VLF Remote Sensing of the Lower Ionosphere: Solar Flares, Electron Precipitation, Sprites, and Giant $\gamma$-ray Flares

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Subionospheric VLF Remote Sensing
VLF Detection of Solar Flares

~24 hours

Quiet Day

Active Day

Source: Ray Mitchell
VLF Signatures of Solar Flares

from Ray Mitchell
VLF Signatures of Gravity Waves
Lightning-induced Electron Precipitation (LEP) Bursts

PALMER ANTARCTICA (L=2.4, 64° W) 20 OCT 82 0340:15 UT

WHISTLER

S81-1/SEEP
TE2 (90° ZENITH) x 5
E > 45 keV

ME1 (0° ZENITH)
E > 45 keV

UT (s) 13215 13225 13235 13245
L 2.28 2.34 2.40 2.46
LAT(deg) 35.56 36.24 36.92 37.59

Whistler
Electrons
LEP Spectra [Voss et al., 1984]
Measurement Methods

- Discrete wave-induced electron precipitation fluxes are relatively low (~$10^3$ to $10^4$ times lower than typical auroral fluxes)
- Electron detectors currently in-orbit are designed for auroral fluxes and do not have sufficient sensitivity (geometric factor) or time resolution
  - One exception may be SAMPEX, which measures >500 keV electrons
- X-rays and optical emissions produced by precipitating electrons are relatively weak and difficult to detect
- Secondary ionization due to expected precipitation fluxes ($10^4$ ergs/cm$^2$-s) is a small fraction of the relatively large ambient electron densities at $E$- (95-130 km altitude) and $F$-regions (160-400 km) of the ionosphere, so that detection by HF or VHF radars, ionosondes, and riometers is not feasible
- On the other hand, the $D$-region (~50-95 km) is mostly devoid of ambient electrons, especially at night, so that the relatively small additional secondary ionization produced by transmitter-induced precipitation fluxes constitutes a substantial (i.e., detectable) modification
- Precipitating electrons must have >100 keV energy to penetrate down to $D$-region altitudes
- VLF radio remote sensing is the only technique suited for detection
VLF Remote Sensing of >100 keV Electron Precipitation

- The ambient nighttime electron densities in the D-region are typically ~1 to 10 el/cc.
- Even the most powerful VHF or HF radars (e.g., Arecibo) cannot measure the D-region at night, since they typically require >1000 el/cc for useful echoes.
- Precipitating energetic electrons with >100 keV energy penetrate to altitudes <85 km, creating secondary ionization therein.
- The additional ionization produced is typically <100 el/cc.
- The reflection height for VLF waves propagating in the Earth-ionosphere waveguide is ~85 km at night.
- Amplitude/phase of VLF signal is highly sensitive to conductivity.
Lightning (Whistler)-Induced Electron Precipitation
VLF Remote Sensing of Lower Ionospheric Disturbances
Lightning-induced Electron Precipitation (LEP) Bursts

- Whistler waves launched by lightning commonly induce precipitation of <1 s bursts of >100 keV electrons, producing secondary ionization
- VLF signatures consist of rapid changes followed by 10-100 s recoveries, representing chemical decay back to ambient levels
Holographic Imaging of the Lower Ionosphere

VLF receivers at 13 high schools
Provides excellent opportunities for outreach
Subionospheric VLF Signatures of LEP Events

The HAIL array captures the full latitudinal extent of the LEP events.
Occurrence Rate of LEP Events

Dependence on geomagnetic conditions
LEP Events Associated with Lightning in Hurricanes

Hurricane Isabel
September 2003

VLF Amplitude Data
-NAU-BO
-NLK-PA
-NLM-PA

Amplitude (dB)

# of LEP Events
Sustained Wind Speed

Date in September, 2003
Occurrence Rate of LEP Events

Variation in Occurrence Rates
Conjugate Hemisphere
VLF Sensing of Ionospheric Disturbances over Europe
Sprites Above Thunderstorms
Elve Observed from Space

from Yoav Yair [2003]

