A Practical Notification System to Identify Incoming Sudden Ionospheric Disturbances

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Contents

1 Introduction

The purpose of this investigation was to develop a notification system to identify incoming sudden ionospheric disturbances (SID). A SID is an abnormally high ionization density in the ionosphere caused by solar flares or coronal mass ejections (CME). Solar flares are the sudden release of high-energy particles from a sunspot caused by the buildup of magnetic energy in the solar atmosphere (1). Along with a solar flare, another burst of energy released

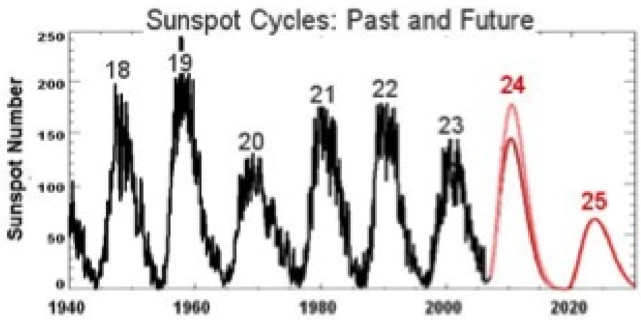

Figure 1: Solar Cycle Past, Present and Future: red lines indicate future solar maximums (http://helios.gsfc.nasa.gov/scycle.html).

from the sun is a CME. A CME releases a massive burst of solar wind and magnetic fields much larger than solar flares that also affect the ionosphere. SIDs are classified based on the peak wattage per square meter of the earths ionosphere (2). The frequency of solar flares and CMEs have a cyclic behavior where every 11 years there is a solar maximum. This is when SIDs most commonly occur (Fig. 1). The Solar maximum for the present solar cycle will occur during the 2013-2014 time period when 85 sunspots are predicted to occur on the Sun (3). The tracking and early detection of solar flares is vital for our modern world because many of our telecommunication systems can be damaged by a large solar flare.

When a SID encounters the earth's ionosphere it immediately increases the (D and E Layer) ionization in the ionosphere and consequently it changes propagation conditions for telecommunication.

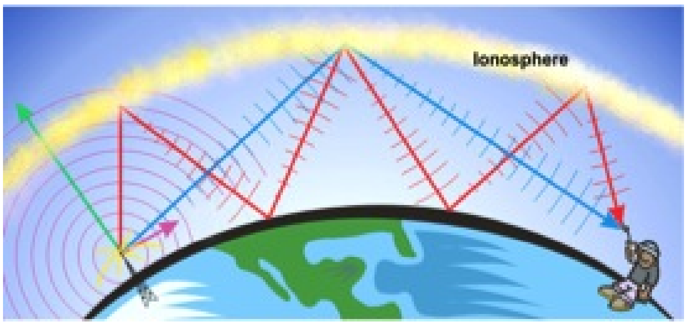

Figure 2: Very Low Frequency(VLF) Signal Transmission: represented by the signal bouncing off the ionosphere (http://solar-center.stanford.edu/SID).

SIDs change the propagation conditions by allowing radio waves to bounce off the more dense ionosphere layers rather than traveling through the ionosphere (Fig. 2). Along with the ability to change propagation conditions in the atmosphere solar flares can induce geomagnetic currents in the ground (4). Geomagnetic currents are due to the fluctuation of the earth's magnetic field producing electrical currents in the ground. These currents can be conducted by wires or electrical systems in the ground where they produce harmonics of the signals being conducted (4). These harmonics are then conducted to transformers where they can produce large amounts of heat; possibly causing the transformers to explode. Transformers are vital components of electrical power grids and could take weeks to repair or replace if a large enough SID hit the earth. One example of a solar flare that was large enough to disable many vital communications systems and affect electric power grids occurred in Quebec, Canada in 1989. Quebec's electrical grid was disabled in less than ninety seconds, causing a 24 hour power outage and 2 billion dollars of repairs (5). Another solar flare affected the Galaxy 4 satellite causing 45 million people to lose TV, radio and pager traffic for a one week period in 1998 (5). These examples illustrate the vulnerability of our technology to these major solar events. Fig. 3 shows the worlds growing dependence on cell phone technology, along with the solar activity cycle. As cell phone use increases, solar activity will have a greater impact on society when vital telecommunication networks are disabled (Fig. 3). Currently solar flares can be predicted using satellites such as the Solar and Heliospheric Observatory

