

1 **Detection of VLF attenuation in the Earth-ionosphere waveguide caused by X-class**
2 **solar flares using a global lightning location network**

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6 **Key Points:**

- 7 • VLF lightning location network detection efficiency is severely impacted by powerful
8 solar flares and other space weather events.
- 9 • By comparing the current stroke-to-station path distribution with a background
10 distribution, VLF attenuation regions can be detected.
- 11 • This technique enables near-real-time VLF attenuation and ionosphere parameter
12 monitoring in the Earth-ionosphere waveguide.
13

14 **Abstract**

15 Solar flares, energetic particles and Earth-impacting coronal mass ejections enhance ionization in
16 the lower ionosphere, inhibiting radio wave propagation in the Earth-ionosphere waveguide
17 (EIWG). This enhanced ionization is observed locally by ionosondes and GPS/GNSS receivers,
18 but spatial coverage of these observations is limited by receiver location. VLF propagation
19 studies have previously been performed to assess the impact of space weather on the EIWG;
20 however, these studies are typically limited by small numbers of fixed VLF transmitters and
21 receivers, and observe only the region of the EIWG along propagation paths between
22 transmitters and receivers. Here, we use global lightning as a VLF source, and an existing
23 lightning detection network as a receiver. By mapping spheric propagation paths between
24 lightning strokes and numerous network stations, and considering how this distribution of paths
25 changes during solar events, we can identify attenuation regions in the EIWG caused by space
26 weather. We describe the VLF response in the EIWG to two X-class solar flares, and compare
27 mapped attenuation regions with those provided by the NOAA D-Region Absorption Prediction
28 (D-RAP) model. The identified attenuation regions associated with these flares match the D-
29 RAP-predicted regions well in both spatial extent and onset timing. Measurements of VLF
30 attenuation caused by solar flares can provide ground-truth confirmation of modeled attenuation,
31 and can inform the detection efficiency of lightning location networks. This analysis also paves
32 the way for real-time VLF attenuation mapping in the EIWG.

33 **Plain Language Summary**

34 Very-low-frequency (3-30 kHz, “VLF”) radio signals can propagate long distances by reflection
35 between the ground and the lower ionosphere. This property enables the detection and location
36 of lightning strokes, which emit radio waves in a large frequency band, with relatively few VLF
37 receiver stations positioned around the world. Solar flares, and other space weather events, can
38 severely reduce the propagation distance of VLF waves around the Earth, limiting the
39 effectiveness of lightning location networks and disrupting other infrastructure that relies on
40 radio wave interaction with the lower ionosphere. We present a technique for detecting VLF
41 attenuation using a lightning location network. This study improves our understanding of the
42 effects of solar flares on lightning detection, and provides the groundwork for a lightning
43 detection network to be used as a real-time monitor of radio attenuation in the lower ionosphere.

44 **1 Introduction**

45 Solar extreme ultraviolet (EUV) radiation generates most of Earth’s ionosphere; and changes in the energetic particle
46 and radiation output of the Sun can dramatically affect the Earth’s ionosphere profile. Solar flares enhance ionization
47 on short timescales, which significantly alter the ionosphere density profile throughout even the lowest layers (e.g.
48 Mitra, 1974). This enhanced ionization in the D region can severely impact VLF radio wave propagation in the Earth-
49 ionosphere waveguide (e.g. Thomson & Clilverd, 2001).

50 Mapping D-region ionosphere density at the global scale and with high time resolution is challenging and
51 often involves using both ground-based radio propagation measurements and in-situ instrument campaigns.
52 Ionosondes and GPS/GNSS TEC measurements can produce accurate profiles of the E- and F-region ionosphere, but

53 usually cannot resolve D-region electron density and are effective only over ground stations. Long-duration in situ
54 measurements are difficult in this altitude band; the D region, at 50-80km altitude, is too high for stratospheric
55 balloons, but thermosphere drag precludes long-duration orbital measurements there. VLF monitoring stations or
56 networks can characterize propagation along transmitter-to-receiver paths; however, such networks operating today
57 rely on a small number of transmitters (e.g. MSK stations) and receivers, and therefore suffer from poor spatial
58 resolution of regional ionosphere features (e.g. Chilton, Steele, & Norton, 1963; Crombie, 1965; Thomson & Clilverd,
59 2001; Boudierba, NaitAmor, & Tribeche, 2016). By using global lightning as a VLF source, we can detect regional
60 VLF attenuation features with higher spatial and temporal resolution.

