the timescales over which that acceleration occurs.

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Advances in modeling high-L* and midlatitude radiation belt dynamics

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The BAS radiation belt model (BAS-RBM) is a state-of-the-art global model of the Earth's radiation belts. By combining this model with data from flagship radiation belt satellite missions, we have been able to investigate the impact of different wave species on radiation belt electron dynamics, carry out long-term simulations of the radiation belts, and forecast the evolution of radiation belt fluxes up to 24 hours ahead of time.

In our current project, we have been investigating the inclusion of data from additional satellites, such as THEMIS and ERG/Arase, with the intent to extend the coverage of BAS-RBM to higher L* regions and mid-latitude regions. Our intent is for this increased coverage to improve our outputs and forecasts, allowing for better understanding of global radiation belt dynamics, as well as improved knowledge of risks and vulnerabilities for satellite operators from space weather.

In this talk, we will discuss our efforts to extend the BAS-RBM coverage. We will compare and contrast the outputs of the model driven by the different satellites, as well as discuss the sensitivity of the model to variations in the initial and boundary conditions of the model.

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Investigating the variability of chorus waves in the Van Allen probes ‘burst-mode’ data for improved understanding of nonlinear interactions

Rachel Black[1,2*], Oliver Allanson[3,1], Nigel P Meredith[2], and Andrew Hillier[1]

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Earth’s radiation belts can be described by two zones containing energetic charged particles; a more stable inner belt, and a highly dynamic outer belt. Wave-particle interactions have been identified as one of several processes responsible for the dynamics of electron populations within the outer region. Being able to describe these mechanisms is becoming increasingly important, given that the highest energy electrons present a risk to functioning satellites; the number of which is steadily growing.

The most common method used by the international community for reproducing radiation belt dynamics involves Fokker-Planck diffusion models. Whilst, in many cases, these models effectively describe the global changes and interactions within the region, the Fokker-Planck approach depends upon a quasilinear theory. This assumes "small" wave amplitudes; however, recent observations have shown that this assumption may not always hold, with chorus waves being one of the most notable cases of high-amplitude waves. Accounting for this type of wave would require an extension of the modelling to include nonlinear effects.

Within two datasets of differing resolutions, the Van Allen Probe satellites provide multiple years' worth of information on the various waves and background fields inside the radiation belts. In this work, we present preliminary results of investigations comparing the lower resolution ‘survey mode’ data, with the high-resolution ‘burst mode’ data, captured during the mission. In particular, the work focusses on identifying chorus wave events in both datasets and assessing how the underlying variability may alter our interpretations of the wave properties. Utilizing the higher resolution data in conjunction with the survey data allows closer inspection of the larger amplitude waves, and their potential implications for energetic electron dynamics in radiation belt modelling.

New Chorus Diffusion Coefficients at Geosynchronous Orbit and Beyond

Kaine A. Bunting[1], Nigel P. Meredith[1], Sarah A. Glauert[1], Richard B. Horne[1], Jacob Bortnik[2], Qianli Ma[2,3], Ryoma Matsuura[2], Alexander R. Lozinski[2]

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Whistler mode chorus waves play a significant role in the dynamics of Earth's outer radiation belt. These magnetospheric wave emissions contribute to both the loss and acceleration of relativistic electrons. The diffusion rates caused by these waves are traditionally calculated with the use of global models of wave spectra and independent global models of the plasma parameters. However, more recent studies have demonstrated the importance of using co-located observations of the wave spectra and plasma properties. In this study, the distribution of chorus waves, as observed by three Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft — THEMIS-A, THEMIS-D, and THEMIS-E — is investigated in relation to various solar wind parameters and geomagnetic indices. Bounce and drift averaged chorus diffusion coefficients are generated using co-located THEMIS measurements of the wave spectra and plasma properties. We present our latest results that demonstrate the role of equatorial chorus on both acceleration and loss from the plasmapause to high L* (L* ~ 10). The derived diffusion rates are compared, within regions of overlap, with the existing chorus diffusion coefficients derived from Van Allen Probe measurements of the coupled wave spectra and plasma properties, which are more limited in spatial range and do not extend beyond geosynchronous orbit.

Revisiting the geomagnetic storm occurred on 1st March 2024: Excess heating of the thermosphere

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Geomagnetic storms are global event that affect the ionosphere and magnetosphere of different regions differently. On the 1st March 1983, a geomagnetic storm occurred at 18:42 IST. Temperatures of the equatorial thermosphere were obtained from the rocket released vapour clouds during (i) geomagnetically quiet and (ii) just after (<2 hrs) a sudden commencement of the event mentioned. The experiment was carried out using rocket launch from Thumba Equatorial Rocket Launching Station, Thumba, India. Excess heating in the thermosphere during a geomagnetic storm on 1st March 1982 was observed. To find the excess heating on that day, the interplanetary conditions are checked. A deep depletion in electron flux of energy, E > 2 MeV at geostationary orbit. The wave data is also analyzed, and chorus activity was found. As space observations are limited, the authors are trying to model the conditions prevailing at that time. The possible reasons will be discussed during the conference.

Can a Parallel Electron Plateau Distribution Generate Chorus Band Gap? Parametric Analysis Using 1D PIC Simulations

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Chorus waves with a gap in intensity near half the electron cyclotron frequency, $f_{ce}/2$, are ubiquitous in the inner magnetosphere, especially near the magnetic equator. Although its presence has been known for a long time, how the power gap is formed remains an open question. One hypothesis invokes the often-observed feature in electron phase space density where two anisotropic populations of warm and hot temperatures, respectively, are separated by a relatively isotropic beam-like component, called the parallel plateau. According to linear theory, it can lead to cyclotron damping in a narrow frequency range near $f_{ce}/2$. Observationally, Chen et al. (2023) reported that banded chorus events are typically accompanied by a more enhanced plateau-like component, with a weak correlation between the gap frequency and beam speed, thereby corroborating the said hypothesis. To test this theory more quantitatively, we carry out multiple one-dimensional particle-in-cell simulations in a parabolic magnetic field with varying plateau density and beam speed. Because of the scale difference between the electron gyro-radius and the curvature radius of Earth's magnetic field line, all simulations are scaled down by a factor of eight to save the simulation time; but otherwise, the plateau population in the simulations was faithfully constrained by the observed parameters. The results show that lower band rising elements can be blocked at the gap with a sufficiently large plateau density ($> \sim 0.002\, n_e$), as well as with carefully chosen two anisotropic populations. However, the minimum density required is somewhat large, and even then, the lower band blocking at the gap is not 100% effective. Investigation on the dependence on beam speed is underway and the simulation results will be available in due course. We will discuss the viability of the plateau-driven gap formation by drawing a comparison between the present findings and the recent observational results.

Chen, H., Chen, R., Gao, X., Lu, Q., Ke, Y., & Kong, Z. (2023). Unraveling the role of electron plateau distributions in the power gap formation of chorus waves: Van Allen Probes observations. *Geophysical Research Letters, 50*, e2023GL102748. https://doi.org/10.1029/2023GL102748

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Rapid deformation of electron distribution function by whistler mode chorus observed by the Arase satellite: Implications for nonlinear wave-particle interaction

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We report on deformation of electron distribution functions associated with whistler mode chorus waves observed by the Arase satellite. The deformation is characterized by a flux increase of 17 - 40 keV electrons in a narrow and oblique pitch angle range and by flux decrease of 7 - 17 keV electrons in a lower pitch angle range than that of the flux increase. Comparison of changes in electron pitch angle distributions with resonant ellipses of the whistler mode chorus waves shows that the deformation appears where effective wave-particle interaction is expected in the velocity space, and the flux increase takes place along the resonant ellipse of the upper frequency of the wave. This fact strongly suggests that the deformation is a consequence of wave-particle interactions between electrons and upper-band chorus waves. The Arase observation demonstrate that the deformation occurs within 30 seconds, which is faster than expected from the quasi-linear diffusion theory. A test particle simulation is performed by using the Arase observations as the input parameters of the simulation. The result indicates that the electron flux enhancement within 30 seconds can be explained by nonlinear acceleration of electrons caused by chorus emissions. Thus, we conclude that the observed flux increases result from the nonlinear wave-particle interaction between electrons and whistler mode chorus waves.