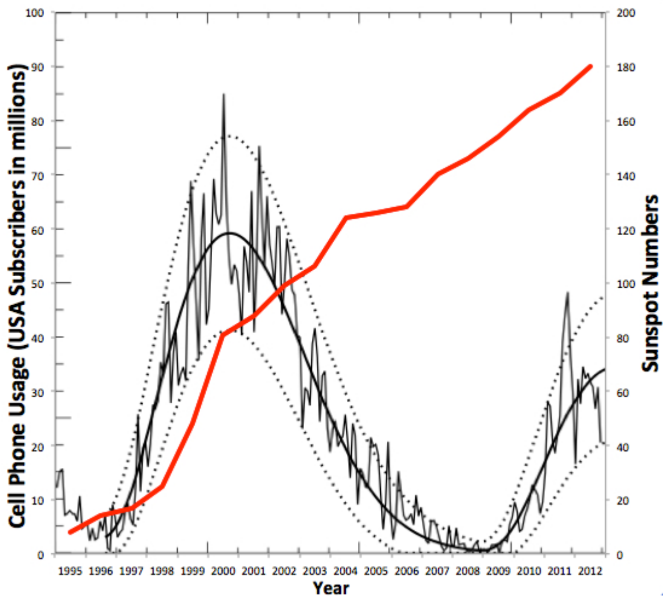

Figure 3: Solar Cycle and USA cell phone subscribers vs. time (Young 2012).

(SOHO), Geostationary Operational Environmental Satellite (GOES) and the Solar Terrestrial Relations Observatory (STEREO) (6). This current system can give warning of an incoming solar flare *up to eight minutes* before they arrive at earth and provide instant notification about an incoming solar flare. Although this system is vulnerable to solar radiation from solar flares which may disable the electrostatic sensitive components in the satellite. Although these satellite systems are efficient, solar flares could potentially disable solar observing satellites by destroying their electrostatic sensitive circuits (5). Currently there is a need to have an inexpensive and accessible detection system for solar disturbances. The system should be able to alert a user that a solar flare is coming before the relative maximum intensity of the solar flare reaches the earths ionosphere. If a sensitive detection system could be developed to work on earth this would allow for a backup to the current system to be in place for universal solar flare notification. The rational for this study was to develop an inexpensive *notification and recognition system* to identify SIDs on earth and also to serve as a backup to the current system. This system would allow for an individual to inexpensively set up a SID *identification* *system*. To carry out this project a Super SID was acquired from

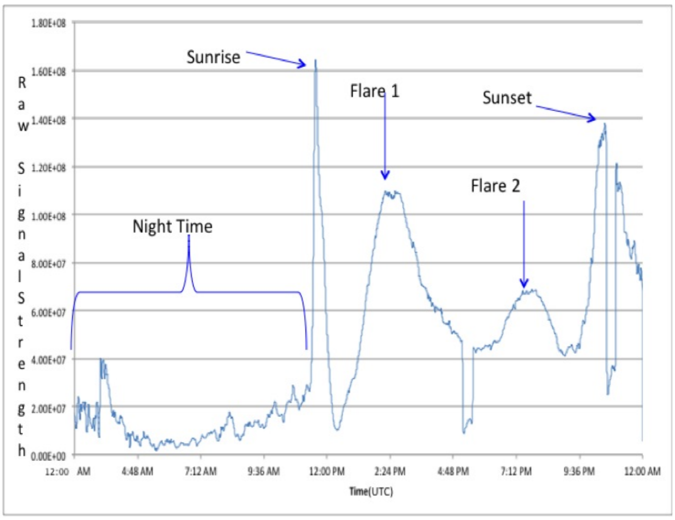

Figure 4: NAA Station Plot: highlighting the increased signal strength of a solar flare

the Stanford Solar Center (http://solar-center.stanford.edu) to amplify the VLF signals received. To receive these VLF signals a PVC antenna was designed and built to receive VLF signals from the different military submarine VLF stations around the world (Appendix 2). A computer program was developed using the MATLAB® programming language to store and analyze the VLF signals acquired from a homemade antenna (Fig. 4, Appendix 3). Once these signals were analyzed a web notification was sent out indicating that a solar flare is occuring and how long it will be until the maximum solar flare intensity. This system can then help people power plant managers or managers of large telecommunications systems, to make the decision of whether or not to take preventative action against a solar flare and limit their economics losses. The normal lead time necessary for any preventive actions to be taken is about 1 hour before the maximum intensity of a solar flare will occur (7).