Elve
19/1/2003 09:05:23.94 UT
(over eastern Australia)

Cloud Top (~20km)

Horizon

~90km

Inan et al. [1997]
Early/fast VLF Events

29 October 2000

NAA at Boulder

NLDN


Linear Amplitude (kA)

6:19:30 6:19:40 6:19:50 6:20:00 Time (UT)

Linear Amplitude (kA)

NAA

NLDN

A

B

Direct Path

Scattered Path

Δo

Xmit

Revr

QE Fields

Ionosphere

85 km
Sprites and Early/fast VLF Events

[Haldoupis et al., 2005]

Sprites and Early/Fast VLF Events July 21, 2003; 0230-0252 UT
Discovery of TGFs by BATSE on CGRO:

- Flashes of duration ~ 1 ms
- 75 events discovered over 9 years
- Hard spectra up to energies >> 300 keV
- Correlation with thunderstorms
Terrestrial Gamma-ray Flashes and Radio Atmospherics

RHESSI Detection Footprint and Propagation Path

RHESSI Data, May 31, 2002, 00:52:35.1860 UT

Palmer Station VLF Data, May 31, 2002, 00:52:35.2181 UT

Histogram of Arrival Azimuth Over 30 Minutes

Average Steric Rate (Per Second)
TGFS Time-correlated with Sferics (94%, 85%, 72%)

Global TGF Distribution and Sferic Detection Range at Palmer

RHESSI Data, Nov 06, 2002, 01:38:19.004 UT

Palmer Station VLF Data, Nov 06, 2002, 01:38:19.501 UT

RHESSI Data, May 31, 2002, 00:52:35.186 UT

Palmer Station VLF Data, May 31, 2002, 00:52:35.2181UT

RHESSI Data, Jan 19, 2005, 03:07:58.167 UT

Palmer Station VLF Data, Jan 19, 2005, 03:07:58.1982UT

RHESSI Detection Footprint and Propagation Path
Disturbance of the Nighttime Ionosphere by SGR 1900+14
Repeated Disturbance of the Ionosphere by SGR 1900+14

NPM at Palmer

30 May 98

NPM at Palmer

27 Aug 98

NPM at Palmer

29 Aug 98

Energy Flux (erg/cm²/s)

May 30, 1998

August 27, 1998

August 29, 1998

0 10 20 30 40 50 60 Time (s)

0 100 10^1 10^2 Energy Flux (erg/cm²/s)

0 10 20 30 40 50 Time (s)

0 10 20 30 40 50 Time (s)

~0.2 dB

~20 dB

~0.2 dB
VLF Detection of the Disturbance of the **Daytime** Lower Ionosphere

- Very large amplitude/phase perturbations on VLF signals, the great-circle propagation paths of which are illuminated by the Flare
- Flare center very near the sun; ionosphere was day-lit
Event Setting and VLF Detection

Event onset clearly evident in broadband spectra, as amplitude reduction on all signals, including VLF transmitters and radio atmospherics.

RHESSI Detectors saturate and stop counting

Palmer EW Antenna: 27 December 2004

Time (seconds) after 2130:25 UT

RHESSI Counts

Frequency (kHz)

0 10 20 30 40 50
CISM Educational Outreach

Professor Phil Scherrer

High School Outreach

Low Cost

Easy to Use

Dual use system

- Daytime: monitor solar activity (x-ray flares)
- Nighttime: monitor lightning-induced electron precipitation, gravity waves, sprites, etc.

Science grade measurement, in terms of resolution, sensitivity, timing, and dynamic range
AWESOME Receiver Overview

B-Field Antenna
Preamp
Long Cable
Line Receiver
Analog to Digital
GPS Antenna
Computer

Atmospheric Weather Electromagnetic System for Observation, Modeling, and Education
Antenna, Preamp, and Line Receiver
National Instruments 6034E
- Plugs into PCI slot; PCMCIA laptop version available
- 200 kS/second, 16-bit; 100 kHz sampling each channel