

1 **Geomagnetic Conjugate Observations of Ionospheric Disturbances in**
2 **response to North Korea Underground Nuclear Explosion on 3**
3 **September 2017**

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10
11 **Key points:**

- 12 1. Geomagnetic conjugate ionospheric disturbances related to UNE were observed by
13 IGS stations and Swarm satellite.
- 14 2. Radial propagation velocity from the UNE epicenter was calculated from temporal
15 and spatial distribution of conjugate ionospheric disturbances.
- 16 3. The ionospheric disturbances present the evidence of the LAIC electric field
17 penetration process.

18 **Abstract**

19 We report observations of ionospheric disturbances in response to North Korea
20 underground nuclear explosion (UNE) on 3 September 2017. By using data from IGS
21 (International GNSS Service) stations and Swarm satellite, geomagnetic conjugate
22 ionospheric disturbances were observed. The observational evidences showed that
23 UNE-generated ionospheric disturbances propagated radially from the UNE epicenter
24 with the velocity of ~ 280 m/s. We propose that the ionospheric disturbances are results
25 of electrodynamic process caused by LAIC (Lithosphere-Atmosphere-Ionosphere
26 Coupling) electric field penetration. LAIC electric field can also be mapped to the
27 conjugate hemispheres along the magnetic field line and consequently cause
28 ionospheric disturbances in conjugate regions. The UNE-generated LAIC electric field
29 penetration plays an important role in the ionospheric disturbances in the region of the
30 nuclear test site nearby and the corresponding geomagnetic conjugate points.

31

32 **Key words:** geomagnetic conjugate ionospheric disturbances; electrodynamic process;
33 LAIC electric field penetration

34 **1 Introduction**

35 Ionospheric disturbances can be generated by various natural processes such as
36 geomagnetic storms, internal electrodynamic instabilities and so forth. Furthermore,
37 human activity can also cause evident ionospheric disturbances. Although underground
38 nuclear explosion (UNE) is detonated deep in the lithosphere, ionospheric disturbances
39 related to UNE can also be observed. By using GNSS-TEC observations, *Park et al.*
40 (2011) reported that traveling ionospheric disturbances (TIDs) with phase velocity of
41 ~ 273 m/s were generated by UNE in the 25 May 2009 North Korea UNE test. They
42 proposed that acoustic gravity waves (AGWs) generated by the UNE can propagate to
43 ionosphere and cause wavelike disturbances.

44
45 While the observations of UNE related ionospheric disturbances have been discussed
46 in (*Park et al.*, 2011; 2013), further investigation is still required to understand the
47 mechanism(s) of ionospheric disturbance generation. Lithosphere-atmosphere-
48 ionosphere coupling (LAIC) mechanisms originally proposed to interpret the linkage
49 between ionospheric disturbances and earthquake activities are the most likely
50 explanation for the ionospheric disturbances in response to UNE. The AGWs theory is
51 one part of LAIC mechanisms (*Liu et al.*, 2016; *Maruyama et al.*, 2016). AGWs excited
52 by the unusual events in lithosphere such as an earthquake or an UNE can propagate to
53 ionospheric height and generate TID and electromagnetic disturbances (*Gokhberg et*
54 *al.*, 1990; *Pokhotelov et al.*, 1994, 1995, 1999; *Mikhailov et al.*, 2000; *Huang et al.*,
55 2011; *Jonah et al.*, 2017). However, the AGWs mechanism cannot fully explain all the

56 observations related to earthquakes. The electrostatic coupling is another candidate for
57 LAIC mechanisms. During earthquakes, LAIC electric field or current can be excited
58 by complex physical and chemical reactions induced by rock rupture and penetrate the
59 ionosphere to promote plasma disturbances by $\mathbf{E} \times \mathbf{B}$ motion (Xu *et al.*, 2011; Zhao &
60 Hao, 2015). Zhou *et al.* (2017) developed an electric field penetration model for LAIC
61 and their simulation results showed that the penetration height of LAIC electric field
62 can reach to 400 km in mid-latitude regions. Because of high electric conductivity along
63 the geomagnetic field lines, LAIC electric field can also be mapped along geomagnetic
64 field lines and cause ionospheric disturbances at the geomagnetic conjugate points
65 (Ruzhin *et al.*, 1998; Zhang *et al.*, 2009; Li & Parrot, 2017).

66

67 In this study, we have used magnetic conjugate GNSS observations and Swarm satellite
68 to investigate the LAIC electric penetration effects of North Korea UNE on 3
69 September 2017.

70

71 **2 Instrument and Data**

72 The IGS stations used in this study are located in East Asia and Australia. The
73 geographical positions of the UNE and the IGS stations are showed in Figure 1. In order
74 to eliminate the noise and multipath effects of GPS signals, only carrier phase
75 observations are utilized to derive the relative slant total electron content (STEC). The
76 time resolution is about 30 s. The ionospheric pierce points (IPPs) height in this study
77 is assumed at 350 km. Figure 2 shows an example of time series of relative STEC

80 obtained by SUWN using satellite PRN 28 between 03:00-05:00 UT on 3 September
 81 2017. To calculate the ionospheric disturbances related to UNE from GNSS
 82 observations, the main trends of relative STEC strongly influenced by the Sun's diurnal
 83 cycle need to be removed. In this study, the numerical third-order horizontal 3-point
 84 derivatives of relative STEC are used for extracting the ionospheric disturbances (*Park*
et al., 2011). In the first step, the numerical first-order horizontal 3-point derivatives
 85 are taken as follows:

$$85 \quad \delta s_i = s_i - \frac{(s_{i-1} + s_{i+1})}{2} \quad i=\{2, \dots, n-1\} \quad (1)$$