Statistical Analysis of Subpacket Structure in Isolated and Overlapping Chorus Elements

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The rising tone chorus elements show a fine structure consisting of multiple subpackets with varying amplitudes and durations. The corresponding wave amplitude modulation could affect the nonlinear interaction between waves and electrons. It has been suggested that subpackets could be formed by wave beating through the superposition of a few narrow-band chorus waves, or it is an inherent part of the nonlinear generation process. In this study, we use 8-year data from Van Allen Probe A to statistically analyze the subpacket structure of isolated individual and overlapping chorus elements, respectively, to separate the characteristics due to the two different mechanisms of chorus subpacket formation. We find that during active conditions, isolated chorus elements are observed more frequently on the nightside and dawnside, corresponding to the shorter repetition time. Conversely, overlapped chorus elements dominate on the dayside due to small frequency difference between the overlapping segments, facilitating wave superposition inside packets. Additionally, we compare the properties of both types, including packet size, frequency chirping, and wave amplitude. Our findings reveal that the packets of isolated waves tend to exhibit longer duration and larger amplitude and show good agreement with the nonlinear theory of chorus wave growth, while wave superposition effects play a role for short chorus subpackets.

4. Wednesday, October 2, 2024

7:30 AM: BREAKFAST

9:00 AM: **Jyrki Manninen:** *Last minutes of the KAN receiver*

9:25 AM: **Ashanti Maxworth:** *Modelling the Equatorial D-Region Ionospheric Plasma Density using Tweeks Observed in Sri Lanka*

9:50 AM: **Robert Marshall:** *The CANVAS CubeSat Mission: Observing Lightning-Generated Whistlers and VLF Transmitters from Low-Earth Orbit*

10:15 AM: BREAK

10:40 AM: **Mark Golkowski:** *VLF Remote Sensing of the Lower Ionosphere during the April 8, 2024 Solar Eclipse*

11:05 AM: **Dong Wu:** *Global D-Region Electron Density Distribution and Diurnal Variations from GNSS-RO*

11:30 PM: BUSINESS MEETING: All are invited!

12:00 PM: LUNCH

6:00 PM: CONFERENCE BANQUET: Twist Restaurant

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Last minutes of the KAN receiver

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In 1992, a very sensitive ELF-VLF receiver was built at Sodankylä Geophysical Observatory with the largest receiver antenna at the time (1000 m2 effective area). Theoretically, it was able to detect wave intensities as weak as 100 aT (=100×10^{-18} T), but after calibration its detection threshold was determined to be 88 aT. This meant that our receiver was the most sensitive ELF-VLF receiver in the world.

Originally the receiver was used only during special campaigns in the 1990s and early 2000s. Until 2005, data was recorded into VHS stereo videotape audio tracks, and from that autumn we tested digital recording. At first, we used a sampling frequency of 39062.5 Hz (= GPS 10 MHz frequency divided by 256), but since autumn 2006 the frequency was doubled to 78125 Hz, and the location of our receiver was changed to Kannuslehto (KAN).

We organized a ‘goodbye’ campaign in March-April 2011, because prof. Tauno Turunen was retiring in the beginning of June 2011. The main purpose of this campaign was to transfer the necessary practical information from Tauno to Jyrki. Fortunately, Tauno was eager enough to join our campaigns until 2016.

Since then, our campaigns have usually started in early September, and ended the following spring in April or May. We replaced our aluminium antenna masts by wooden ones. Even then we were worried about thunderstorms, so we kept our summer break from May till early September. In 2022, our former PhD student Liliana Macotela asked if we could continue our campaigns over the summer to get some important data for her. We had successful summer recordings in 2022 and 2023, and while data was strongly masked by sferics, everything worked.

Unfortunately, an exceptional strong thunderstorm appeared over Finland in May 2024, and this were too much for the KAN receiver. On 28 May 2024 at 1516:16 UT KAN NS antenna mast was hit by a strong lightning stroke that evaporated a steel wire keeping the antenna loop near the top of the mast. The rest of the story will be presented in the workshop.

Figure: North-South antenna after lightning hit the left mast.

Modelling the Equatorial D-Region Ionospheric Plasma Density using Tweeks Observed in Sri Lanka

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The tweek atmospherics or in short tweeks are generated due to the lightning strokes. These tweeks are within the extremely low frequency (ELF: 300Hz – 3kHz) or very low frequency (VLF: 3kHz – 30kHz) phenomenon hence can be captured by the magnetic loop antennas used as ELF/VLF receivers. Given that these waves are lower than the ionospheric D-region plasma frequency, they propagate within the Earth-ionosphere waveguide (EIW) in different modes.

The transverse electromagnetic (TEM) mode propagates within the speed of light and in this mode all frequency components arrive at the receiver at the same time. But the transverse magnetic (TM) modes show dispersion at the cutoff frequency for that mode. The tweeks propagating in the TM modes are identified by their dispersion characteristics (resembling a hockey stick) in a spectrogram. Based on the ionospheric reflection height and density, these tweeks can propagate in multiple modes. Based on the cutoff frequencies of each mode, we can profile the D-region ionospheric density with respect to the altitude.

This work analyzes the equatorial D-region ionosphere using the midnight tweeks observed in Sri Lanka. The ELF/VLF receiver station in Peradeniya, Sri Lanka (7.27°N, 80.59°E) is currently the closest ELF/VLF station to the equator.

According to our preliminary results there is a very high occurrence of tweeks in the equatorial ionosphere due to the high amount of lightning activity. The strong intensity of these tweeks allow them to propagate within the Earth ionosphere waveguide showing multiple modes. The highest mode observed so far is m=7. Up to mode 5, the reflection heights and the electron densities derived based on these cutoff frequencies are within a similar range with the previously published for the mid and low latitude regions. Currently we are continuing data analysis focusing on modes 6 and 7 to verify the reflection heights and to observe the signatures of plasma bubbles and the atmospheric compression.

The CANVAS CubeSat Mission: Observing Lightning-Generated Whistlers and VLF Transmitters from Low-Earth Orbit

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The Climatology of Anthropogenic and Natural VLF wave Activity in Space (CANVAS) CubeSat mission will make continuous measurements of VLF wave activity from low-Earth orbit. These measurements aim to provide a global picture of VLF wave injection from the ground, primarily due to lightning and VLF transmitters, into the magnetosphere, covering frequencies from 0.3 to 40 kHz. The mission will quantify the energy injected into the magnetosphere from below; assess the wave-normal angles of injected waves; and quantify the transionospheric absorption of these VLF waves, by utilizing conjunctions with ground- based VLF receivers. CANVAS is a 4U CubeSat form factor, and the mission is currently scheduled to launch in September 2025 from Vandenberg, California, into a 70-degree inclination orbit at 475 km altitude.