2 Methods and Results

2.1 Preamplifier Acquisition and Antenna Construction

Figure 5: Super Sid unit: Preamplifier (http://solar-center.stanford.edu/SID).

The Stanford Solar Center was contacted to obtain the Super Sid monitor (8). The Super SID monitor was used to amplify the signals received from the antenna (Fig. 5). To receive the VLF signals an antenna was constructed. The antenna can be seen in Figs. 6, 7. The materials are listed in Appendix 1. In total 8 meters of 0.5 inch PVC pipe, a terminal connector, 2 meters of wood and 50 meters of enameled copper wire(22 gauge) were required. The enameled wire was wrapped through the slits at the outer ends of the wooden support part of the antenna (Fig. 6). The wire was wound with uniform tension to obtain the optimal receiving signal strength (9). The wires ends were screwed into the terminal connector so that the signal could be transferred to a coaxial cable(50 ohm). The coaxial cable was screwed into the terminal connector with blade connectors. After completing the construction of the antenna the VLF signals could be received by the Super SID (Fig 7). No impedance matching was done in this investigation since reception of the raw signals from all of the monitored VLF stations were desired.

Figure 6: Antenna Slits.

Figure 7: Antenna Construction consisting of custom PVC base, coil and coaxial cable connections.

2.2 Computer set up

The coaxial cable was connected to the Super SID preamplifier and the power adapter was plugged into a wall outlet (Fig. 5). The stereo plug on the Super SID module was then plugged into the ”line in” of the computer’s sound card. Then the program used a data acquisition algorithm to capture the amplitude data of several VLF wave stations and stores them into a comma separated data file. Noise in the data due transient factors such as electrical appliances and power line interferences was attenuated using a finite impulse response filter.

2.3 Data Acquisition

The VLF signals were acquired by running a custom built program which sampled the signal strength of each monitored VLF stations every 5 seconds. These signal strengths were then stored in a comma separated data file and graphed against time using Microsoft Excel to get a station plot for the day, for the stations seen in Appendix 2.

3 Results

3.1 Data Collection

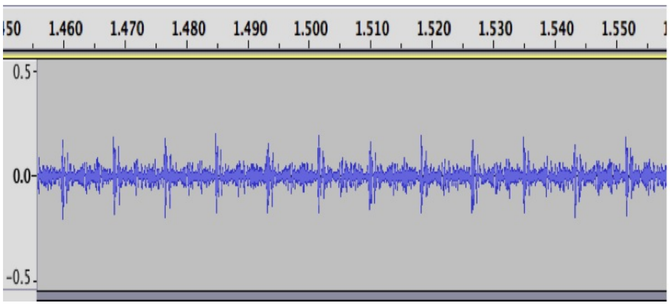

Figure 8: Raw Data from Sound Card: x axis time(sec) y axis signal strength(AU).

The data acquired from the Super SID front end during this investigation also was acquired using a MATLAB ® script (Appendix 3) that had been written to create the notification system. This script recorded one second of data from the sound card and then sent the data to be analyzed by other MATLAB® scripts. When the data came from the sound card the data was scaled from zero to one based on the signals read from the preamplifier. Fig. 8, represents a combined signal with all the VLF stations. To isolate a single station the Fourier transform must be applied to analyze the signal strength of one station against time.

3.2 Data Transformation

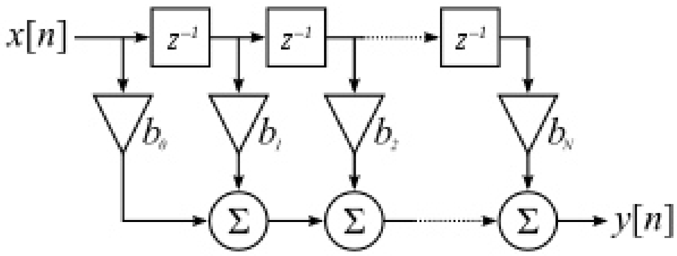

Figure 9: Finite Impulse Response Filter (http://en.wikipedia.org/wiki/Finiteimpulseresponse).