86 where s_i is the i^{th} data point, δs_i is the first derivative, and n is the number of relative
 87 STEC observations. The main relative STEC trends are removed through this process.
 88 Figure 3(a) shows the time series of first-order derivatives of relative STEC. Waves
 89 with small amplitudes occurred at around 3.9 and 4.1 hours, even though it was not
 90 certain whether they were meaningful signals or just noises. The numerical derivative
 91 formula is repeatedly performed on relative STEC derivatives to extract the ionospheric
 92 disturbances related to UNE. The second-order derivatives can be written in the
 93 following expression:

$$94 \quad \delta\delta s_i = \delta s_i - \frac{(\delta s_{i-1} + \delta s_{i+1})}{2} \quad i=\{2, \dots, m-1\} \quad (2)$$

95 where $\delta\delta s_i$ is the second derivative, and m is the number of first derivative
 96 observations. Figure 3(b) shows the time series of second-order derivatives of relative
 97 STEC. Compared to the first-order derivatives presented in Figure 3(a), the amplitude
 98 around the 3.9 hour was amplified while others were not significant. The third-order

99 derivatives are given as follows:

$$100 \quad \delta\delta\delta s_i = \delta\delta s_i - \frac{(\delta\delta s_{i-1} + \delta\delta s_{i+1})}{2} \quad i=\{2,\dots,l-1\} \quad (3)$$

101 where $\delta\delta\delta s_i$ is the third derivative, and l is the number of second derivative
102 observations. Figure 3(c) shows the time series of third-order derivatives of relative
103 STEC. Compared to the second-order derivatives presented in Figure 3(b), the
104 disturbances around the 3.9 hour was further amplified. Therefore, compared to the
105 standard first derivatives, the numerical third-order horizontal l -point derivatives can
106 emphasized the more significant wave components with small amplitudes. Moreover,
107 to further remove the background noises of third-order derivatives of relative STEC,
108 the harr wavelet decomposition process is applied to the third-order derivatives.
109 Equations (4) and (5) give the harr wavelet function and scale function, respectively.

$$110 \quad \psi_H(t) = \begin{cases} 1 & 0 \leq t \leq 1/2 \\ -1 & 1/2 \leq t < 1 \\ 0 & \text{others} \end{cases} \quad (4)$$

$$111 \quad \phi_H(t) = \begin{cases} 1 & 0 \leq t < 1 \\ 0 & \text{others} \end{cases} \quad (5)$$

112 Figure 3(d) shows the wavelet de-noised third-order derivatives. From Figure 3(d), it
113 was found that the background noises in Figure 3(c) were completely removed and only
114 valuable wave components were retained.

115

116 Swarm mission operated by the European Space Agency (ESA) mainly focuses on the
117 survey of global geomagnetic field and its temporal evolution. Swarm mission consists
118 of three satellites named Alpha (A), Bravo (B), and Charlie (C). By using the magnetic

119 field data detected by Vector Field Magnetometer (VFM) on Swarm, the ionospheric
120 radial current (IRC) density could be calculated by using spatial gradient of residual
121 magnetic field data through Ampère's law (*Ritter et al.*, 2013). The field-aligned current
122 (FAC) density could be also obtained by the ratio of the IRC density to the sine of the
123 magnetic inclination angle. The FAC density and IRC density used in the study were
124 provided by Swarm level 2 dataset with a time resolution of 1 s. The ionospheric current
125 disturbances associated with UNE can also be calculated by the above method.

126

127 **3 Observations**

128 According to the measurements of China Earthquake Network Center (CENC), the
129 approximate location of UNE on 3 September, 2017 is at 41.35 °N and 129.11 °E. The
130 explosive time was at 03:30:01 UTC. The geomagnetic K_p index was less than 3 and
131 AE index was less than 500 nT before and after the UNE, which indicates that the
132 geomagnetic activity was not so active.

133

134 Figure 4 shows the time sequences of 3rd-order derivatives of carrier phase derived
135 relative STEC by GNSS observations from different IGS stations in East Asia and
136 Australia on 3 September 2017. All the GNSS observations from northern and southern
137 hemisphere showed obvious short-period fluctuations within 2 hours after the UNE. It
138 was also found that time delay after the UNE was different according to different IPPs
139 of GPS signals. Figure 5 presents the IPPs tracks of relative STEC derivatives. In order
140 to investigate the propagation velocity of ionospheric disturbances, we assumed that

141 the UNE-generated ionospheric disturbances propagate radially with a certain velocity.

142

143 Figure 6 illustrates the satellite Swarm B ionospheric current derivatives. Compared to

144 observed results of ionospheric current in quiet time, it was seen that the FAC

145 derivatives and IRC derivatives at conjugate hemispheres both showed obvious short-

146 period fluctuations after the UNE. The ionospheric current disturbances could reach 0.5

147 $\mu\text{A}\cdot\text{m}^{-2}\cdot\text{s}^{-3}$.

148

149 Based on the UNE-IPPs horizontal distances and the ionospheric disturbances arrival

150 time, the horizontal propagation velocity of ionospheric disturbances could be

151 estimated by linear fitting model. The horizontal distance from IPPs to epicenter and

152 time delay of the UNE-generated ionospheric disturbances (STEC disturbances and

153 ionospheric current disturbances) are presented in Figure 7. Black triangle and green

154 triangle presented in Figure 7 represent the position of ionospheric current disturbances

155 in the northern hemisphere and the geomagnetic conjugate position of ionospheric

156 current disturbances in the southern hemisphere, respectively. The value of horizontal

157 velocity obtained by the least square estimation was ~ 280 m/s.