To enable measurements of VLF waves, a five-channel VLF receiver has been developed to fit within a CubeSat form factor. Three components of the magnetic field are measured using three 9.5 cm-long search coils, mounted on the end of a 1-meter deployable carbon fiber boom. The boom, deployment mechanism, search coils, integrated preamplifier, and holder fit in under 2U volume. Two channels of electric field are measured by four 40 cm deployed rigid antennas, creating two orthogonal dipoles 90 cm in length tip-to-tip. These antennas deploy using a simple hinge mechanism built into the CubeSat top panel, with an integrated preamplifier board. The instrument electronics include analog amplifiers and anti-alias filters, ADC drivers, and ADCs for each channel, which feed a single FPGA for data processing. All electronics fit on two 90 × 94 mm PCBs, together using only 0.2U volume. Onboard processing in the FPGA reduces the data to 1-second spectra and cross-spectra with 57 log-spaced frequency bins, plus ten bins dedicated to known VLF transmitter frequencies. This processing reduces the data to about 200 MB per day, enabling downlink of continuous data. Both instrument components have been built and tested in their flight-ready configurations, and are undergoing integration into the CANVAS spacecraft. In this talk we present an overview of the CANVAS mission science goals; the design and development of the spacecraft; and the instrument design and performance, demonstrating the capability of high-quality VLF measurements in a CubeSat form factor.

VLF Remote Sensing of the Lower Ionosphere during the April 8, 2024 Solar Eclipse

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Solar eclipses provide rare opportunities to study the short timescale dynamics of the physical and chemical processes of the ionospheric D-region. Past work has shown that the D-region density decreases as solar radiation is blocked by the moon, but the gradients and spatial structure of the ionospheric electron density has not been fully determined. We use the full solar eclipse across the eastern United States in April 8, 2024 to collect new multi-point ELF and VLF observations. We utilize ELF and VLF receivers to achieve strategic transmitter-receiver geometries relative to the eclipse trajectory to characterize the D-region structure and dynamics in and near the totality zone, improving the spatial resolution of past works to characterize (1) how steep the electron density gradients in the vicinity of totality; (2) the observed ionospheric perturbations when the region of totality is near a powerful VLF transmitter; (3) the lower ionosphere characteristic reaction time to a point like perturbation from the eclipse.

Global D-Region Electron Density Distribution and Diurnal Variations from GNSS-RO

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A new retrieval of global D-region electron density (N_e) from the high-rate GNSS radio occultation (RO) observations is available from recent SmallSat/CubeSat constellations. The much improved spatiotemporal sampling reveal many interesting features in the diurnal, seasonal, solar-cycle, and magnetic-field-dependent variations in the D-region N_e. The GNSS-RO N_e observations were compared to the 2-parameter model for the best fitted reference height H' (km) and exponential growth rate of N_e with height or β (km^{-1}), as used widely by the VLF/ELF observation community. The fitted H' from GNSS-RO shows a similar daytime variation of 70-73 km, compared to 71-77 km from VLF. However, the GNSS-RO β parameter shows a little variation around 0.31 km^{-1} during day, compared to 0.25-0.4 km^{-1} as reported from the VLF observations. For nighttime, the GNSS-RO H' and β values are also lower, with H' varying between 71 and 76 km compared to 82-86 km from VLF, and β varying between 0.29 and 0.30 km^{-1} compared to 0.4-0.6 km^{-1} from VLF. Because the H' and β parameters are strongly coupled in the parameterized model, a further reconcile of the differences between GNSS-RO and VLF D-region N_e observations is needed.

Reference:

Wu, D.L.; Emmons, D.J.; Swarnalingam, N. Global GNSS-RO Electron Density in the Lower Ionosphere. Remote Sens. 2022, 14, 1577. https://doi.org/10.3390/rs14071577
https://www.mdpi.com/2072-4292/14/7/1577

5. Thursday, October 3, 2024

7:30 AM: BREAKFAST

9:00 AM: **Ondřej Santolik:** *Analysis of Poynting flux of whistler mode waves in the inner magnetosphere*

9:25 AM: **Amani Reddy:** *Whistler Mode Remote Sensing of Field-aligned Ion densities: Measurements of O+/H+ Transition Height as a Function of L-shell*

9:50 AM: **János Lichtenberger:** *Experimental evidences for generation of plasmaspheric hiss by whistlers echos and triggered emissions*

10:15 AM: BREAK

10:40 AM: **Ivana Kolmašova:** *Unusual lightning whistler echo train observed by the Cluster spacecraft within an interval of quasiperiodic emissions*

11:05 AM: **Raahima Khatun-E-Zannat:** *Modeling Whistler Mode Wave Propagation Using Ray Tracing and Full Wave Methods*

11:30 AM: **Mark Gołkowski:** *Determination of ELF Signal Azimuth and Diffraction from Ionospheric Gradients*

12:00 PM: LUNCH

1:00 PM: **František Němec:** *VLF Transmitter Signals and Propagation Observed by Spacecraft*

1:25 PM: **Paul Bernhardt:** *Avoidance of Satellite Damage with the Use of VLF Plasma Waves in Space for Reduction of Energetic Particle Fluxes and Detection of Harmful Space Debris*

1:50 PM: **Claudia Martinez-Calderon:** *First results from VLF-CHAMP: Analyzing Latitudinal Propagation and Characteristics of VLF Waves in Finland*

2:15 PM: **Alexandra Wold:** *Trans-ionospheric propagation and attenuation of very low frequency waves*

2:40 PM: BREAK

3:05 PM: **Mark Clilverd:** *Ionospheric D region: Characteristics near Dawn and Dusk*

3:30 PM: **Pauline Teysseyre:** *Effect of ground conductivity on VLF propagation*

3:55 PM: **Paul Bernhardt:** *VLF Chirp Sounding of the Auroral Electrojet and the D-Region with HAARP*

4:20 PM: **Jodie McLennan:** *Determining Size of a Precipitation Event with AARDDVARK system of VLF radio wave receivers*

4:45 PM: DISCUSSION

Analysis of Poynting flux of whistler mode waves in the inner magnetosphere

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The Poynting theorem can be used to investigate the energetics of the interactions of electromagnetic waves with charged media. The energy flux carried by the electromagnetic waves, defined by their Poynting vector, may be dissipated into the medium and/or stored in the electromagnetic field. If the energy density of the electromagnetic field doesn't substantially change, then a positive divergence of the Poynting vector indicates plasma instabilities as sources of these waves. Conversely, a negative divergence of the Poynting vector indicates the opposite energy transfer, into heating of the plasma medium by the absorption of waves.

Experimental determination of the Poynting vector in space plasmas relies on simultaneous measurements of magnetic and electric components of the analyzed electromagnetic waves, and on capturing their amplitude and phase relations. It was previously demonstrated by the measurements of the Polar spacecraft that electromagnetic whistler mode chorus waves in the plasma trough systematically show a positive divergence of the Poynting vector close to the geomagnetic equator. This was later confirmed by multipoint measurements of the Cluster spacefleet. Moreover, the dataset collected by the Polar spacecraft demonstrated that a reabsorption of approximately 1% of the Poynting flux of chorus could be sufficient to explain the observed flux increases of relativistic electrons in the outer Van Allen radiation belt on the timescale of days. No such analysis has yet been done for the plasmasphere, which is known to be constantly filled by the electromagnetic radiation of whistler-mode plasmaspheric hiss.

Continuing the efforts of the late Craig Kletzing, we analyze the data set collected by the EMFISIS Waves instrument on Van Allen Probes to investigate the Poynting flux of whistler mode waves in the inner magnetosphere. As the density-dependent sheath effects play a significant role in the measurements of the wave electric fields, we use a newly developed method to recalibrate the data using the local plasma density estimated from the upper hybrid resonance. We analyze the entire operational period of both Van Allen Probes to obtain accumulated spatial distribution of the Poynting vector with respect to the plasmapause position. Our results indicate a negative divergence and a possible heating of the equatorial plasmasphere by the hiss waves, while we confirm that the outer zone shows the positive divergence and hence sources of whistler mode waves in the equatorial region.

