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Quantifying the radiation belt response to lightning via ground-based VLF and Van Allen Probe data

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Abstract

Many factors contribute to the loss mechanisms of electrons in the Earth's radiation belts, but the relative significance of these causes remains a subject of mystery and debate. One such component is lightning-produced whistler-wave radiation. These electromagnetic waves, which take on a unique "whistler" dispersion profile under the plasma conditions of the magnetosphere, dislodge trapped electrons in the radiation belts and cause precipitation in the D region of the ionosphere. We are able to detect these Lightning-induced Electron Precipitation (LEP) events using Very Low Frequency (VLF remote sensing). In our work, we assembled a large database of 7720 LEP events from November 2017 to August 2019. We separated the days in January-June 2019 into "High LEP" and "Low LEP" days. Using data from the Van Allen Probes over this period, we found a significant difference in the observed electron flux between these two datasets. This indicates that whistler waves from terrestrial lightning play a significant role in the radiation belt electron distribution, but further research and modeling is required to quantify this role.

1 Introduction

Since ALLEN et al. [1958] first identified the radiation belts over 60 years ago, researchers have been investigating what the dominant mechanisms are that grow and shrink the belts, and what mechanisms add or remove particles. Walt and MacDonald [1964] showed that Coulomb collisions between particles play a role in the lower magnetic altitudes ($L < 1.25$) where particle density is higher. At higher L values, Very Low Frequency (VLF) radio waves, which range from 3 to 30 kHz, form the dominant mechanism.

The three principle sources for these VLF waves are plasmaspheric hiss, man-made VLF signals from transmitters, and lightning-generated radiation Helliwell [1965]. The third category represents what are known as Lightning-induced Electron Precipitation (LEP) events.

When electromagnetic waves dislodge particles from the radiation belt, the particles precipitate into the ionosphere, changing the electron density in a given region. We can then observe this event through perturbations in VLF waves propagating through the disturbed region. The Earth's ionosphere and surface form a waveguide structure for VLF waves, allowing long distance transmission of signals. When a section of the ionosphere along the transmitter-receiver path is disturbed, the received signal is perturbed as a result of the scattering.

The research presented aims to measure the impact LEP events have towards electron loss in the radiation belt by collecting a large dataset of events in the continental United States. We then use this dataset to partition the days over a six-month period of 2019 into "High LEP" and "Low LEP" days based on the rates of LEP occurrence. Finally, we compare satellite measurements of the radiation belt electron flux in the corresponding region between these two partitions to see if there is a statistically significant difference in flux levels.

2 Methodology

To collect a large dataset of candidate LEP events, we advantage of the Georgia Tech LF Radio Group's network of VLF receivers [Cohen, 2018] throughout the continental United States, along with five US Navy VLF Transmitters that are within detectable range of the receivers. Perturbations in the ionosphere impact the ability for VLF signals to propagate, meaning that they can be observed in corresponding perturbations in the received signal.

To search for candidate events, we used the National Lightning Detection Network's (NLDN) database of lightning strokes in the United States [Cummins et al., 1998]. We filtered out all strokes occurring at daytime, defined at an altitude of 80 km, as the the sun's ionization makes it difficult to detect meaningful perturbations from electron precipitation. Lauben et al. [1999] suggests that for a geographic latitude range of 39 degrees, the precipitation will be polewardly displaced from the lightning stroke by 6-8 degrees due to the oblique propagation of the whistler waves. We approximated this as a standard 700 km displacement. As these models predict a range of possible displacements at different latitudes, we approximated the maximum radius of the possible disturbance to be 400 km, drawn as a circle around the polewards location. If this circle overlapped with a transmitter-receiver path, we treated the VLF data corresponding to the time of the lightning stroke as a candidate event.

Figure 1 shows an example of this geographical search, as well as a plot of the VLF signal detected at the Dover receiver.

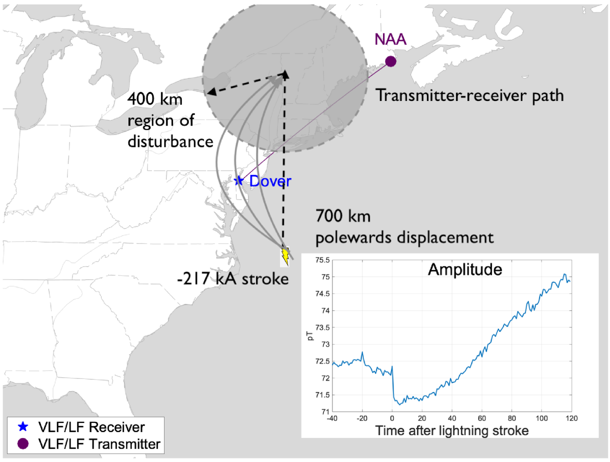

Figure 1. An LEP event displayed over a map of North America. This event was generated by a -217 kA stroke that occurred on October 27th, 2018 at 07:36:18.217 UT.