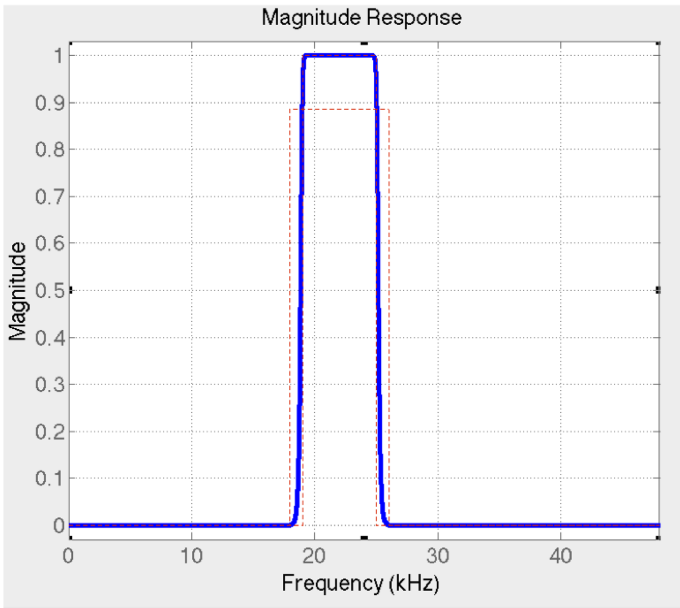

Figure 10: 19-26 kHz Band-Pass Filter created using MATLAB ®

After the data was acquired from the sound card a finite impulse response filter was applied to these signals. This helped to remove noise from the original raw data. A finite impulse response filter is a mathematical filter that removes selected frequencies from a time domain signal (10). The filter does this by taking each of the incoming samples and multiplying it by a coefficient and summing it up with the newest sample coming in and the oldest sample

Finite Impulse Response Filter Equation:

$$y[n] = b_o x[n] + b_1 x[n-1] + ... + b_n x[n-N] = \tag{1a}$$
$$\sum_{i=0}^{N} b_i x[n-i] \tag{1b}$$

Figure 11: Finite Impulse Response Filter (http://en.wikipedia.org/wiki/Finiteimpulseresponse). x[n] represents the incoming sample from the sound card and x[n-i] is the ith sample from the current sample, bn represents coefficients multiplied to these signals to remove outside frequencies and y[n] represents a filtered output of one incoming sample

(Fig 9 , 10). After this process is complete the signals out of the frequency range of 19-26 kHz are cancelled out. This script that applies the filter and creates the coefficients to cancel out other frequencies was created using the MATLAB digital signal processing library. This helps the investigation since it may remove some lower harmonics in the data and reduces the run time of the Fast Fourier Transform(FFT). Then in order to analyze each of the VLF stations individually the FFT is applied. The FFT is used in this case to look at the changing amplitude

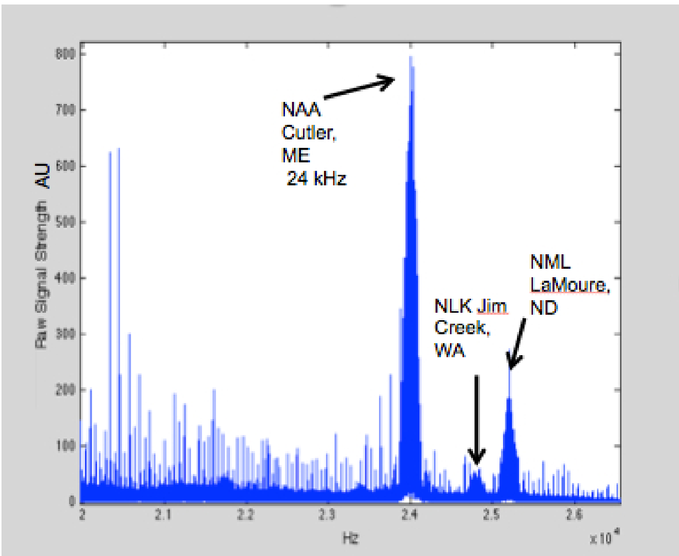

Figure 12: Fast Fourier transform of data from sound card: x axis frequency y axis signal strength (AU).