Whistler Mode Remote Sensing of Field-aligned Ion densities: Measurements of O+/H+ Transition Height as a Function of L-shell

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Knowledge of the electron and ion densities profiles along geomagnetic field lines and O^+/H^+ transition height is required to understand processes such as plasmasphere erosion and refilling, dynamics of the topside ionosphere, ionospheric outflows, magnetospheric particle precipitation, wave-particle interactions that regulate the response of the coupled magnetosphere-ionosphere-thermosphere (MIT) system and plasmasphere dynamics. Whistler mode echo propagation paths are close to geomagnetic field lines (B_0). Therefore, unlike other space- and ground-based methods, Whistler mode (WM) radio sounding from the IMAGE satellite has provided a new measurement technique that, for the first time, permitted remote sensing of electron and ion density profiles along field lines and thus the O^+/H^+ transition height [Sonwalkar et al., 2011]. These measurements, combined with advanced physics-based model simulations, provide a powerful new approach [Reddy et al., 2018] to determine the underlying processes that play a role in the storm-time dynamics of the highly-coupled MIT system.

We present O+/H+ transition height measurements as a function of L-shell on the dayside (MLT~13) and nightside (MLT~1) during a geomagnetically quiet to moderate period (23 September to 06 October 2005 period; $1 < Kp < 4^-$). The transition height measurements were obtained using the field-aligned ion density profiles deduced from analyzing whistler mode echoes observed on the IMAGE satellite. Our results show that during the daytime, transition height increases rapidly with L-shell from 900 km at L~1.7 to 1400 km at L~2.8, whereas during the nighttime, there are no significant changes in the transition height with L-shell. Transition height at nighttime resided at ~600-650 km in the L-shell range of ~2.0 to 3.5. During the daytime, solar radiation and photoionization lead to photodissociation of atomic oxygen generating O^+, whereas during nighttime, lack of radiation and ionization results in continuous chemical loss of O^+ in the F-region. Thus, the transition height during daytime is greater than that at nighttime.

Our measurements of O^+/H^+ transition heights are consistent with near-simultaneous DMSP satellite measurements of the O^+/H^+ ratio at 850 km. Our results of transition height variation agree with past in situ measurements of transition height from satellites and measurements from incoherent scatter radar. WM sounding measurements of nightside transition height in the $2 < L < 3.5$ and dayside measurements for $L < 2.5$ agree with those predicted by the IRI model. Above $L > 2.5$, WM sounding measurements are lower than those predicted by IRI.

Possible factors that influence the transition height as a function of latitude include: (1) neutral winds, (2) O^+ to H^+ charge exchange reactions, (3) plasma temperature, and (4) E x B drifts. Our measurements of transition height combined with physics-based model simulations such as SAMI2/SAMI3 will provide a unique way to determine the thermospheric processes that control plasma flow along the geomagnetic field lines and relative contributions of variations in ionospheric/thermospheric parameters (e.g., electric field, neutral winds, neutral densities, and temperature) to the flow of ionospheric and magnetospheric plasma. We plan to discuss our preliminary findings on comparing WM sounding with SAMI2 simulations and the extension of this study to storm time dynamics of the plasmasphere and MIT system.

References

1. Sonwalkar, V. S., A. Reddy, & D. L. Carpenter (2011), J. Geophys. Res., Space Physics, 116, A11211.
2. Reddy, A., Sonwalkar, V. S., & Huba, J. B. (2018), J. Geophys. Res., Space Physics, 123, 1356–1380.

Experimental evidences for generation of plasmaspheric hiss by whistlers echos and triggered emissions

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The origin of plasmaspheric hiss is still not fully known. There are several widely accepted theories such as growth and amplification of background electromagnetic turbulence, chorus wave propagating to the plasmasphere, finally evolving to hiss and the evolution of a spectrum of electromagnetic waves generated by lightnings. None of them is fully proved by experimental evidences and most probably, there are more then one mechanisms, they are operating parallel.
We have found experimental evidences for hiss generation in ground based VLF data by whistlers. Recordings of AWDANet (Lichtenberger et al, 2008, JGR) exhibit long series whistler echos. The amplitude of echos are maintained/amplified that assumes gaining energy from wave-particle interaction. The echos last for minutes and overlapping each other, gradually forming a wide noise band, hiss. The band corresponds to whistler frequency band, 3-10kHz.
Beside whistler echos, emissions triggered by the whistlers also lead to hiss structure, often mixed with hisses generated by whistler echos.
The events happen not only in disturbed period (during storms and substorms,) but during geomagnetically calm periods as well.

Additionally, there is another point: the vast majority of hisses generated by whistler echos and triggered emissions were recorded by the AWDANet station in Dunedin, New Zealand. Only a few exceptions were found at Rothera, Antarctica, while the whistler activity in the World is the highest in the Antarctic Peninsula. The number of whistlers detected by AWDANet in Rothera is more than twelve times higher then the one in Dunedin. One may expect a similar ratio in the hiss generation, but it is not the case. A similar exclusive characteristic of the plasmasphere around the magnetic longitude of New Zealand were already reported at Kyoto VERSIM.
These may lead to the assumption of the violation of cylindrical symmetry of the torus like shape of the plasmasphere and/or the outer radiation belt – at least in certain cases.

Unusual lightning whistler echo train observed by the Cluster spacecraft within an interval of quasiperiodic emissions

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We present observations of long duration echo trains of lightning whistlers which occur within an interval of intense quasiperiodic emissions. These trains were observed by the WBD instruments on all four Cluster spacecraft in the plasmapause density gradient region during the close separation interval on 23 April 2002. The time-frequency spectrograms of recorded whistler emissions show that the traces of whistlers are clearly divided in two parts around a frequency of about 3.5 kHz. The lower frequency parts of the whistlers arrived to the Cluster spacecraft by about two seconds later than the higher frequency part. This leads to unusual gaps in the whistler traces. We did not observe these gaps 20 minutes earlier when the WBD instrument onboard Cluster 1 recorded a similar echo train of lightning whistlers.
The ray tracing analysis reveals that whistlers in the unusual echo train were propagating within a ducting density structure with a density sharp variation. The whistlers propagating southward were surprisingly detected at frequencies above one half of the equatorial cyclotron frequency which might indicate the absence of the duct in the low latitude region.

Modeling Whistler Mode Wave Propagation Using Ray Tracing and Full Wave Methods

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Magnetospheric chorus waves play a dominant role in accelerating high energy electrons and in precipitating energetic electrons in the radiation belts. Numerous simulation techniques have been employed to investigate chorus wave propagation, among which ray tracing theory has been the most commonly utilized method.

Ray tracing theory treats propagating waves as discrete rays and has been successful in explaining various observed phenomena of the propagation of chorus waves within the magnetosphere. In a smooth magnetosphere, ray theory predicts a linear increase in wave normal angle with latitude for chorus waves generated at the equator. However, in the presence of magnetospheric ducts observations show the wave normal angles are lower on average at high latitudes, and the waves exhibit parallel propagation. Magnetospheric ducts can effectively guide whistler-mode waves to high latitudes and enforce parallel propagation. In this work, we use ray tracing and finite difference time domain (FDTD) or full wave model to simulate whistler mode wave propagation in both the homogeneous and inhomogeneous cold plasma media in a realistic dipole geomagnetic field.

Both the FDTD and ray tracing model produce the linear increase in wave normal angle with latitude for non-ducted wave propagation in a smooth magnetosphere. However, when ducts are introduced, the waves show a combination of guiding and refraction in the full wave model that is considerably more complex. The ducts also enforce strong spatial modulation, guiding of waves inside the duct region and creating a shadow region due to geomagnetic curvature. These phenomena are consistent with observation from the Van Allen Probes spacecraft. The full wave model offers a more realistic representation in capturing the small- scale characteristics within the presence of geomagnetic curvature in the magnetosphere. Nevertheless, the ray tracing results provide an additional qualitative understanding of the wave propagation initiated inside and outside the ducts.