61 Previous work by other authors has shown that the Wait and Spies 2-parameter ionosphere (e.g. Thomson,
62 N., 1993) can be inferred from measurements of lightning-launched sferics. Cummer, Inan, and Bell (1998) compared
63 modeled and measured VLF and ELF sferics to infer nighttime D region electron density. Jacobson, Holzworth, Lay,
64 Heavner, and Smith (2007) demonstrated a method of lower-ionosphere sounding by opportunistic use of LF sferics
65 launched by Narrow Bipolar events. Jacobson, Shao, and Holzworth (2010) reported on a steep-incidence VLF/LF
66 sounding method for studying transient, localized disturbances in the nighttime D region. Carvalho, et al. (2017)
67 presented a method to measure the ionospheric effective reflection height along 200-250km paths from VLF sferics
68 launched by triggered lightning. Gross, Cohen, Said, and Gołkowski (2018) used MSK transmitter stations as well as
69 lightning sferics to infer ionosphere parameters from polarization of VLF signals, and McCormick, Cohen, Gross, and
70 Said (2018) calculated ionosphere parameters using a comparison of simulated and measured sferics from several
71 thunderstorms; both these techniques were presented for continent-scale regions, with possible extensions to global
72 coverage in future work. A technique to provide a large-scale D region diagnostic using a small number of receivers
73 to measure ELF sferic group velocity was presented by Gołkowski, et al. (2018). Thus far, a real-time global lower
74 ionosphere monitor has not been demonstrated.

75 1.1 Lightning-generated sferics in the Earth-ionosphere waveguide

76 Cloud-to-ground lightning strokes typically discharge voltages of >1 MV over ~ 70 μ s, with peak current in the 10-
77 100 kA range (Uman & Krider, 1982). Each lightning stroke can be thought of as a short-lived transmission line
78 antenna that emits broad-spectrum electromagnetic waves in a dipole-like radiation pattern. These radio waves are
79 reflected by the lower ionosphere at an altitude where their frequency matches the electron plasma frequency ω_{pe} (e.g.
80 Parks, 2004):

$$\omega_{pe}^2 = \frac{n_e e^2}{m_e \epsilon_0}$$

Where n_e is the electron number density, e is the electron charge, m_e is the mass of the electron and ϵ_0 is the permittivity of free space. The lower ionosphere acts as a reflector to radio waves in the ELF (3-3000Hz) and VLF (3-30kHz) frequency range. For a given frequency ω , the ionosphere can be thought of as a conductive spherical shell. Earth's surface, having electrical conductivity much greater than the intervening atmosphere, forms a conductive inner shell (e.g. Siingh, et al., 2007). Together, the lower ionosphere-atmosphere-Earth surface forms the Earth-ionosphere waveguide (EIWG), through which ELF and VLF radio waves may propagate long distances. VLF waves launched by lightning strokes that propagate in the EIWG are called atmospheric waves, or sferics.

By detecting sferic wave packets that propagate large distances in the EIWG, we can observe global lightning with a relatively small number of observing stations. The World Wide Lightning Location Network (WWLLN) is a network of ~80 stations, distributed globally between $\pm 80^\circ$ latitude. Each station listens for sferics and reports the time of group arrival (TOGA) to a processing server; this server then combines TOGAs from each detecting station, and determines the location and time of the lightning stroke (Dowden, Brundell, & Rodger, 2002), (Dowden, et al., 2008), (Hutchins, et al., 2012).

1.2 Impact of solar flares on radio attenuation in the EIWG

Increased X-ray and EUV flux from solar flares has been shown to enhance ionization in the lower ionosphere (e.g. Mitra, 1974). This electron density enhancement at low altitudes lowers the reflection altitude of radio waves propagating in the EIWG, including lightning-launched sferics. Because of increased neutral particle density at lower altitudes, more energy is lost to electron-neutral collisions during radio wave reflection, and hence the wave is more attenuated while ionization in the lower ionosphere is enhanced.

Using near-real-time lightning location information from WWLLN, we can detect VLF attenuation in the EIWG caused by solar flares. By leveraging the spatial distribution of WWLLN network stations, we can approximately map VLF attenuation regions on timescales of ~10 minutes.

Detection of attenuation regions relies on differing timescales of solar flares and thunderstorms. Thunderstorm flash rate and geographic location typically vary on the order of hours (Rakov & Uman, 2003), while solar flare onset typically occurs in minutes and X-ray irradiance decays by an order of magnitude within ~1 hour (Codrescu, Mihail; NOAA Space Weather Prediction Center, 2010). Enhanced low-altitude ionization from solar

108 flare activity will occur in a circular region centered on the Earth subsolar point (Sauer & Wilkinson, 2008), (Levine,
109 Sultan, & Teig, 2019).

110 In addition to increased attenuation in the lower-frequency portion of the VLF band (<10 kHz), solar flares
111 can cause enhancement of VLF signals in the higher-frequency VLF (>15 kHz) (Volland, 1995). Such enhancements
112 have been observed recently by Wenzel et al. (2016), which used four receivers in Europe and North America to
113 measure amplitude and phase changes in VLF transmitter signals during M- and C-class flares; and George et al.
114 (2019), which measured amplitude enhancements in the NPM 21.4 kHz signal using a receiver at Scott Base,
115 Antarctica, during several X-class solar flares. Since WWLLN uses the <16 kHz portion of VLF sferics to locate
116 lightning strokes, it is sensitive to VLF attenuation caused by solar flares, but not enhancement in the higher-frequency
117 VLF.