158

159 **4 Discussion**

160 By utilizing geomagnetic conjugate GNSS TEC observations and ionospheric current

161 products from Swarm, we introduced the ionospheric disturbances which are

162 considered as a result of the UNE carried out by North Korea on 3 September 2017.

163 The method of the numerical third-order horizontal 3-point derivatives was applied to
164 the GNSS TEC and the ionospheric current of Swarm to extract the ionospheric
165 disturbances, which can also be found in *Park et al.*, (2011). Ionospheric disturbances
166 derived from GNSS TEC observations in our study are consistent with the results of
167 North Korea UNE on 25 May 2009 obtained by *Park et al.* (2011).

168

169 The effects of UNE on the ionosphere could be very similar to that of earthquakes on
170 the ionosphere. In previous studies, AGWs are considered as the most likely mechanism
171 for atmospheric and ionospheric disturbances excited by UNE or earthquakes
172 (*Mikhailov et al.*, 2000; *Che et al.*, 2009; *Garrison et al.*, 2010; *Park et al.*, 2011, 2013;
173 *Yang et al.*, 2012; *Maruyama et al.*, 2016). *Klimenko et al.* (2011) proposed that the
174 ionospheric disturbances were generated by small-scale internal gravity waves (IGWs)
175 through propagation and dissipation processes during seismic activity. *Liu et al.* (2016),
176 and *Chum et al.* (2016, 2018) suggested that co-seismic ionospheric disturbances could
177 be generated by long-period infrasound waves excited by seismic waves. Based on
178 GNSS receiver observations over Brazilian sector, *Jonah et al.* (2017) presented
179 daytime MSTIDs observed in the conjugate hemispheres. They proposed that the
180 gravity wave-induced polarized electric fields could map into the conjugate hemisphere
181 and further generate ionospheric disturbances in conjugate region. However, compared
182 with TEC disturbances induced by MSTIDs presented in *Jonah et al.* (2017),
183 ionospheric disturbances in response to North Korea UNE in both hemispheres were
184 smaller and lasted within 5 minutes in our work. Therefore, electric field disturbances

185 induced by UNE-generated TEC disturbances presented in Figure 4 may be very small
186 and cannot generate obvious ionospheric disturbances in conjugate region.

187

188 Recent researches have shown that earthquake ionospheric disturbances could be
189 attributed to not only the AGW mechanism but also the electrostatic coupling, which
190 means the electric field or current penetration into ionosphere induced by earthquakes.
191 Based on the observations of INTERCOSMOS-BULGARIA-1300 satellite and
192 DEMETER satellite, *Gousheva et al.* (2008, 2009) and *Zhang et al.* (2014) reported
193 ionospheric quasi-static electric field perturbations during seismic activities. By using
194 the magnetometer observations, *Hao et al.* (2013), and *Liu et al.* (2016) showed obvious
195 ionospheric current and magnetic field perturbations after the Tohoku earthquake. They
196 proposed that the seismo-traveling atmospheric disturbances (STADs) caused by
197 infrasonic waves can propagate vertically into the ionosphere and modify the *E* layer
198 Hall and Pedersen conductivity, resulting in background ionospheric electric field and
199 magnetic field disturbances. *Pulinets et al.* (2000) proposed a quasi-electrostatic model
200 for the LAIC mechanism. The simulation results indicated that the abnormal electric
201 field induced by an earthquake can penetrate into the ionosphere to cause the
202 ionospheric electric field disturbances (*Sorokin et al.*, 2001). The enhancement of TEC
203 at the epicenter and its geomagnetic conjugate points were reported by *Liu et al.* (2011),
204 which indicated that the earthquake-generated electric field penetration can be mapped
205 along geomagnetic field lines to promote ionospheric disturbances at its conjugate
206 points by electrodynamic process through $\mathbf{E} \times \mathbf{B}$ drift. Therefore, the geomagnetic

207 conjugation effects of ionospheric disturbances in Figure 4 can be explained by the
208 UNE-generated electric field penetration. A schematic sketch of geomagnetic conjugate
209 effect related to UNE in the region of the nuclear test site nearby and the corresponding
210 geomagnetic conjugate region is shown in Figure 8. The UNE-generated electric field
211 or current penetrates into the ionosphere and further generates an abnormal electric field
212 at ionospheric altitude. The distribution of ionospheric electric field showed in Figure
213 8 were calculated by LAIC electric field penetration model proposed by *Zhou et al.*
214 (2017). Because of the existence of high conductivity of geomagnetic field, the
215 abnormal ionospheric electric field could be mapped along geomagnetic field lines.
216 Geomagnetic conjugate ionospheric disturbances could be generated by abnormal
217 ionospheric electric field through $E \times B$ drift. Our study provides observational
218 evidences of LAIC electric penetration rather than acoustic gravity wave mechanism.
219
220 Geomagnetic conjugate observations in ionosphere have been reported by a few
221 researchers. *Otsuka et al.* (2002; 2004) reported simultaneous observations of
222 equatorial airglow depletions and medium-scale TIDs at geomagnetic conjugate points
223 in both hemispheres by two all-sky imagers. Their results also suggested that
224 polarization electric field, which is important for airglow depletion and MSTIDs
225 generation, can be mapped along the field lines.
226
227 In our observations, we found that the ionospheric disturbances in both hemispheres
228 caused by the UNE-generated electric field penetration propagated radially at the

229 velocity of roughly 280 m/s in Figure 5 and Figure 7. LAIC electric field can be roughly
230 estimated to be 14.5 mV/m, which is consistent with the magnitude of the earthquake-
231 generated ionospheric electric field presented by *Zhang et al. (2014)*. Figure 6 presents
232 the results of the ionospheric current disturbances detected by the satellite Swarm B
233 after the UNE. The reason may be that the ionospheric disturbances from the UNE
234 propagate here to generate the current disturbances by electrodynamic process.