Determination of ELF Signal Azimuth and Diffraction from Ionospheric Gradients

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We explore a new method for deriving extremely low frequency (ELF: < 400 Hz) wave arrival azimuths using a wide range of signal amplitudes, rather than relying solely on high amplitude impulses. This method is applied to data from the magnetic sensor at the Hylaty station in Poland, which features an 18-bit dynamic range. We tested this procedure on data from January 15, 2022, to extract ELF signals generated by the Hunga Tonga volcano eruption. By complementarily filtering power line 50 Hz signatures, we can precisely extract azimuth information for waves from multiple thunderstorms, which vary throughout the day. We observed a phenomenon of successive regular variations—decay or activation—of thunderstorm activity with varying azimuth, possibly due to the passage over the solar (day/night) terminator, along with signatures of azimuth direction changes during this passage. Specifically, the Hunga Tonga related signals showed a discrepancy of approximately 10° smaller than the geographic great circle path, likely due to propagation through the polar region and near the solar terminator.

In further observations from September 2023, we performed azimuth time tracking of multiple global thunderstorm centers, sources of ELF electromagnetic waves propagating in the spherical Earth-ionosphere cavity. We identified azimuths of numerous global emission centers. Our observations confirmed significant and relatively regular thunderstorm azimuth variations during the solar terminator passage over the observation site. The magnitude and duration of these azimuth deviations depend on the observed azimuths and vary between successive days, reflecting changes in detailed thunderstorm activity patterns. The maximum azimuth deviations, reaching above 20°, were observed preferentially at sunrise and sunset times. We discovered particular composite deviation structures, with negative azimuth deviations preceding larger positive ones during the morning terminator passage. Distant from the terminator, we observed a decrease in the magnitude of regular deviations and occasional lower magnitude deviations with the opposite sign. These variations are expected to result from varying thunderstorm activity and ionospheric parameters, particularly charge gradients and nonuniformities along the terminator. We postulate that the observed deviations result from signal diffraction at ionospheric gradients.

VLF Transmitter Signals and Propagation Observed by Spacecraft

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Military very low frequency (VLF) transmitters are a major human-made source of electromagnetic waves propagating through the inner magnetosphere. These waves, particularly at night when ionospheric attenuation is minimal, can significantly contribute to pitch angle scattering and trigger energetic electron precipitation from the Van Allen radiation belts. Despite their importance, measuring the precise propagating wave power and differentiating between ducted and nonducted propagation modes is experimentally difficult due to their relatively high frequencies, which are in the tens of kilohertz range.

We use measurements taken by the low-altitude DEMETER spacecraft near the transmitter location and in the geomagnetically conjugated region to estimate the ratio of wave power propagating in the ducted mode. This is supported by a raytracing analysis, which reveals that for specific transmitter locations, the ducted and nonducted waves arrive in quite separate regions in the conjugate hemisphere. We further use wave measurements performed by the Cluster spacecraft to investigate the latitudinal dependence of the transmitter wave power. We show that the signals from selected transmitters are readily observable by Cluster and that their power generally drops significantly upon crossing the geomagnetic equator. Finally, we discuss the diurnal and seasonal variations in the measured wave intensities.

Avoidance of Satellite Damage with the Use of VLF Plasma Waves in Space for Reduction of Energetic Particle Fluxes and Detection of Harmful Space Debris

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The number of satellites launched into low Earth orbit (LEO) is increasing at an exponential rate. Launches support deployment of multi-satellite constellations for many applications. Experiments with electric field sensors on Swarm-E and with HAARP in Alaska have been conducted to (a) better locate the positions of satellites and space debris for prevention of collisions and (b) reduce the fluxes of energetic particles that can destroy satellite electronics.

Currently, there are about 27,000 known space objects and over 100 million of unknown pieces of space debris. Collision avoidance requires precise knowledge of the positions for all space objects. New techniques are being developed to detect the small, < 10 cm, objects by the plasma waves they generate in space. The bases for this technique is that all space objects in orbit around the Earth (1) pass through a magnetized plasma, (2) become electrically charged, and thus (3) produce detectable plasma waves. Field aligned irregularities (FAIs) in the path of orbiting space objects are monitored by the SuperDARN radar backscatter and by in situ electron density probes. Space debris and satellites moving through these irregularities and can excite plasma emissions such as whistler, compressional Alfven, or lower hybrid waves. Orbital kinetic energy is the source of lower hybrid waves which is converted into an electromagnetic plasma oscillation when a charged space object encounters a field aligned irregularity (FAI). Such whistlers propagate undamped at around 9000 km/s from the source regions and can be detected at ranges of several earth-radii.

Satellites also have to avoid collisions with energetic particles that can damage solar panels and electronic components. Whistler and electromagnetic ion cyclotron (EMIC) can scatter trapped radiation into the atmospheric loss cone and, thus, reduce energetic particle fluxes. New techniques have been developed to excite and to amplify these waves in the ionosphere using simultaneous HF transmissions two separate radio beams. The first HF beam generates VLF and whistler waves by modulation of the electrojet currents with X-Mode transmissions. These whistlers normally propagate through the F-layer to be captured by field aligned ducts and guided to the radiation belts. The amplitude of the whistlers from electrojet modulation is typically 5 pT or less. The second beam of the HF facility uses a vertical O-Mode beam to excite lower hybrid (LH) waves in the F-region. These LH waves provide a pump for a whistler traveling wave parametric amplifier (WTWPA) that intensifies the VLF signals. Satellite measurements of the VLF wave amplitudes in the ionosphere in have reached values between 200 pT and 10 nT. HAARP HF can be modulated with both continuous wave or linear frequency ramps to generate VLF whistlers. Simulations have shown the HF amplified whistlers can reduce trapped electron fluxes at a rate 5000 times those from unamplified whistlers. All of these experiments with space debris detection and radiation belt remediation can conducted by both by the HAARP HF Facility in Alaska, USA.

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First results from VLF-CHAMP: Analyzing Latitudinal Propagation and Characteristics of VLF Waves in Finland

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In recent years, the PWING project has allowed us to investigate the longitudinal characteristics of natural VLF emissions [1, 2]. Some interesting results from these previous studies have motivated us to focus on the latitudinal propagation and possible ionospheric propagation of certain types of VLF waves, particularly unusual high-frequency VLF bursty-patches [3, 4].

In this study we will use three VLF receivers installed in Finland at approximately the same longitude but at three different latitudes (separated by 300-400 km). These are Kannuslehto (KAN, MLAT=65.0°N, L=5.5) active since 2006, Oulujärvi (OUJ, MLAT=61.3°N, L=4.4) since 2022, and the yet unnamed new guy (GUY, MLAT~66.1°N, L~6.3) from August 2024.

Here we will present the first results from this latitudinal chain comprising:

- General wave propagation and characteristics from ground-based data, including the properties of the ionospheric exit point of waves.
- Results from conjugated events from multi-point observations, incorporating when possible, ray tracing for bursty-patches with an analysis of their eventual ionospheric propagation.
- Effect of energetic electron precipitation on wave propagation to the ground at these latitudes using nearby riometer data.
- Preliminary results of the PHLR/sferics filter to be installed at all PWING stations.

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Trans-ionospheric propagation and attenuation of very low frequency waves

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When very low frequency (VLF) waves generated by lightning or VLF transmitters propagate through the lower ionosphere, the waves accelerate ionospheric electrons, which then collide with neutrals, transferring energy from the wave to the neutral atmosphere. The wave is attenuated as the electromagnetic energy is converted to thermal energy. The amount of attenuation is highly dependent on ionospheric electron density and collision frequency. The attenuation experienced through the ionosphere affects the wave amplitudes that reach the magnetosphere and their effectiveness in scattering radiation belt electrons; hence, a better understanding of this trans-ionospheric propagation is important for magnetospheric studies. Graf et al. (2013) presented attenuation factors for 2 kHz and 20 kHz waves for day and night ionosphere conditions for a range of geomagnetic latitudes. Graf et al. (2013) improved upon the earlier Helliwell (1965) attenuation estimates, which showed significant disagreement with VLF transmitter observations (Starks et al., 2008, Tao et al., 2010), by using more accurate ionospheric densities with the Stanford Full Wave Method (FWM; Lehtinen & Inan, 2009).