118 The method presented here for detection of solar flare effects relies on the decrease of WWLLN detection
119 efficiency near the subsolar point. This means the network, like other VLF lightning detection networks, is adversely
120 affected by ionizing events from space, and these modifications to the network affect interpretations of lightning data.
121 By studying the impact of solar flares on WWLLN lightning detection, we can improve our understanding of the
122 effects of space weather on lightning detection networks and other technologies that rely on VLF reflection in the
123 EIWG.

124 **2 Methods**

125 **2.1 Global lightning stroke-to-station path distribution**

126 WWLLN detects 0.5-1.5 million lightning strokes per day. These stroke locations are processed in real time,
127 and by plotting great circle paths between stroke locations and the stations that detect each stroke, we can build a
128 global stroke-to-station path distribution with a 10-minute timestep. A stroke-to-station path distribution for a 10-
129 minute time window ending at time t is notated here as $ss(t)$: a matrix of integers, where each element counts the
130 number of stroke-to-station path crossings of the geographic area that element represents. We chose 1°
131 latitude/longitude grid regions, such that $ss(t)$ has 180×360 elements that cover the Earth and do not overlap. A
132 sample stroke-station path distribution for a 10-minute time window is shown in Figure 1.

133 Grid locations near high-quality WWLLN stations or active thunderstorm regions typically are traversed by
134 10^3 - 10^4 stroke-station paths every ten minutes, whereas locations near the poles or far from both WWLLN stations
135 and active thunderstorms may be traversed by only a few stroke-station paths per day. Ground composition along the

136 path is also important; since ice is much less conductive than dry land or ocean water, spheric propagation across the
 137 North pole is only possible via a few ocean routes, and propagation across Greenland and Antarctica is rare
 138 (Westerlund & Reder, 1973), (Barr, Jones, & Rodger, 2000).

139 2.2 Model comparison: D-Region Absorption Prediction

140 We used the NOAA D-Region Absorption Prediction (D-RAP) model to inform our guess for VLF
 141 attenuation region geometry and timing (Codrescu, Mihail; NOAA Space Weather Prediction Center, 2010). The D-
 142 RAP model predicts HF radio attenuation using X-ray, electron and proton flux detected by the GOES constellation.
 143 Absorption at the subsolar point is calculated with an empirical relation between the highest affected frequency (HAF)
 144 and X-ray flux (Sauer & Wilkinson, 2008):

$$145 \quad HAF \text{ (MHz)} = (65 + 10 \log_{10}[flux \text{ (W m}^{-2}\text{)}]) (\cos \chi)^{0.75}$$

146 Where χ is the solar zenith angle. For example, the HAF for an X9.3 flare ($flux = 9.3 \times 10^{-4} \text{ W m}^{-2}$) is about 35 MHz,
 147 decaying to 0 at the day/night terminator.

148 Although the D-RAP model addresses HF, not VLF, attenuation in the EIWG, it is still a useful comparison
 149 for a VLF attenuation analysis. HF and VLF attenuation in the EIWG during solar flares are both primarily caused
 150 by increased low-altitude ionization, and thereby increased electron-neutral collision frequency during wave
 151 reflection. Hence, both D-RAP and this VLF attenuation analysis are addressing changes in the lower ionosphere that
 152 should be approximately collocated and simultaneous.

153 2.3 Attenuation region visualization

154 We can gain insight into spatial and temporal variation in EIWG parameters by looking for changes in the global
 155 stroke-station path distribution through time. Energetic solar flares are particularly useful events to study, because of
 156 their predictable ionization enhancement in the lower ionosphere. With the assumption that far-field solar flare
 157 radiation can be treated as a planar radiation packet that is not appreciably distorted by Earth's magnetic field, nor
 158 does it contain fine structure relative to the size of the Earth, the pattern of enhanced ionization in the lower ionosphere
 159 is a circular region centered on the subsolar point (Codrescu, Mihail; NOAA Space Weather Prediction Center, 2010),
 160 (Levine, Sultan, & Teig, 2019).

161 We can use the WWLLN stroke-station path distribution to look for VLF attenuation regions in the EIWG.
 162 First, we identify a background stroke-station path distribution at the time just before flare onset. Next, we measure

163 the stroke-station path distribution immediately following flare onset, and calculate attenuation of stroke-station paths
 164 relative to the background distribution.

165 A background stroke-station path distribution is generated by taking the median of several consecutive
 166 stroke-station path distributions during a period of quiet solar activity. For any time t , a background distribution is
 167 constructed by taking the median of the previous hour's stroke-station path distributions,

$$168 \quad ss_b(t) = \text{Median}(\{ss(t_i)\}_{i=1}^6)$$

169 For a 1° latitude-longitude grid, ss_b is a 180×360 matrix, where each element is the median number of stroke-station
 170 paths crossing that grid location in the set of 10-minute time intervals ending at $t_i = (t - i \times 10 \text{ minutes})$. This time
 171 interval ranges from $t - 70$ minutes to $t - 10$ minutes; it is the hour preceding the 10-minute interval covered in
 172 $ss(t)$.

