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Radio Science: VLF Part 1

<Insert Figures 1, 2, 3A & 3B>

Introduction

The very low frequency (VLF) electromagnetic (EM) spectrum ranges in frequencies from 3000 to 30000 hertz (Hz) or wavelengths from 100 to 10,000 metres (m). It was once the domain of high-powered, transoceanic commercial wireless stations and civilian/military use hyperbolic navigation systems for aircraft, ships and submarines (OMEGA, Decca, LORAN-A and C). Today, it’s used by government time signal stations such as JJY (Japan) and WWVB (US) et al, Radio Amateur and other “citizen science” radio hobbyists, solar scientists, seismic study (“skyquake”) researchers and the world’s major navies. Navies use high-powered VLF transmitters to send narrow bandwidth, low data rate encrypted messages to submerged submarines. We can use any VLF transmitter’s signal strength plus phase and time difference of arrival (TDoA) for other purposes, but, obviously, can’t decode messages. VLF radio waves have the magical ability to diffract (bend) around and/or penetrate solid objects so they’re very useful for underground communications and also for geophysics (see Figure 1) to non-destructively map inaccessible subterranean areas down to depths of 100 m or 10 times deeper than ground penetrating radar (GPR).

Sudden Ionospheric Disturbance

A sudden ionospheric disturbance (SID) occurs whenever the Earth’s sunlit side is hit hard by an X-ray solar flare event usually M and X-class (see Figure 2) or an extreme ultraviolet (EUV) radiation/particle storm event caused by a coronal mass ejection (CME) that often follows behind at sub-light speeds a day or two after an X-ray solar flare event (usually M and X-class). Their intense radiation penetrates deeply down through the ionosphere to the bottom daytime “D” or absorption layer (height ranges from 48 to 90 km above the surface of the Earth), increasing its ionization level (electron density), which in turn increases its radio wave absorption range from about 300 kHz right up to 30 MHz causing a radio “blackout”.

The really weird thing is, that for VLF radio signals, the reflection coefficient or the value measuring how much or not a wave is reflected by a medium, actually increases (and I don't know why) creating a stronger than normal VLF skywave (the component reflected by the D-layer). Interference (mixing) between the ground wave (the component received via direct propagation) and the skywave will either sharply and suddenly increase or decrease a VLF transmitter's signal strength relative to you, with a gradual decay back down or up, creating a very distinctive vertical or inverted "shark fin" shape (see Figure 3A). It's akin to the Earth's "bell" being "rung". Strong C-class X-ray solar flares can create "baby" shark fins but usually it takes M-class X-ray solar flares to produce pronounced ones, while "Great White" fins are generated by X-class X-ray solar flares. But, most of the time, VLF radio signal strengths normally increase at night and decrease during the day except for two (sometimes only one) noticeable signal drop/rise that occur at the monitored VLF transmitter's local sunrise/sunset times as the day/night terminator line crosses between you and the VLF transmitter. It's usually more pronounced (both fall and rise) if you are both located in the same local solar time zone (see Figure 3B).

Depending on how much energy, measured in watts per square metre (W/m^2) slams Earth's sunlit side, the duration of an event and its effect can range from a few minutes, hours to even days in the case of a super solar radiation/particle storm (a 21st century Carrington Event will literally blast us back to the past). From creating spectacular aurora and radio blackouts, to satellites, cellular systems, power grids, etc., being disrupted, disabled or destroyed. After an event is over, fortunately most are short duration, excessive free electrons recombine with ions and the D-layer returns to its normal daytime behaviour albeit recombination happens at a slower pace than ionization because energy (temperature) levels have to drop low enough for ions to grab and hold on to free electrons to reform neutral atoms. It's just so much easier to blast electrons free from cold atoms.