We will further improve modeling of trans-ionospheric propagation with the FWM by implementing the newest version of the International Reference Ionosphere (IRI) in conjunction with the Faraday-International Reference Ionosphere (FIRI; Friedrich et al., 2018). FIRI is a semiempirical model of lower ionosphere electron densities from 60 km to 150 km; as most attenuation occurs in the lower ionosphere, accurate densities in this region are especially important. We will compare our attenuation estimates with the Graf et al. (2013) results. We will present attenuation estimations for frequencies up to 40 kHz so that they may be used for validation against lighting observations with the upcoming CANVAS mission (Marshall et al., 2022). We will also assess the modeled wave normal angles at the top of the ionosphere and show how initial wave normal angle variation affects magnetospheric propagation using the Stanford ray tracer (Inan & Bell, 1977).

Ionospheric *D* region: Characteristics near Dawn and Dusk

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Electron density characteristics of the Earth's ionospheric *D*-region, in the height range ~55-90 km, have been determined using phase and amplitude measurements of man-made, very low frequency (VLF) radio propagation in the Earth-ionosphere waveguide. Time variations of the 'Wait' height and sharpness parameters, *H'* and *Beta*, were identified through long-wave propagation modelling of VLF observations recorded over many years, and on many transmitter-receiver paths. This work was primarily undertaken by Neil Thomson, aided and abetted over the years by Craig and Mark. Since 2010 Neil Thomson has led ten key papers describing the variation in *H'* and *Beta* over a wide range of relevant propagation situations, i.e., during the day, during the night, and over low-mid-high latitudes. Interpretation of the results illuminates the geophysical effects controlling *D*-region electron concentration profiles, including the dominant role of solar Lyman-alpha at low and mid-latitudes, and the greater role of galactic cosmic rays at increasingly higher mid-latitudes.

In the most recent of the Thomson papers (in review), Wait parameters have been determined through dawn and dusk for the first time. The analysis provides *H'* and *Beta* values to constrain *D*-region modeling efforts, thereby extending the capabilities of VLF propagation monitoring for geophysical phenomena such as lightning, solar flares, and energetic particle precipitation. This talk summarises the recent work, focusing on dawn and dusk observations, and putting the resultant *H'* and *Beta* variations into context with day and night values, over a range of latitudes.

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Effect of ground conductivity on VLF propagation

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The ionospheric D-layer is responsible for a large part of the HF absorption, which is a frequency band used by civil aviation and ham-radio transmissions amongst others. It is a dynamic layer, which can be perturbed by different sources of forcing such as lightning discharges, TLEs and solar flares. It is thus crucial to monitor this layer in the context of space weather. However, it is too high for balloons, too low for satellites and does not respond to radar sounding. The typical method to monitor this layer relies on the propagation of Very Low Frequency (VLF, 3 - 30 kHz) waves.

VLF waves can propagate over thousands of kilometers in the waveguide formed by the Earth and the D-layer. Several modes propagate in this waveguide. Each mode depends on the boundary conditions which are determined by the electron density in the D-layer for the upper waveguide boundary and the ground conductivity for the lower boundary. Any change of the D-layer electron density will modify the propagating modes, and thus the signal (amplitude and phase) measured at a receiver. Using a propagation code such as the Longwave Mode Propagator (LMP), the electron density in the D-layer can then be inferred from the VLF amplitude and phase measurements.

While numerous studies concentrate on the impact of a change in the D-layer electron density on VLF propagation, few studies have investigated the effect of a ground conductivity change. We aim to answer two questions :

- How accurate should the path ground conductivity description be to obtain a given accuracy on the ionospheric electron density?
- Are the currently-available ground conductivity maps accurate enough ?

The accuracy on the absolute values of the ground conductivity and their spatial extension is investigated through modeling with the LMP code. We show that accurate knowledge of the ground conductivity value is crucial, especially for low conductivity regions ($\sigma \leq 3 \times 10^{-3}$ S/m). Accurate description of the spatial extension of the ground conductivity regions is also essential, and should have a precision of a few tens of kilometers.

However, ground conductivity depends on many physical parameters, such as the ground temperature, moisture and the irregularity of the terrain. Seasonal variations are also expected, especially in case of heavy thawing, and the effect of cities on the ground conductivity has not been quantified yet. This work thus highlights the need for an update of the existing ground conductivity maps.

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VLF Chirp Sounding of the Auroral Electrojet and the D-Region with HAARP

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The auroral electrojet is of interest to space physicist, geophysicist and communication engineers because it provides a link between (a) understanding the impact of high-latitude electron precipitation on the D-Region near 70 to 90 km altitude and (b) the ability to contact submarines with ELF/VLF waves below 30 kHz. The auroral electrojet can be modulated by high power HF waves to launch signals into the earth-ionosphere waveguide for navigation or communications applications and through the ionosphere and magnetosphere for studies of wave induced precipitation of the radiation belt electrons. Measurements of the D-region electron densities and the horizontal currents in this high-conductivity layer are also of interest to understand the generation of current driven fluctuations in observed by ground magnetometers.

Electron density profiles of the auroral D-Region can be obtained with (1) density probes on sounding rockets, (2) coherent and incoherent scatter radars, and (3) HF modulation of the auroral electrojet with high power radio waves [Fujimaru, and Moore, 2011]. The electrojet modulation technique has used time-of-arrival (TOA) during ELF/VLF wave generation experiments using the high power HF transmitters under varying ionospheric conditions and using various transmission formats.

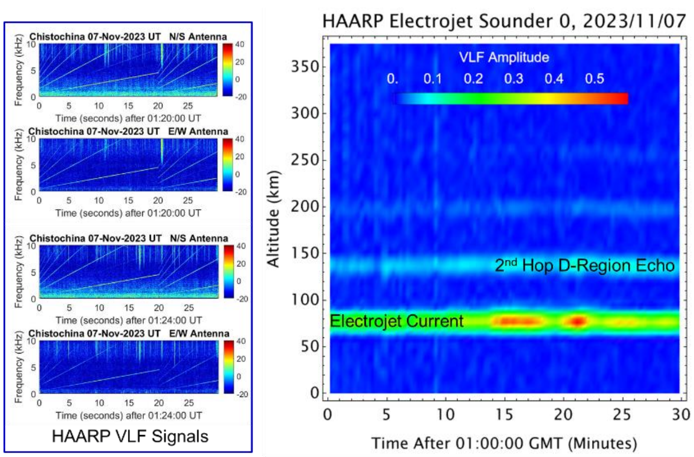

Figure 1. HF modulation of a strong electrojet by HAARP provides (left) VLF chirp waveforms with bandwidths of 4, 12, and 20 kHz and 20-second repetition periods. De-chirp analysis yields (right) images of the electrojet and bottom-side D-region with 7.5 km altitude resolution. The auroral D-layer reflection point and electrojet peak altitude are 6.25 km and 75 km respectively.

New experiments with the HAARP HF Facility in Alaska employ linear frequency modulation (LFM) waveforms specifically designed for ELF/VLF mapping of the lower ionosphere. Chirped HF transmissions with HAARP are converted into VLF chirps in the electrojet. Single-hop and two-hop reception at the UF Chistochina receivers located 35 km from HAARP are analyzed with chirp compression algorithms [Fernet and Stevens, 1990] to yield ranges to the electrojet and the D-layer reflection altitude (Figure 1). This technique is used to compare the D-region VLF chirp profiles with electron densities obtained using Poker Flat Incoherent Scatter Radar (PHISR) during the solar flare period of 8 to 11 May 2024.