173 The 10-minute sample size is chosen because it is short enough to capture the onset of solar flare ionization,
 174 while still containing a large population of stroke-station paths. Additionally, WWLLN writes files containing stroke-
 175 station path and stroke power information every 10 minutes, so this is a convenient duration for a real-time analysis.
 176 A 1-hour median timescale was chosen to be shorter than typical mesoscale convective system lifetime (Markowski
 177 & Richardson, 2011), while acknowledging that individual thunderstorm flash rate can vary significantly minute-to-
 178 minute. A longer median timescale would reduce the median distribution's relevance to t as an immediate
 179 background, while a shorter median timescale would be more susceptible to varying thunderstorm flash rate.

180 Next, the 10-minute stroke-station path distribution immediately following a solar flare is compared to the
 181 last hour's background stroke-station path distribution. Solar flare times are identified as peaks in GOES-13 X-ray
 182 irradiance data (NOAA NCEI, 2019). VLF attenuation regions can be characterized by the attenuation \mathcal{A} , in decibels,
 183 of stroke-to-station paths,

$$184 \quad \mathcal{A}(t) = 10 \log_{10} \left(\frac{ss(t)}{ss_b(t)} \right)$$

185 This measure of VLF attenuation is only accurately defined at matrix locations with sufficient counts in both matrices;
 186 it is most accurate at geographic locations near WWLLN stations and/or frequent thunderstorm regions.

187 Additionally, we can validate attenuation region timing by computing the characteristic size of VLF
 188 attenuation region, and comparing the change of the size of this region with geostationary X-ray flux data (NOAA
 189 NCEI, 2019). We correlate X-ray flux recorded by the GOES-13 satellite with the size of the largest circular contour

190 centered on the subsolar point within which the average stroke-station path attenuation exceeds 6 dB. This threshold
191 can be tuned to accept attenuation regions generated by lower-power flares, but is particularly useful for observing
192 the onset timing of large attenuation regions and the radial change in stroke-station path attenuation within the region.

193 **3 Results and Discussion**

194 In this analysis, we considered the X9.3 and X8.2 solar flares of September 6 and 10, 2017. The solar events of this
195 period are well-studied (Yasyukevich, et al., 2018), (Gary, et al., 2018), (Qian, et al., 2019), (Levine, Sultan, & Teig,
196 2019). Sunspot group AR2673 produced several flares between late August and September 10, as well as solar
197 energetic particles (SEPs) and coronal mass ejections (CMEs). Although these particle events had a significant impact
198 on the ionosphere, this was mostly contained in the polar caps, and solar flare ionization was still the primary effect
199 on the lower ionosphere at low- to mid-latitudes. Among several powerful solar flares originating from this sunspot
200 group, we chose the X9.3 flare at 12:10 UT on September 6, and the X8.2 flare at 16:10 UT on September 10, because
201 radio propagation in the low-latitude ionosphere was expected to be nominal in the hours leading up to flare onset, as
202 predicted by D-RAP.

203 Attenuation in the EIWG caused by the solar flares of September 6 and 10, 2017, was investigated by plotting
204 the attenuation in WWLLN stroke-station path crossings using a 10-minute timestep and 1-hour median baseline
205 distribution. A comparison between the WWLLN response and the D-RAP predicted absorption is shown in Figure
206 2. A timing comparison between attenuation region radius and GOES-13 X-ray irradiance is shown in Figure 3.
207 Finally, WWLLN stroke detection count rate for a sample 1000-km-radius region near the subsolar point during the
208 September 10, 2017 flare is compared with GOES-13 X-ray irradiance in Figure 4.

209 Figure 2 shows comparisons between the D-RAP HAF maps and WWLLN-detected VLF attenuation. Figure
210 times are chosen to reflect peak X-ray irradiance at flare onset; in the cases of both the September 6 and September
211 10 flares, maximum extent of both HF and VLF attenuation occurs within a few minutes of peak X-ray irradiance.

212 The September 6 flare at ~12:00 UT is preceded by an X-class flare at ~9:00 UT, and solar energetic particles
213 (SEPs) that enhance ionization near the poles. The HAF map at 12:10 UT shows the subsolar attenuation region
214 produced by the solar flare, but also polar attenuation regions produced by earlier and ongoing particle effects. The
215 September 10 flare at ~16:00 UT is not immediately preceded by other powerful flares or SEPs, but SEPs are launched
216 at the same time as the flare and arrive at the Earth within an hour of the peak X-ray irradiance. These generate polar
217 attenuation regions as well.

218 The VLF attenuation regions mapped using WWLLN stroke-station paths closely match D-RAP-predicted
219 HF attenuation regions at flare onset. For both the September 6 and 10 flares considered, the extent of 6dB median
220 stroke-station path attenuation tracks that of ~ 10 MHz 1 dB absorption predicted by D-RAP, with the exception of polar
221 attenuations, which are not captured by the WWLLN stroke-station path difference. It should be noted here that both
222 D-RAP-predicted HF attenuation and VLF attenuation mapped here extend nearly to the terminator, which is the
223 expected limit for attenuation caused by solar EM radiation.