But it doesn't take a direct hit or a powerful X-ray solar flare and/or CME to be both destructive and costly. On 4 February 2022, Elon Musk's SpaceX Company learned that lesson when a constellation (group) of Starlink internet service providing satellites, in a too low perigee orbit was lost. An M-class X-ray solar flare grazed the Earth and created a short-lived G1 (the weakest) geomagnetic storm. Much ado about nothing, you would think? Except that the edge-of-space atmosphere heated up and increased its density, which increased its drag by 50 percent. Starlinks are small in size and mass but are attached to a long, vertical solar panel and the extra atmospheric drag made it impossible to maintain stable orbits or boost them higher. At least 40 Starlinks were commanded to de-orbit and burned up (as they are designed to do) with an estimated loss of at least $50 million USD. But I digress…

<Insert Figures 4A, 4B & 5>

SuperSID and Radio Science

The Society of Amateur Radio Astronomers (SARA) and Stanford SOLAR Center teamed up to develop a solar space weather monitoring program designed to detect, record and archive SID events. An excellent educator's guide is available for classroom use. From the SuperSID brochure:

> "Earth's ionosphere reacts strongly to the intense X-ray and ultraviolet radiation released by the Sun during solar events and also by lightening during thunderstorms. Students track these sudden ionospheric disturbances by using the SuperSID receiver and a computer sound card to monitor the signal strength (but not content) from distant very low frequency (VLF) transmitters of signals sent by nations to communicate with their submarines. Data show unusual changes as the VLF radio waves bounce off the ionosphere during these disturbances."

The latest SuperSID receiver (see Figure 4A) is a USB powered low-frequency preamplifier with an audio cable that plugs into your sound card's microphone input. To demodulate VLF signals up to 48 kilohertz (kHz) in frequency, a sound card with at least a 96 kHz sampling rate is required. The supplied DSP software (Python source code is also provided) has a configuration file that you setup with your locale's geographical name, latitude/longitude, the VLF stations being monitored (call sign and frequency), whether or not you want to live-stream your raw signal data to the Stanford SOLAR Center web server plus a unique station identifier (I use my Amateur Radio call). The software (see Figure 4B) records one second's worth of raw signal data every five seconds (default), date and time (UTC) plus signal strength, and saves the values for each VLF transmitter monitored in a separate, automatically created each UTC day, comma-separated values (CSV) file. *Note: I monitor three North American stations: NAA in Cutler, Maine on 24 kHz at 1000 kilowatts (kW); NLK in Jim Creek, Oso, Washington on 24.8 kHz at 250 kW; NML in LaMoure, North Dakota on 25.2 kHz at 500 kW and NPM in Lualualei, Oahu, Hawaii on 21.4 kHz at 566 kW (see Figure 5).*

You can process locally stored CSV files using the supplied software to perform simple signal analysis or with Excel (or another spreadsheet) for a more detailed analysis. But If you aren't spreadsheet savvy, the Stanford SOLAR Center web server automatically performs signal analysis and graphing (up to three days forward or back at a time) plus it overlays any X-ray solar flares and intensities on graphs as well as provide a signal reception quality number for each VLF station you live-stream (Figure 3B refers). *Note: A free ancillary program called "SID Data Grabber" (SDG) is available from the American Association of Variable Star Observers (AAVSO). Once a month, it's used to manually analyze your locally stored CSV files in more detail for each day of the month, convert it to the required format and send your report to the AAVSO solar group. Submissions are peer reviewed for accuracy, and a compilation of all SDG user reports is published in the AAVSO monthly "Solar Bulletin" journal (more in part 2).*

RFI Issues
Radio frequency interference (RFI) can be very problematic and puzzling to track down, eliminate or even reduce. Both my external switching power supplies used by various transceivers plus one backup uninterruptable power supply (UPS) generated RFI between 20 kHz and 60 kHz—right in the VLF transmitter monitoring sweet spot! The UPS was replaced with an RFI quieter APC model plus I went back to old-school, low noise, linear power supplies. Computer USB RFI can be tamed by putting snap-on ferrite chokes on the SuperSID USB power and microphone audio cables. Power line alternating current (AC) can be another RFI source but it's usually well below the VLF frequencies of interest, unless you also happen to be near a failing hydro pole transformer arcing and spewing harmonics every 60 Hz up the entire EM spectrum!