235

236 Moreover, compared with the magnitude and time scale of ionospheric disturbances
237 caused by earthquakes, there are inconsistencies in our study. Based on IGS station
238 observations around Tibet and Nepal, *Kong et al. (2018)* reported that TEC disturbances
239 exceeded 0.3 TECU and lasted for 15-20 minutes during 2015 Nepal earthquake.
240 However, it was found that the UNE-generated ionospheric disturbances were relatively
241 smaller and lasted within 5 minutes in Figure 4. The reason for difference of TEC
242 disturbances may be that earthquake magnitude and background ionosphere are
243 different.

244

245 **5 Summary**

246 In this study, we have shown that the geomagnetic conjugate observations of GNSS
247 TEC and ionospheric current from Swarm considered as a response to North Korea
248 UNE on 3 September 2017. The LAIC electric penetration effects of UNE have been
249 discussed in details. The main results are summarized as follows:

250

251 1. The ionospheric TEC and current disturbances were observed in both hemispheres
252 after the UNE. According to the spatial-temporal relation, UNE-generated ionospheric
253 disturbances propagated radially from the explosion epicenter with the velocity of ~
254 280 m/s.

255

256 2. The ionospheric disturbances may be caused by LAIC electric penetration rather than
257 AGWs. LAIC electric field induced by UNE penetrates into the ionosphere and causes
258 plasma density disturbances near the nuclear test cite and its conjugate points by
259 electrodynamic process.

260

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265 [access](https://earth.esa.int/web/guest/swarm/data-access)). The work is supported by the National Natural Science Foundation of China
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369

370 **Figure Captions**

371 **Figure 1.** The positions of UNE and IGS stations. The position of 3 September 2017
372 North Korea UNE is represented by black hollow start mark. The locations of IGS
373 stations in both hemispheres are represented by red and blue squares, respectively.
374 Lines of constant geomagnetic latitude are represented by black dashed lines.

375 **Figure 2.** An example of time series of relative STEC obtained by SUWN using
376 satellite PRN 28 between 03:00-05:00 UT on 3 September 2017. The explosive time is
377 represented by the red line.

378 **Figure 3.** The time sequences of derivatives of relative STEC obtained by SUWN
379 station using satellite PRN 28 between 03:00-05:00 UT on 3 September 2017. (a) first-
380 order derivatives, (2) second-order derivatives, (c) third-order derivatives, and (d)
381 wavelet de-noised third-order derivatives. The explosive time is represented by the red
382 line.

383 **Figure 4.** The time sequences of 3-order derivatives of carrier phase derived relative
384 STEC by GNSS observations from different IGS stations in East Asia (left and middle
385 column) and Australia (right column) on 3 September 2017. The blue lines indicate the
386 wavelet de-noised 3-order derivative of relative STEC. The black lines indicate the GPS
387 signal's elevation between the GNSS satellite and IGS stations. The explosive time is
388 represented by the red line.

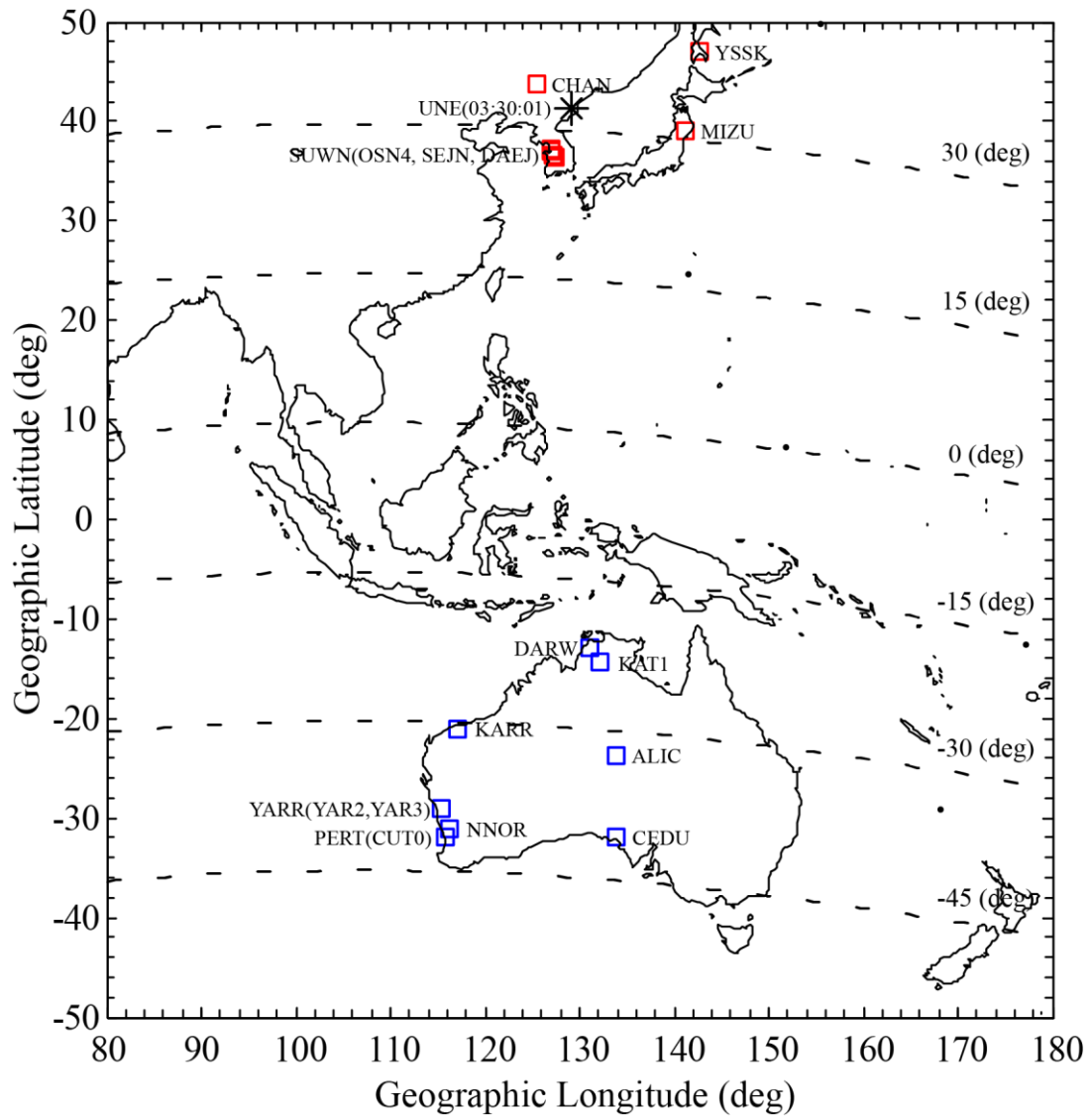
389 **Figure 5.** The IPPs tracks of relative STEC derivatives. The red lines indicate the IPPs
390 tracks obtained by IGS stations in the northern hemisphere. The blue lines indicate the
391 magnetic conjugate positions of the IPPs tracks obtained by IGS stations in the southern
392 hemisphere. The positions of the maximum amplitudes of relative STEC derivatives in
393 the northern hemisphere are represented by red triangles. The geomagnetic conjugate
394 positions of the maximum amplitudes of relative STEC derivatives in the southern
395 hemisphere are represented by blue triangles.