224 Figure 3 shows that the onset timing of subsolar VLF attenuation regions occurs within this analysis' 10-
225 minute time resolution of peak X-ray irradiance measured at GOES-13. X-ray irradiance peaked at 12:02 UT on
226 September 6, 2017 and 16:03 UT on September 10; VLF-attenuation region radius on both these days peaked during
227 the ten-minute intervals containing these times.

228 X-class flares have a significant impact on WWLLN detection of lightning strokes, as shown in Figure 4.
229 Here, the WWLLN-detected occurrence rate of lightning strokes in 1000-km-radius region in the Caribbean is plotted
230 for September 10, 2017. At the onset of the X8.2 flare at around 1600 UT, stroke rate drops 90% in a few minutes,
231 and does not rise above the previous minimum recorded that day for several hours. We interpret this short-term
232 decrease in stroke rate as sferics' inability to propagate out of the VLF attenuation region with sufficient power to be
233 detected and used in lightning detection by WWLLN.

234 **4 Conclusions**

235 This analysis demonstrated the use of a global lightning detection network to map VLF attenuation in the EIWG
236 caused by solar flares. Previous work has studied solar flare impact on low numbers of VLF transmitter-receiver
237 paths, often only single paths (e.g. Boudierba, NaitAmor, & Tribeche, 2016). More recently, lightning detection
238 networks have been used in conjunction with fixed VLF transmitters to study multi-path flare effects (Raulin, et al.,
239 2010), and small numbers of receivers have probed the D-region ionosphere using lightning sferics as a VLF signal
240 (Han & Cummer, 2010), (McCormick, Cohen, Gross, & Said, 2018). This work demonstrates global VLF attenuation
241 mapping using a lightning detection network, with the ability to resolve equatorial attenuation features associated with
242 solar flares.

243 The VLF attenuation mapped in this study has significant implications for the detection efficiency of
244 WWLLN and other VLF lightning detection networks. WWLLN requires a minimum of 5 stations to detect a sferic
245 in order to locate a lightning stroke; therefore, if multiple VLF propagation paths between a thunderstorm and

246 WWLLN stations are not viable due to increased low-altitude ionization, and the total number of WWLLN stations
247 able to detect strokes from that thunderstorm falls below 5, WWLLN will be unable to detect those strokes. Strokes
248 occurring inside VLF attenuation regions during X-class solar flares are unlikely to be detected, as demonstrated in
249 Figure 4.

250 There are several shortcomings of this analysis that will be addressed in future work. First, the flares
251 considered here are relatively “clean” and temporarily isolated events; that is, there are no flares of any significant
252 magnitude preceding or following them by less than 1 hour, nor any other obvious sources of lower-ionosphere
253 ionization enhancement (NOAA NCEI, 2019). Additionally, they are both very powerful, X-class events. As such,
254 we expect them to produce a predictable and significant attenuation region on the day side lower ionosphere (Sauer &
255 Wilkinson, 2008). Less powerful events may not produce attenuation that is as evident in a WWLLN stroke-station
256 path analysis. So far, analyses of recent C-class flares (2 orders of magnitude less irradiance than X-class) have not
257 shown an obvious attenuation effect on WWLLN sferics. Future work should address the lower limit on flare
258 irradiance that is detectable as a single-event attenuation region, and perhaps the lower limit that is detectable in a
259 superposed epoch analysis.