Poor Ham's VLF Receiver and Antenna
Most people don't know this, but we often have very good VLF receivers sitting in front of us because most new and better quality laptops and desktops usually have internal sound cards that can sample up to 96 kHz and can be used if their internal gain is high enough. But you won't know until you experiment. I use a 2 m tall active (amplified) antenna but you can build a small passive (not amplified) VLF loop by winding about 120 m of #22 insulated wire around a 1 m x 1 m (or larger) cross frame made from treated wood or schedule 40 PVC plastic pipe. Alternatively, an outdoor random wire short wave/high frequency (HF) receiving antenna or an 80 or 40 m wire dipole can be connected to your sound card's microphone input using adapters plus signal clipping diodes to protect the sound card microphone input (ditto for VLF loops). Because of the extremely high levels of transmitter power used by the military/navy VLF transmitters (1 million watts for NAA!), I can easily receive NAA with a several metres of insulated wire lying on the ground. *Note: Disconnect any antenna tuner, preselector and/or other inline frequency limiting devices from any antennas being used for VLF reception.*

My Final
I'll continue on in part 2. Hopefully a few readers interest in radio science have been piqued.

References and Resources

AAVSO SID Data Grabber and Solar SID Project
https://tinyurl.com/2n62mh3t
https://tinyurl.com/5d74brtu

Carrington Event
https://tinyurl.com/4ed3zra8

Stanford SOLAR Center
https://tinyurl.com/ypft4ky2

SuperSID Database and Archive
https://tinyurl.com/2p8852rd

SuperSID Software
https://tinyurl.com/2p8369e3

Society of Amateur Radio Astronomers (SARA)
https://tinyurl.com/2p99mnxr

SpaceX Losses Starlinks to Solar Storm
https://tinyurl.com/ymfmn3f8

The Ionosphere
https://tinyurl.com/2p8js6nj

Using a PC Soundcard as a VLF Receiver
https://tinyurl.com/yckp8wfk

VLF Antenna Options
https://tinyurl.com/h4rzfcam

VLF Signal Identification Guide
https://tinyurl.com/yeyuh4ef

What is a Coronal Mass Ejection?
https://tinyurl.com/43yxr6yv

What Is a Solar Flare?
https://tinyurl.com/2p8hsb5e

Figures and Captions

Figure 1: VLF Geophysics
A touch probe detects the ground wave component and an antenna simultaneously receives the sky wave component of multiple VLF transmitters. Variations in resistivity affects the VLF ground wave's signal strength, phase and TDoA, which is compared against the sky wave's to generate false-colour contour maps. Credit: GEM Systems, Inc.

Figure 2: X-ray Solar Flare Classes
Credit: Space Weather Prediction Center, NOAA.

Figure 3A: X-ray Solar Flare Shark Fin SID Event
Wow! Credit: Deborah Scherrer, Stanford SOLAR Center.

Figure 3B: VLF Diurnal Propagation
Sunrise signal drop and sunset signal rise on NAA's signal. Blue arrows are my sunrise/sunset times and black arrows are NAA's sunrise/sunset times. I circled what appears to be a minor SID event coinciding with a brief M1.4 X-ray solar flare event just after sunrise (more in part 2). The lag between sunrise signal drop and sunset signal rise indicates that ionization is a faster process than recombination. Credit: My data as processed by the Stanford SOLAR Center web server.

Figure 4A: SuperSID Receiver
This older version used a wired-in "wall wart" adapter, which was later switched to USB power in the newest version (same preamplifier design). Credit: Deborah Scherrer, Stanford SOLAR Center.

Figure 4B: DSP Software Display
Received VLF raw signal data are locally processed and displayed in real-time as power spectral density (PSD) in watts per hertz (W/Hz).

Figure 5: VLF Transmitters Map
Credit: Deborah Scherrer, Stanford SOLAR Center.