In total, we assembled a database containing 746,081 nighttime samples associated with strokes with $|I| > 100$ kA, from November 4, 2017 to August 13, 2019. However, a given LEP event may appear in multiple different samples, if multiple transmitter-receiver paths overlap with a given event. The total number of distinct candidate events reduces to 89279.

Not all perturbations in the received VLF signal represent LEP events. We make use of a neural network to classify collected VLF signals as LEP events, or non-events. To train our classifier, we used 2200 manually classified samples. We oversampled the number of real events to have a total set of 684 events and 1516 non-events. The classifier achieved an 85% test accuracy and an 82% detection efficiency.

Of the 89279 total unique candidate events, we classified 7720 as actual LEP events, representing an occurrence rate of 0.0865.

The Van Allen Probes were a pair of satellites orbiting the Earth in operation from 2012 to 2019. Each probe was equipped with the Magnetic Electron Ion Spectrometer (MagEIS), used to detect electrons with energies from 30 keV to 4 MeV Boyd et al. [2019]. The probes orbited the Earth in a highly eccentric equatorial path, meaning that the data captured represents measurements from a wide range of locations in the radiation belts.

We used data from the Van Allen Probes to compare electron flux in the radiation belts during days with high rates of LEP event occurrence versus days with lower LEP occurrence. We defined "High LEP" days as days where at least 20% of candidate strokes caused actual detected LEP events, and treated the rest as "Low LEP" days.

3 Results

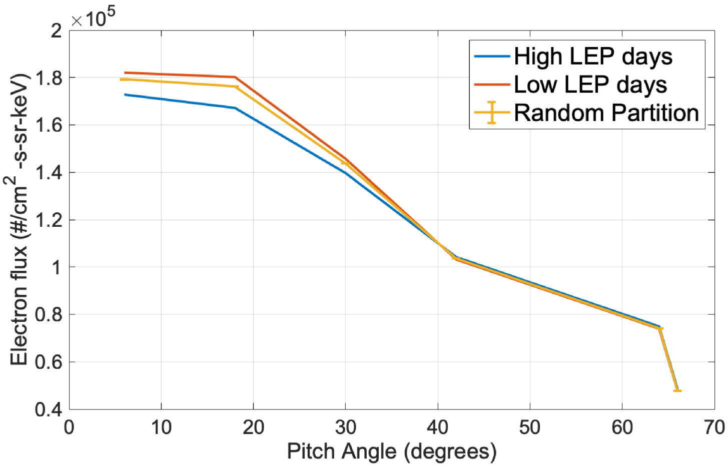

Figure 2. Electron flux measured on days with high and low LEP occurrence

Our findings, shown in Figure 2, suggest a stark contrast in the particle distribution between days when LEP events are occurring frequently versus days when they are not, particularly at lower pitch angle ranges. The middle bar, labeled "random partition" is an attempt to illustrate the statistical significance. We divided the data into random partitions 100 times. The average flux measured along one such partition is plotted in yellow, while the average difference between the partitions is shown in the error bars. Note that the error bars are not easily visible, and are far smaller than the actual gap in observed electron flux.

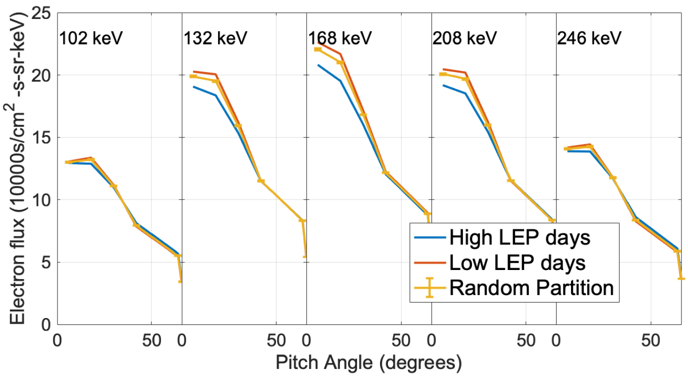

Figure 3. Electron flux measured on days with high and low LEP occurrence, grouped by electron energy level

Examined across different energy levels, as shown in Figure 3, we see the highest gaps present at the 132-208 keV range, although the gaps are larger pitch angles at most energy levels.

This indicates that LEP events may account for a substantial portion of electron flux changes in the corresponding geographical region. However, this correlation alone does not necessarily mean that LEP events are the cause for the observed gap. In order to confirm this, we must test if our existing models for electron precipitation can describe this gap. Further work requires approximating electron flux changes from the ground measurements of LEPs, and comparing this result to the observed variance in electron flux in the belts.

4 Acknowledgements

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