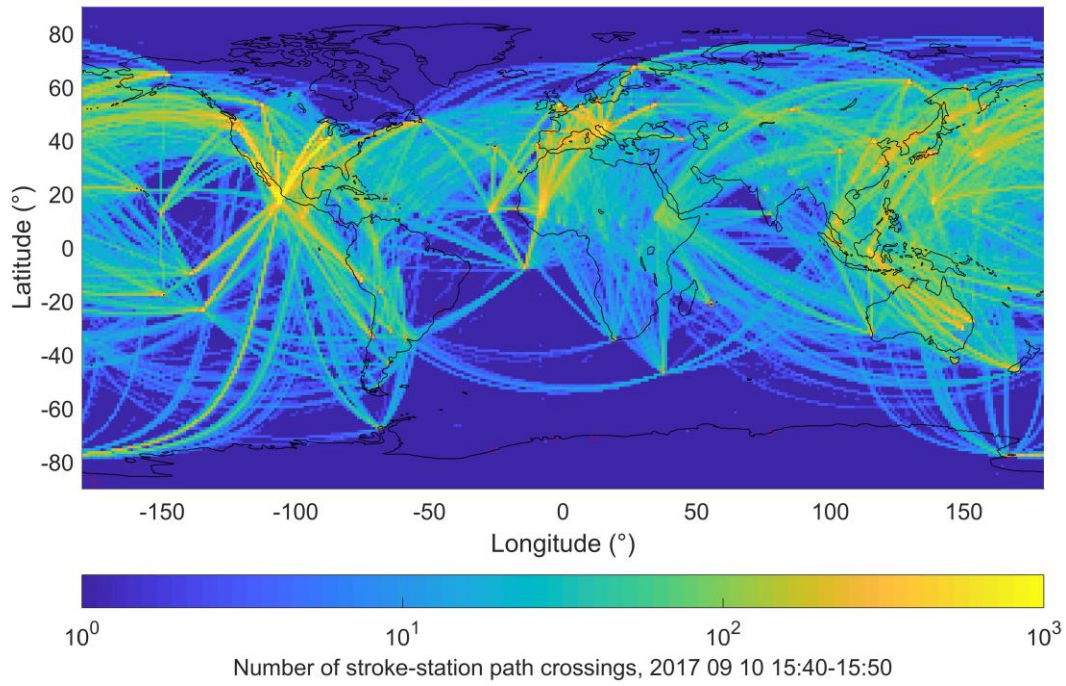
260 Second, this analysis relies on a 1-hour averaging threshold, chosen to fall between the timescales of flare
261 onset (~1-10 minutes) and thunderstorm lifetime (hours) (Rakov & Uman, 2003). This threshold is effective at
262 detecting attenuation produced at flare onset, especially when the hour preceding flare onset has relatively constant,
263 low levels of X-ray irradiance. As soon as the flare occurs, however, the 1-hour average of stroke-station path
264 crossings is disturbed, and as such the ionosphere recovery after peak flare irradiance cannot be effectively
265 characterized by stroke-station path crossing differences. This could potentially be addressed with multiple averaging
266 thresholds with different periods, or with the development of a no-flare path distribution prediction, which guesses
267 the stroke-station path crossing distribution based on the pre-flare distribution of stroke-station paths and lightning,
268 and a predicted lightning distribution that accounts for lightning strokes inside the attenuation region.

269 Finally, this work takes advantage of the globally-distributed nature of lightning strokes and WWLLN
270 stations to provide adequate stroke-station path coverage over regions of interest. Unfortunately, sferic propagation
271 is sparse over polar regions, due in part to the concentration of global lightning near the equator and mid-latitudes.
272 Without increasing the number of stations in polar regions, this technique will be far more effective at characterizing
273 equatorial VLF attenuation regions caused by solar flares than polar events associated with SEPs and CMEs.

274 In addition to addressing the shortcomings detailed above, this work is being developed into a real-time
275 monitor of VLF attenuation in the EIWG. The WWLLN files needed for this analysis are available every 10 minutes,
276 and the software used here runs in less than that time.