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Determining Size of a Precipitation Event with AARDDVARK system of VLF radio wave receivers

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We analyze subionosphere propagating very low frequency (VLF) radio waves observed by several receivers to determine an approximate area of the pulsating aurora precipitation event during the LAMP rocket launch. With the size of the event and the in situ rocket results we can better understand the total energy input during the event. We use amplitude and phase measurements from the Antarctic-Arctic Radiation-belt Dynamic Deposition VLF Atmospheric Research Konsortia (AARDDVARK) set of radio wave receivers and transmitters whose propagation paths are in the northern hemisphere. These paths are defined as the propagation of the VLF radio waves between a transmitter and receiver, and we use receivers in Fairbanks, Alaska and Edmonton, Cananda with transmitters located in North Dakota, Seattle, Maine and Iceland. We subtract the background noise of each phase and amplitude measurements by using a set of the respective averaged measurements for days with little geomagnetic activity and are temporally close to the event of interest. Since this pulsating aurora event has an energetic electron flux content (>30 keV), by observing the perturbations in resulting amplitude and phase measurements from each path we can estimate when the pulsating aurora event crossed the path's lines of sight and approximate the area of the pulsating aurora event.

6. Friday, October 4, 2024

7:30 AM: BREAKFAST

9:00 AM: **Jacob Bortnik:** *Machine-Learning Reconstruction and Interpretation of the Earth's Inner Magnetospheric Environment*

9:25 AM: **Zhi-Gu Li:** *Quantifying the spatial and temporal extent of precipitation drives through the modeling of multi-point POES/MetOp observations*

9:50 AM: **James Cannon:** *Deployment and First Results of the Array for VLF Imaging of the D-Region (AVID)*

10:15 AM: BREAK

10:40 AM: **Donglai Ma:** *Simulating the Earth's Outer Radiation Belt Electron Fluxes and Their Upper Limit: A Unified Physics-Based Model Driven by the AL Index*

11:05 AM: **Paraksh Vankawala:** *Computer Vision-Guided Analysis of Plasma Waves in the Inner Magnetosphere*

11:30 AM: **Narges Ahmadi:** *Reconnection Signatures (Type II) in Kelvin Helmholtz Instability in PIC Simulations*

12:00 PM: LUNCH

1:00 PM: **Milla Kalliokoski:** *Origin of dispersed ion injections into the plasma sheet*

1:25 PM: **Allison Craig Rodger:** *Geomagnetically Induced Currents and Harmonic Distortion: Using VLF measurements to gain context into Space Weather impacts*

1:50 PM: DISCUSSION

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Machine-Learning Reconstruction and Interpretation of the Earth's Inner Magnetospheric Environment

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The Earth's inner magnetospheric environment consists of various quantities, including cold plasma, whistler-mode waves such as chorus and hiss, as well as high-energy electrons and protons that are trapped by the geomagnetic field, presenting a hazard for spacecraft and astronauts. Accurate specification and prediction of the dynamic variability of these quantities, has been a long-standing, and extremely challenging problem which has traditionally been addressed using a variety of approaches that are typically disconnected from one another. For example, radiation belt dynamics are typically modeled 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 modeling the dynamical behavior of a number of these quantities, including the Outer Radiation belt Electron Neural network (ORIENT) model that reproduces 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. The ORIENT model shows a high overall correlation to out-of-sample observed data (in the range 0.78-0.95) and is demonstrated on an example event in our talk.

Such machine learning models are valuable for specification and forecast of the radiation belt electron fluxes, but are hard 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, we show that the black box ORIENT model can be successfully interpreted. We show its ability to interpret individual storm responses, we use it in a “SHAP-Enhanced Superposed Epoch Analysis” framework to show statistical behavior, and we use it to infer the causative differences between enhancement and depletion type storms. This work shows tremendous promise for the use of machine learning models not only as a prediction tool, but also for scientific insight discovery.

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Quantifying the spatial and temporal extent of precipitation drives through the modeling of multi-point POES/MetOp observations

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In-situ measurements provide invaluable information regarding the local wave properties and plasma conditions within the magnetosphere; however, these measurements are confined to the transient time of the spacecraft through a particular region in space. Such measurements cannot accurately determine the spatial or temporal distribution of active wave regions, leading to difficulties in assessing relativistic electron precipitation and their impacts on our terrestrial atmosphere. We address this issue by employing a drift-diffusion model, its evolution constrained by 5 POES/MetOp satellites, to simulate and quantify the relativistic electron distribution, as well as the spatial, temporal and strength of pitch angle diffusion. These results can be used as a proxy to infer the active wave regions within the magnetosphere on a cadence of ~2 hours. During an event on October 15, 2016, in the recovery phase, the Waveform Receiver (WFR) instrument onboard the Van Allen Probes observed plasmaspheric hiss waves at L~3.9 in the midnight sector on both its inbound and outbound orbits. These hiss waves likely caused the observed decay of <2 MeV relativistic electron flux. Our model quantification results of the temporal and spatial distribution of hiss wave amplitudes are consistent with the statistical hiss wave amplitude as parametrized by the AE-index (Meredith et al., 2004). Further, the model quantified MLT-dependent hiss wave amplitude showed remarkable agreement with the observed hiss wave amplitudes as measured by the WFR. This drift-diffusion model, constrained by low-altitude data, presents a novel approach for quantifying the spatial, temporal, and rates of pitch angle diffusion, and in turn, can be used as a proxy to determine active wave regions and their wave amplitude distribution in MLT. Such model results can complement the in-situ measurements to gain a better understanding of magnetospheric conditions.

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Deployment and First Results of the Array for VLF Imaging of the D-Region (AVID)

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The D-region of the ionosphere responds dynamically to energy deposited by solar Lyman-α radiation, solar X-rays, precipitating radiation belt electrons, and other energetic particles. Continuous measurement of the D-region can be used to identify phenomena that couple into the ionosphere from other areas within the heliosphere. Sub-ionospheric very-low-frequency (VLF) remote sensing is the best way to continuously measure the D-region. VLF radio waves efficiently reflect between the Earth's surface and the D-region of the ionosphere. These VLF waves are then sensitive to changes in the ionospheric density within the D-region when probed downrange from a source such as an anthropogenic VLF transmitter or a lightning discharge. The major shortcoming of the subionospheric VLF technique is that any given measurement, taken at a single point in space, represents the effect of the entire path from source to receiver.

This work presents a continued effort to extract spatial information about the D-region state by overlapping path-integrated VLF measurements in an array configuration with 22 distinct transmit-receive paths covering the same region of Canada. This Array for VLF Imaging of the D-region (AVID) covers a ground area of approximately 3 million km^2 (~1300 km x ~2300 km) at a latitude range that corresponds to L-shells between L=3 and L=7. Site locations and transmit-receive paths are shown in Figure 1. AVID is made up of 13 VLF receivers, 11 of which are operated by our team at the University of Colorado Boulder. The final two sites are AWESOME VLF receivers generously operated by Dr. Morris Cohen and the Georgia Institute of Technology. For our 11 AVID receivers, we made a major revision to the AWESOME VLF receiver: modernizing component choice, simplifying the timing circuitry, adding a custom power board, and consolidating the electronics into a single deployable rack-mount enclosure. Here we discuss the development of the AVID VLF receiver, the successful deployment of the 11 instruments operated by the University of Colorado Boulder, and present a first look at the data returned from the array.

Prior work has established an inversion technique for a simulated array of receivers using a Local Ensemble Transform Kalman Filter (LETKF). This technique will be discussed alongside simpler estimation techniques that have been used with preliminary data from AVID as the last few sites have just come online in the summer of 2024. Once a data analysis pipeline is established for AVID using LETKF or other estimation techniques, rapid analysis of D-region dynamics for specific events will be possible.