of a signal VLF station against time. The FFT is a mathematical process that takes a signal and separates it down into its frequency components, or in this case, into the different VLF stations (Fig. 12). After the FFT is applied to the acquired data each VLF station's amplitude

$$\hat{f}(\varepsilon) = \int_{-\infty}^{\infty} f(t) e^{-2\pi i t \varepsilon} dt \tag{2}$$

Figure 13: Fourier Transform Equation: f(t) is the raw function from the sound card, t represents time, ε is the frequency range which is being looked at.

was then stored in a station specific file. These files were then read back into the program to be analyzed. SIDs are identified as a large peaks because the VLF signals in the atmosphere were

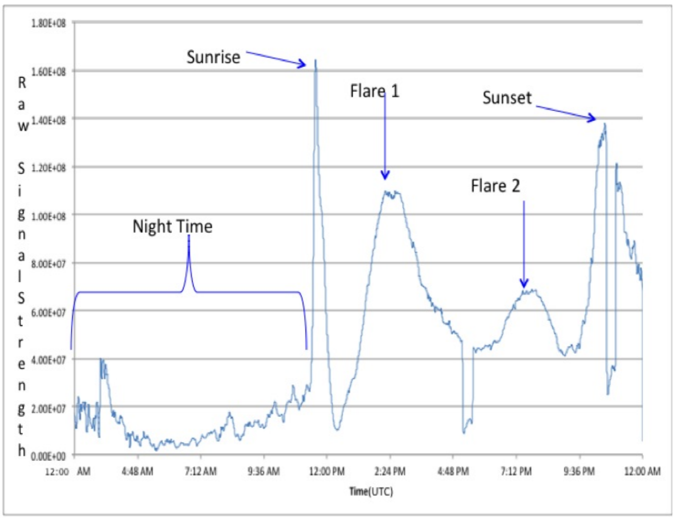

Figure 14: Resulting anomalies identified in the data: nigh time data, sunrise/sunset flares and solar flares.

now bouncing back with a greater amplitude due to the increasing reflectivity of the ionosphere (Fig. 14) as a result of a SID. Based on the gradient of the amplitude rise against time if this value is larger than an amount determined by the program a notification flag was then sent to the *notifying script* warning of a possible SID. The threshold value that is checked to determine if a solar flare is present in the data was determined by taking 30 confirmed solar flares by using the GOES satellite and finding their gradient as they were peaking and then averaging all their peaking gradients. The notifying script then sends an email to an email server which is then set to initiate a programming script to post a twitter notification (Fig. 15). The program can differentiate a SID from a sunrise sunset event by using the time of day and night and also the derivative at the current data point. While analyzing the data one notices that sunrise-sunset

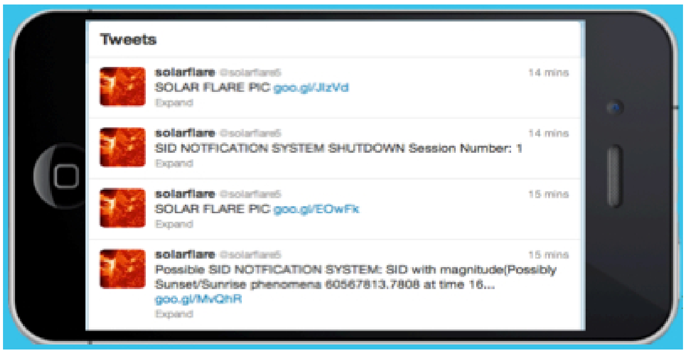

Figure 15: Notification via Social Media.

events have a greater rate of change than SID so one can use this as a way to differentiate the two. Also one can use the time of day to determine if there are sunrise-sunset peaks because someone will know approximately when this is going to occur so it can be coded into the program a function to monitor the sunrise and sunset flare timings. The program was fully tested using past data from a solar flare on January 22 2012. The red circles represent the solar flares detected using the program (Fig. 16). The program was confirmed to work using corresponding solar flare data from the GOES and the SOHO satellite for January 22 2012. Overall the program created in this investigation gives an hour and a half lead time before the maximum damage from a solar flare can be done to the earth-based telecommunication systems. This would give a reasonable amount of time for managers to take preventive action against the possible effects of a solar flare. The program was tested over a period of 10 weeks and it was determined that the program has an 88% success rate in detecting a solar flare. Although the program had a 100% success rate in determining the solar flares the could damage earth's telecommunication systems. Finally this system cost $50 to build all together.