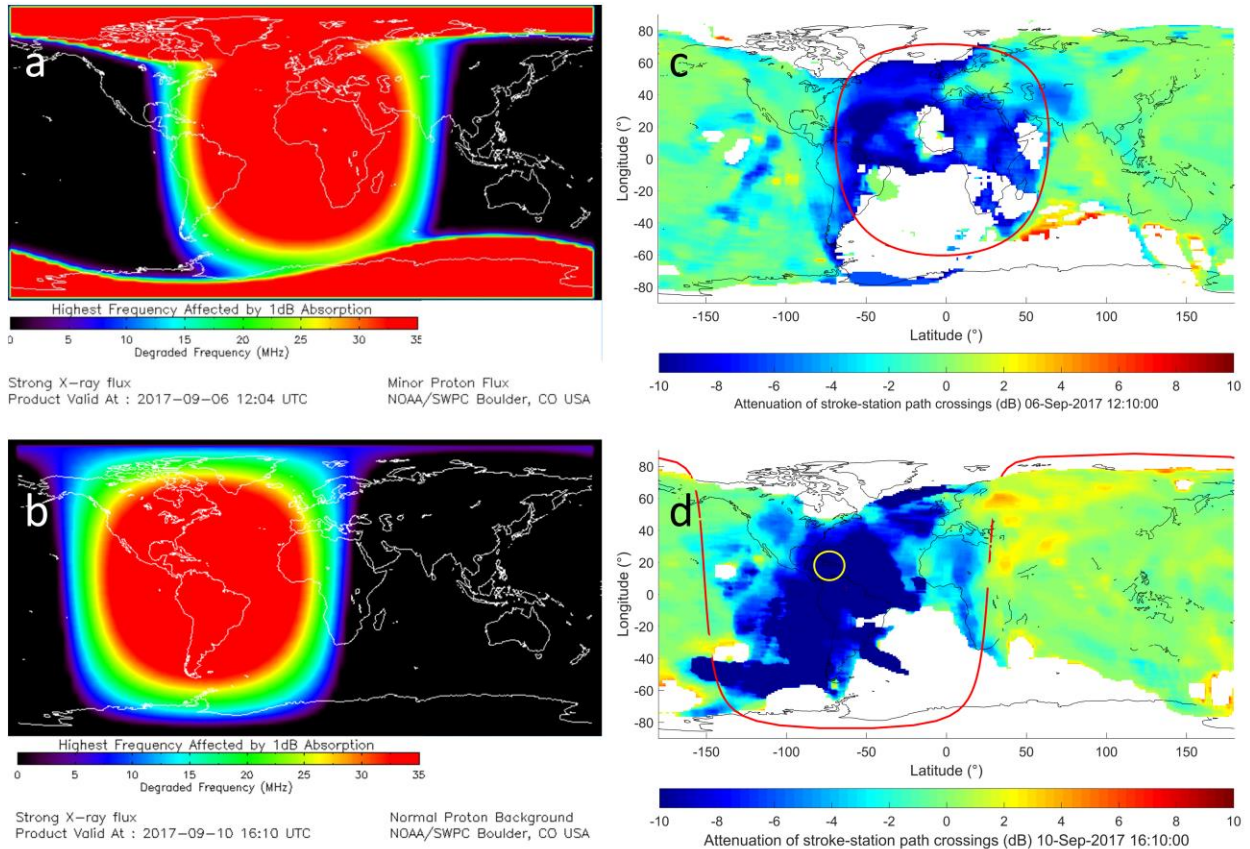
277 **Acknowledgments**

278 The authors would like to thank the World Wide Lightning Location Network, a collaboration among over 50
279 universities and institutions, for providing the lightning location data used in this work. These data are available at
280 (DOI, or in supporting information), and upon request at <https://wwlln.net>. D-Region Absorption Prediction and
281 GOES satellite data and plots are provided by the NOAA National Centers for Environmental Information (NCEI).
282 D-RAP data are available at <https://www.ngdc.noaa.gov/stp/drap/data/>. GOES SEM data are available at
283 <https://www.ngdc.noaa.gov/stp/satellite/goes/dataaccess.html>. This work was internally funded by the University of
284 Washington.
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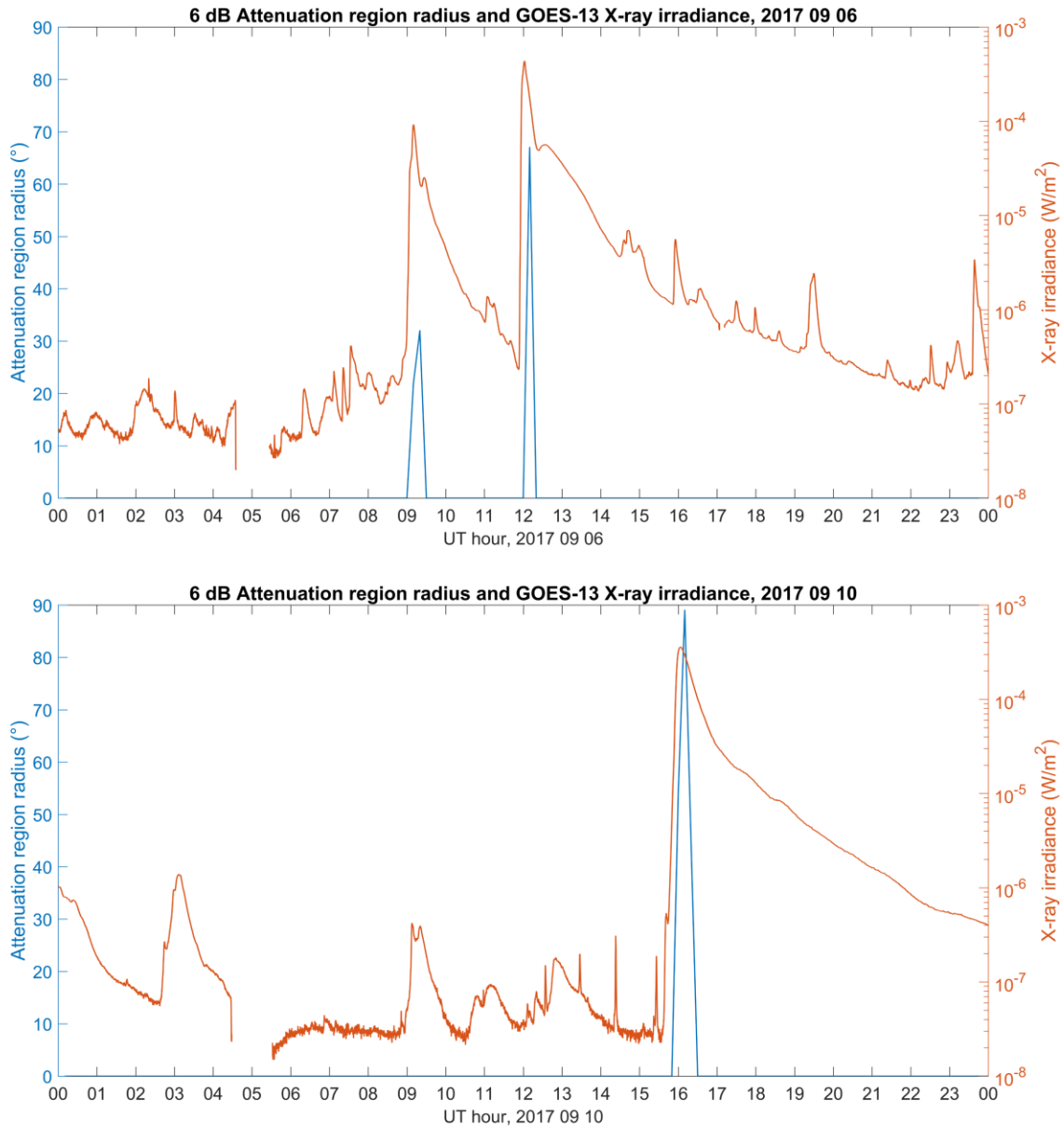