396 **Figure 6.** Results of Swarm B ionospheric current data analysis for the 2017 UNE: (a),
397 (c), and (e) are the FAC, (b), (d), (f) are the IRC. From top to bottom, they indicate
398 observations of Swarm B on 19 August 2017 (quiet time), 3 September 2017 (UNE

399 time), and 18 September 2017 (quiet time), respectively. The ionospheric current
400 disturbances in response to UNE are represented by the red rectangles.

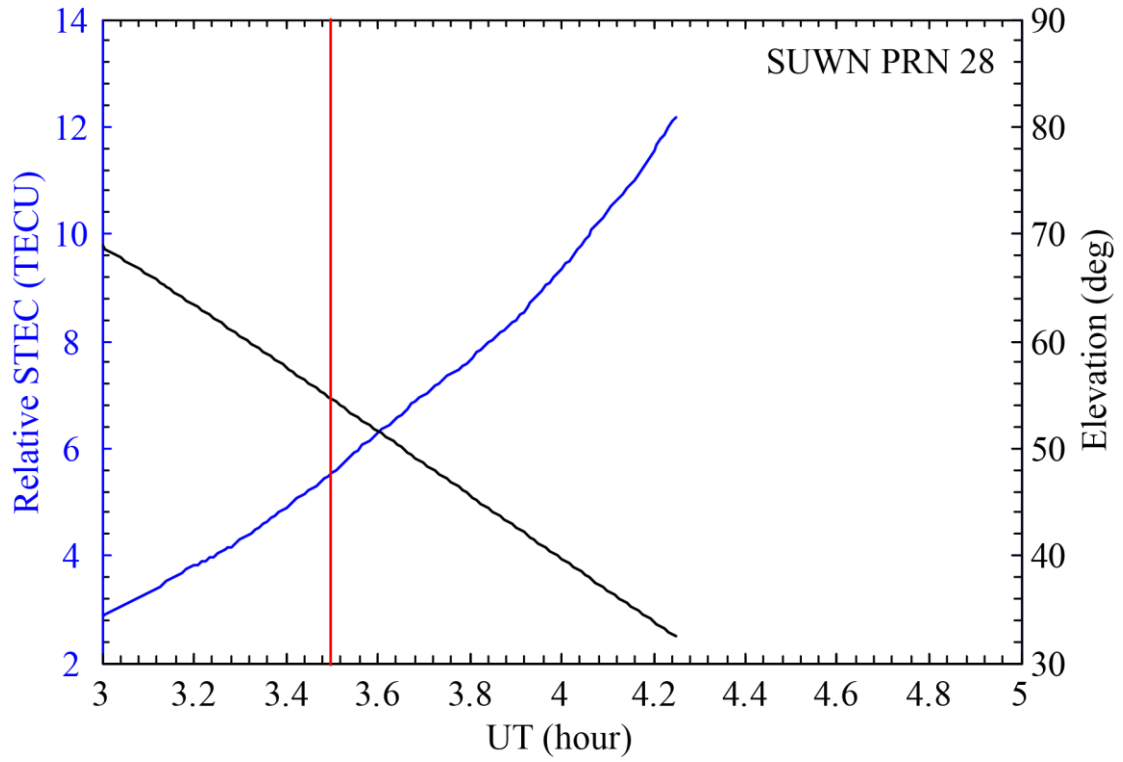
401 **Figure 7.** Horizontal distance-time data for the UNE-generated ionospheric
402 disturbances. The black line indicates the fitting curve obtained by the least square
403 method. The gray lines represent the boundaries of 95% confidence intervals. The red
404 and blue triangles indicate same meanings as in Figure 5. The black triangle represents
405 the position of ionospheric current disturbances in the northern hemisphere. The green
406 triangle represents the geomagnetic conjugate position of ionospheric current
407 disturbances in the southern hemisphere.