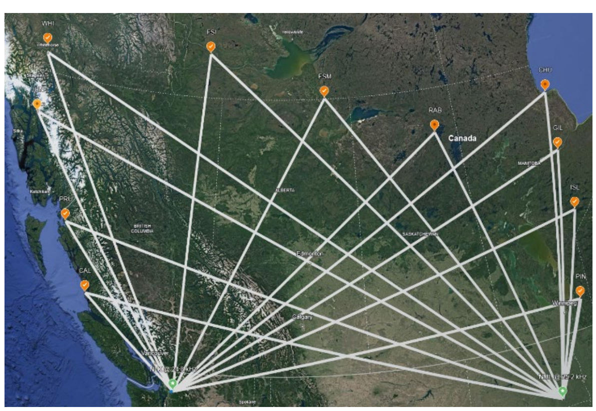

Figure 1: A map of the AVID array sites and VLF transmit-receive paths

Simulating the Earth's Outer Radiation Belt Electron Fluxes and Their Upper Limit: A Unified Physics-Based Model Driven by the AL Index

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Using particle and wave measurements from the Van Allen Probes, a 2-D Fokker-Planck simulation model driven by the time-integrated auroral index (AL) value is developed. Simulations for a large sample of 186 storm-time events are conducted, demonstrating that the AL-driven model can reproduce flux enhancement of the MeV electrons. More importantly, the relativistic electron flux enhancement is determined by the sustained strong substorm activity. Enhanced substorm activity results in increased chorus wave intensity and reduced background electron density, which creates the required condition for local electron acceleration by chorus waves to MeV energies. The appearance of higher energy electrons in radiation belts requires a higher level of cumulative AL activity after the storm commencement, which acts as a type of switch, turning on progressively higher energies for longer and more intense substorms, at critical thresholds.

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Computer Vision-Guided Analysis of Plasma Waves in the Inner Magnetosphere

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Plasma waves such as chorus, hiss, EMIC and lightning-generated whistlers (LGWs) in the inner magnetosphere are a primary driver of radiation belt dynamics. While chorus drives acceleration from seed electron energies (hundreds of keV) to relativistic energies, each of these wave types contribute to the scattering of those energetic electrons into the loss cone, a key loss process for radiation belt electrons. Numerous missions have flown VLF receivers to measure these waves, leading to new insights into how these waves drive the radiation belts. The Van Allen Probes and Arase missions measure all six components of VLF waves while orbiting through the radiation belts. The DSX mission similarly made excellent observations of VLF waves from June 2019 to May 2021. Missions such as DEMETER have measured VLF waves in LEO.

A key challenge for interpretation of these VLF waves is the identification of the different wave types. Manual identification is most common: most scientists in the field can identify and distinguish different wave types in spectrograms by eye. But automatic identification and classification remains time consuming and challenging, because hiss, chorus, and LGWs overlap in frequency range and observations are susceptible to spacecraft noise. Previous work to classify chorus and LGWs have used manual classification (Teng et al, 2018), or identification based on the observation location and wave properties (Li et al, 2016; Green et al, 2020); however, those methods presume knowledge of the distribution of these waves to reduce data for identification. This limits the possibility of redefining the regions these plasma waves exist within the inner magnetosphere.

This project proposes to build a database of LGW, chorus, and hiss measurements using AI-based automatic detection image processing techniques. The project will use six years of Van Allen Probes burst-mode data processed into spectrograms, revealing the time-frequency structure that enables the identification of plasma waves. From these images, we generate a database of annotations for each class of wave, and train a YOLO v8 machine learning model to provide detection and classification of these features. These annotations will then be used on the continuous, yet lower resolution, survey data from the same mission to train a new model. This will allow for a complete classification of plasma wave occurrences during the entire duration of the Van Allen Probes mission.

Future work will apply our techniques to the DSX, Arase, and DEMETER missions. The resulting databases can then be used in neural networks or other machine learning tools to aid our study in the distributions of VLF waves as a function of space (L-shell, MLT, longitude, etc) and geomagnetic parameters (Dst, Kp, etc).

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Reconnection Signatures (Type II) in Kelvin Helmholtz Instability in PIC Simulations

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We performed 2D PIC simulations of Kelvin Helmholtz instability (KHI) with symmetric and asymmetric density and temperature profiles along the flow shear with primarily a northward interplanetary magnetic field with a small uniform in-plane field. The Magnetic Flux Transport method, field topology and magnetic field minimums are used to identify the reconnection X-lines. We start to observe the reconnection signatures such as magnetic field and flow reversals at the vortex edges in the nonlinear phase of the KHI when the vortices are rolling up. The number of reconnection regions increases at the turbulence phase. The signatures eventually decrease and finally disappear at late stages of KHI developments. Our results qualitatively agree with MMS observations of reconnection signatures at the spine regions of KHI along the magnetospheric flanks.

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Origin of dispersed ion injections into the plasma sheet

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The ion population in the Earth's plasma sheet and ring current is sourced from solar wind plasma and ionospheric outflow. The relative dominance of each source during geomagnetic storms and different solar wind driving conditions is not yet clear. One pathway into the plasma sheet that can bring in both solar wind and ionospheric ions is through injections at the nightside near the magnetotail reconnection region when the interplanetary magnetic field is southward. The injected ions transfer energy from the solar wind into the magnetosphere and have been shown to drive various phenomena such as field-aligned electron flows and broadband electromagnetic waves. The aim of this study is to determine the origin location of energy and time-of-flight dispersed ion injections into the plasma sheet during geomagnetic storms. We analyze the omnidirectional and pitch angle resolved flux measurements of hydrogen (H+) and oxygen (O+) ions from the Arase LEP-i instrument. The injections in our case studies appear as both energy and pitch angle dispersed structures, as the injected ions reach the satellite at different times depending on their velocity and pitch angle. Multiple dispersions are sometimes observed, indicating that the ions originate from the same injection location but have traveled different distances due to having undergone a different number of bounce periods. We derive inversed velocity distributions to estimate the location of the injection point. In addition, we analyze wave measurements to find if there is correlation between the dispersion features and concurrent waves.

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Geomagnetically Induced Currents and Harmonic Distortion: Using VLF measurements to gain context into Space Weather impacts

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Large geomagnetic storms are a space weather hazard to power transmission networks due to the effects of Geomagnetically Induced Currents (GICs). GIC can negatively impact power transmission systems through the generation of even-order current and voltage harmonics due to half-cycle transformer saturation. It is clear that GIC-generated harmonic distortion contributed significantly to the Hydro Québec blackout in 1989.

In New Zealand at the Halfway Bush substation inside the city of Dunedin we have data coverage from a unique combination of instrumentation: measurements of GIC on the single phase transformer T4 (now decommissioned), as well as GIC at both 3-phase transformers T3 and T6, nearby magnetic field perturbation measurements, reactive power observations from the power grid, 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. 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. VLF radio wave data are used to provide high resolution measurements of mains harmonic distortion levels within the nearby substation. We can also use the nation-wide low time resolution power network harmonic distortion measurements to better understand harmonic production across the grid as a whole.

In this talk I will discuss our findings [1] about even order harmonic production in the New Zealand power grid using measurements from 139 substations across the country during 10 geomagnetic storms. Analysis identified 5 key substations, which appeared to act as sources of harmonic distortion. The majority of these substations include a particular transformer design which is known to be more susceptible to GIC issues, as well as evidence of significant GIC. I will also provide new examples of GIC, VLF measurements of harmonic distortion, and reactive power changes during the September 2017 and May 2024 storms.

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

References

[1] Crack, M., Rodger, C. J., Clilverd, M. A., Mac Manus, D. H., Martin, I., Dalzell, M., et al. (2024). Even-order harmonic distortion observations during multiple geomagnetic disturbances: Investigation from New Zealand. Space Weather, 22, e2024SW003879. https://doi.org/10.1029/2024SW003879