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Figure 1. Sample WWLLN stroke-station distribution during a low-attenuation time, about 20 minutes before the X8.2 flare on September 10, 2017. WWLLN stations used in this analysis are marked with red triangles (Δ). Note that this distribution includes only integer values of stroke-station crossings, and the 10^0 minimum also includes cases of 0 stroke-station path crossings. Much of the dark blue regions in this figure, especially near the poles, have no stroke-station path crossings.

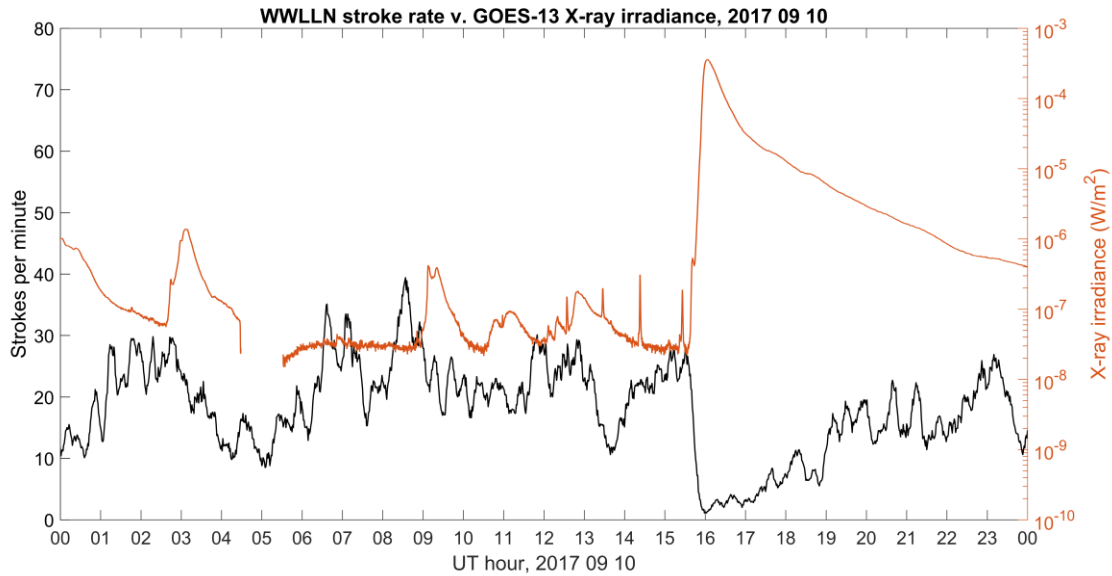


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 296 **Figure 2.** Comparison between D-RAP predicted HF attenuation region (left) and WLLN stroke-station path
 297 attenuation (right) for the first 10 minutes of the September 6 X9.3 flare (top row) and the September 10 X8.2
 298 solar flare (bottom row). Cooler colors in (c) and (d) correspond to attenuation of stroke-station paths, while warmer
 299 colors correspond to enhancement. The red circles in (c) and (d), centered on the sub-solar point, are the largest
 300 such circles enclosing a region of median attenuation above 6dB (see also Fig. 3). The yellow circle in (d) outlines a
 301 1000-km-radius region in which WLLN stroke count rate was analyzed; a time series of stroke count rate from
 302 this region is plotted in Figure 4. D-RAP maps are adapted from (NOAA NCEI, 2019)
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 306 **Figure 3.** Comparison of 6-dB VLF attenuation region radius (blue, left axis) and GOES-13 0.05-0.4 nm X-ray
 307 irradiance (orange, right axis), for September 6 (top) and 10 (bottom). The blue curve is the radius, in degrees, of
 308 the largest circular subsolar region inside which the median stroke-station path attenuation is at least 6 dB. 6-dB
 309 regions are plotted as the red circles in Figure 2c and 2d; which correspond to the maxima of the blue curves in the
 310 upper and lower panels in this figure, respectively.

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Figure 4. Comparison of WWLLN-detected lightning stroke count rate inside a near-subsolar region (black, left axis) and GOES-13 0.05-0.4 nm X-ray irradiance (orange, right axis). The region considered here is a 1000-km-radius area near the subsolar point, and is plotted as a yellow circle in Figure 2d. WWLLN detections of lightning strokes occurring within this region are plotted as the black curve. Stroke rate has been smoothed with a 10-minute moving average. At the onset of the X8.2 flare at around 1600 UT, WWLLN stroke rate inside this near-subsolar region drops an order of magnitude from around 25 to 2 strokes/minute.

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