408 **Figure 8.** A sketch of geomagnetic conjugate effect related to UNE in the region of the
409 nuclear test site nearby and the corresponding geomagnetic conjugate region.



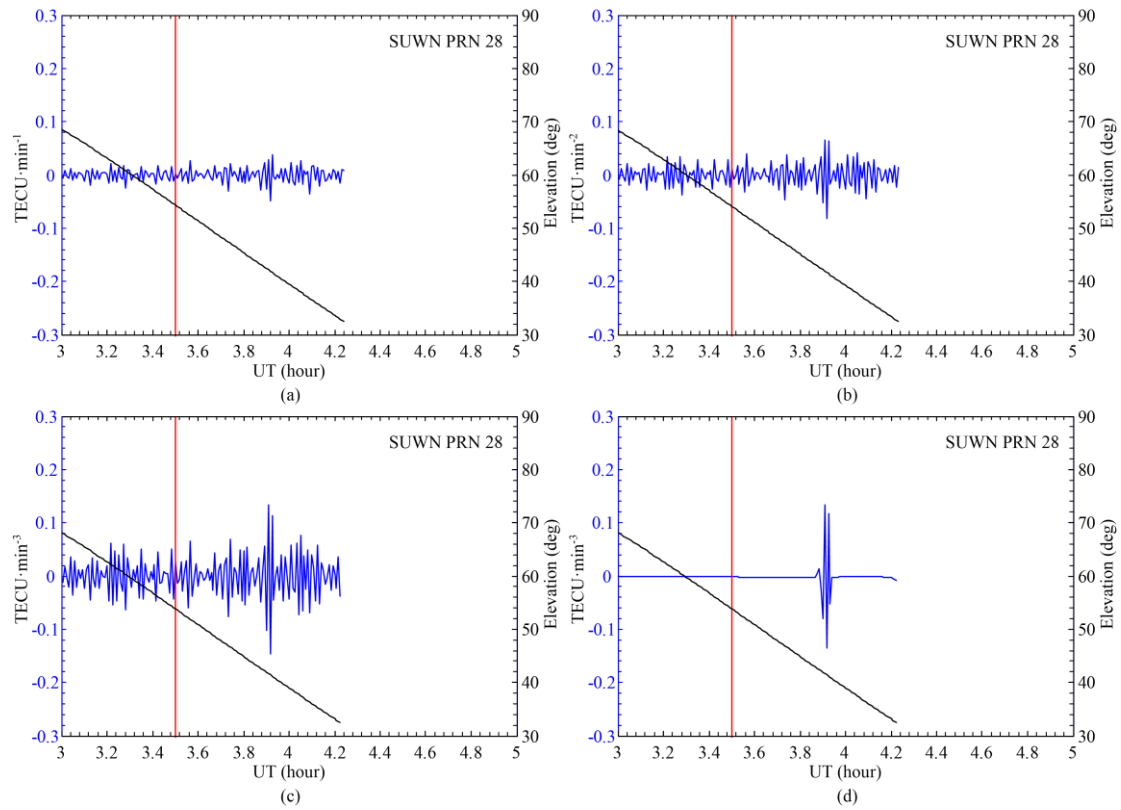
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Figure 1. The positions of UNE and IGS stations. The position of 3 September 2017 North Korea UNE is represented by black hollow star mark. The locations of IGS stations in both hemisphere are represented by red and blue squares, respectively. Lines of constant geomagnetic latitude are represented by black dashed lines.