4 Discussion and Conclusion

This system may be able to protect power plants from possible equipment loss due to the effects of a solar flare. If a power station management team were to use this system

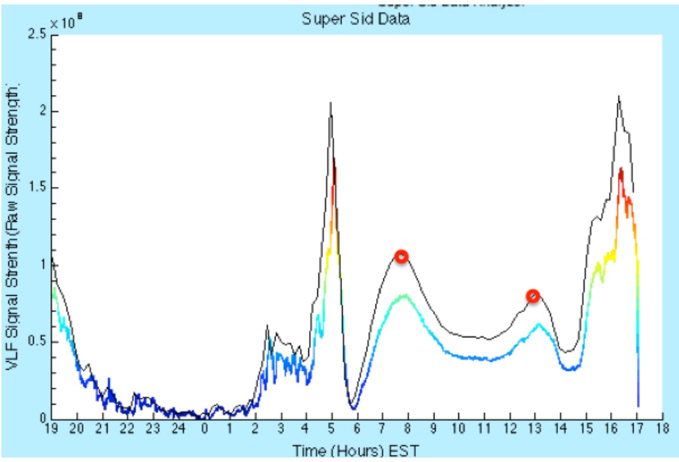

Figure 16: Solar Flare Data 01/22/12: two flares shown with red circles.

they could possibly set up multiple systems in an area all running at once to identify and notify people of a possible incoming SID. This system, with a better antenna for example, could be fine-tuned to more accurately and precisely identify solar flares and a power station manager could be notified of a definite incoming SID because VLF stations could be received better resulting in a better prediction. With more antennas, pointing in different directions, data could be better obtained from each cardinal direction allowing for a better signal overall. This idea of using multiple antennas is a future study to look into since this investigation had noisy data which limited the identification of solar flares. The station manager could then make the decision of what to do with the plant. A possible response is to reduce the current through the power lines, thereby protecting the transformers from damage. As seen in Fig. 15 the power plant manager would receive information in the form of graphs and text pertaining to the SID, which will then allow for an informed decision to take preventative actions.

This study involved the development of a functional notification system to warn of a possible SID. The notification system is fully functional based on the scripts that I have written. This system can be set up as described in this paper, and with the proper software coded in MATLAB ® . The system would then be run continuously on a computer that interfaces with the VLF antenna-preamplifier system. This notification system would allow power plant operators or others involved in power, communication and computer systems to be notified of possible SID threats that could adversely impact the technology they are in charge of.

To make this system fully operational, specific steps are needed. The system must be calibrated to analyze all the VLF stations for SIDs rather than looking at one station for SIDs by changing the gradient factor, which flags a solar flare. Another step that must be taken is that multiple antennas should be used in order to receive the strongest signals from each direction to get a more precise identification of a SID. By taking these steps the system can be improved in terms of its ability to most accurately and precisely identify SIDs.

All together the system in this investigation does the same main job as a satellites to detect solar flare. Although solar flares can disable the satellites used to detect them. Also comparing the cost of a satellite system to this $50 system this system can do the same effect as a satellite system in warning a user of a incoming solar flare with less a cost. Finally the system can detect the solar flares that could damage earth's telecommunication system.

5 References

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Appendix 1 Antenna Materials

- 8 0.12 meter PVC pieces
- 17 0.3 meter PVC pieces
- 1 1.2 meter PVC piece
- 4 elbow PVC joints
- 11 T PVC connectors
- 2 quad PVC joints
- 50 meters of enameled copper wire
- 2 1 meter pieces of 3 centimeter by 0.5 centimeter wood
- 7 centimeter bolt with nut
- Terminal connector
- Coaxial Cable
- Blade Connectors

Appendix 2 VLF Stations

VLF transmitters used in the investigation

Appendix 3 Program Algorithm