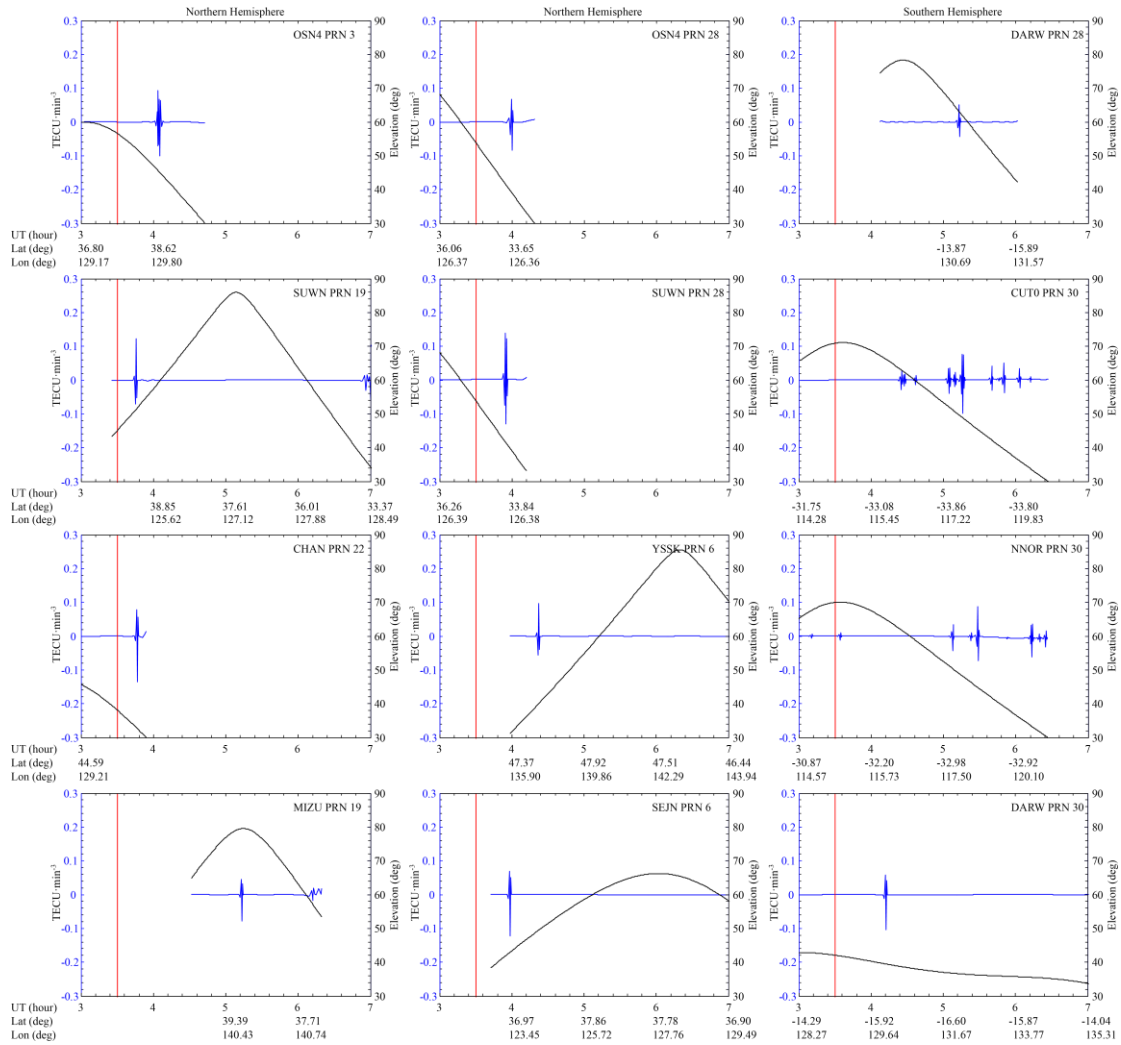
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419 **Figure 2.** An example of time series of relative STEC obtained by SUWN using
 420 satellite PRN 28 between 03:00-05:00 UT on 3 September 2017. The explosive time
 421 is represented by the red line.



422

423 **Figure 3.** The time sequences of derivatives of relative STEC obtained by SUWN
 424 station using satellite PRN 28 between 03:00-05:00 UT on 3 September 2017. (a)
 425 first-order derivatives, (2) second-order derivatives, (c) third-order derivatives, and
 426 (d) wavelet de-noised third-order derivatives. The explosive time is represented by the
 427 red line.

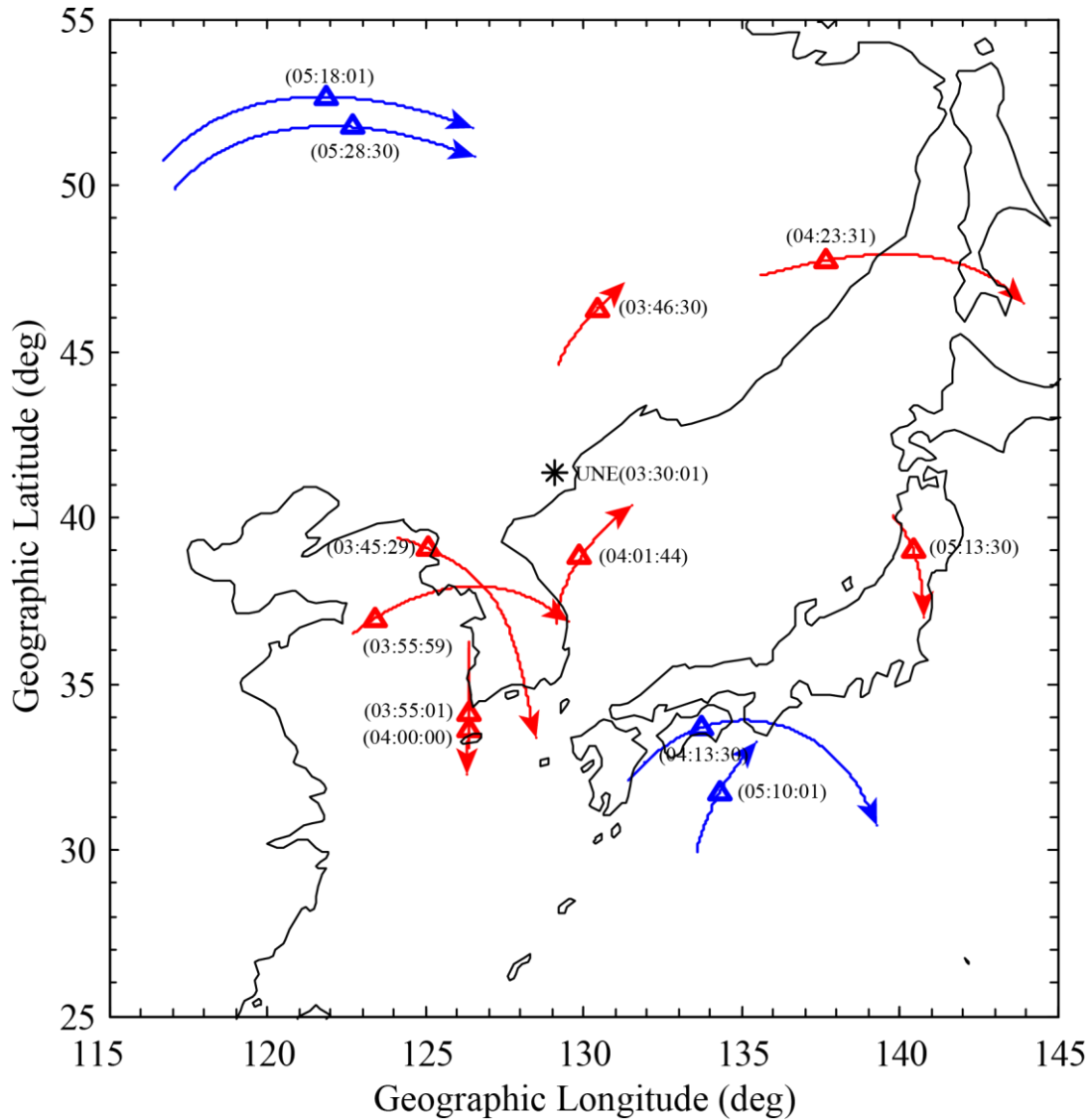


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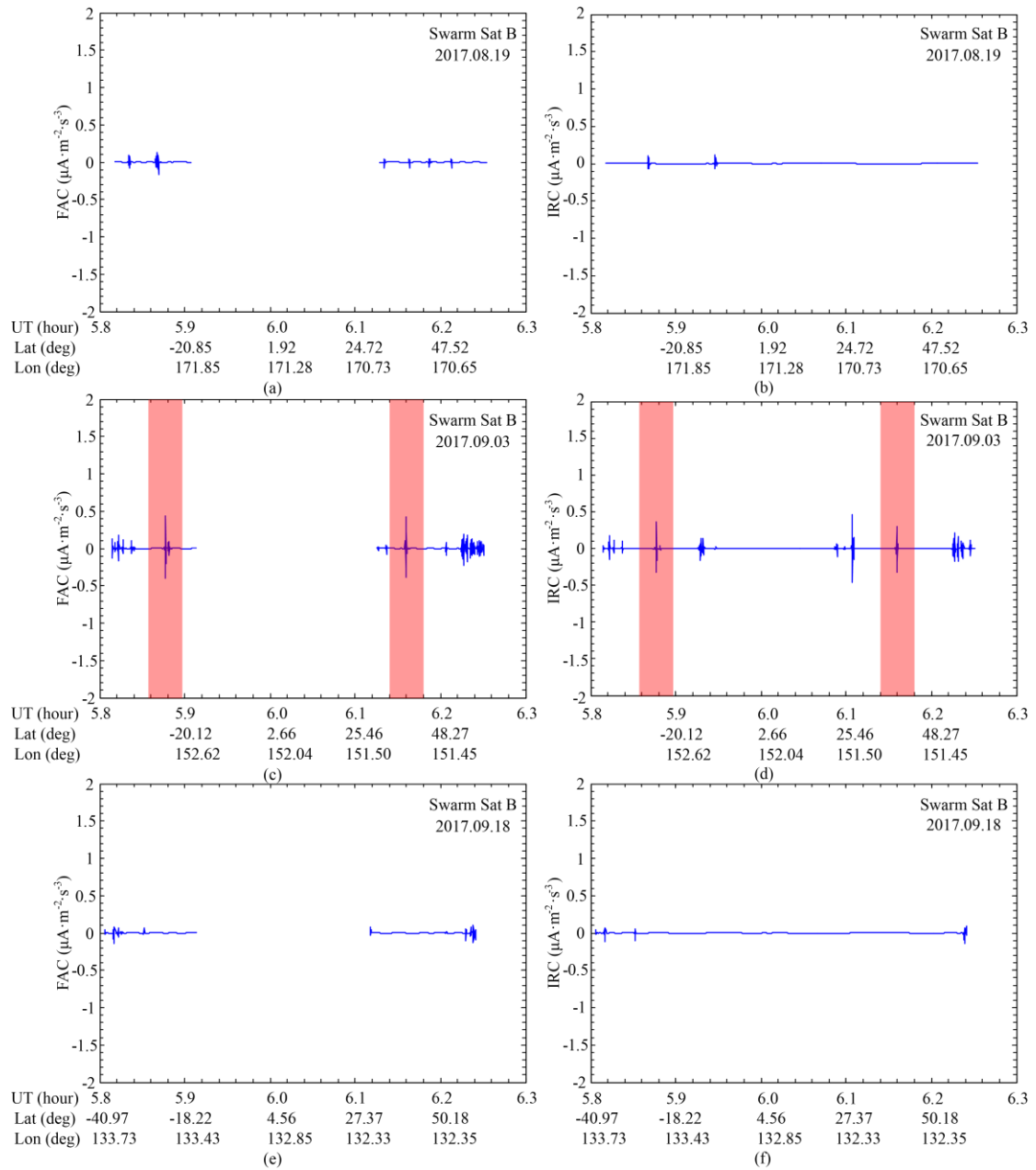
Figure 4. The time sequences of 3-order derivatives of carrier phase derived relative
 430 STEC by GNSS observations from different IGS stations in East Asia (left and middle
 431 column) and Australia (right column) on 3 September 2017. The blue lines indicate
 432 the wavelet de-noised 3-order derivative of relative STEC. The black lines indicate
 433 the GPS signal's elevation angle between the GNSS satellite and IGS stations. The
 434 explosive time is represented by the red line.

435



436

437 **Figure 5.** The IPPs tracks of relative STEC derivatives. The red lines indicate the
 438 IPPs tracks obtained by IGS stations in the northern hemisphere. The blue lines
 439 indicate the magnetic conjugate positions of the IPPs tracks obtained by IGS stations
 440 in the southern hemisphere. The positions of the maximum amplitudes of relative
 441 STEC derivatives in the northern hemisphere are represented by red triangles. The
 442 geomagnetic conjugate positions of the maximum amplitudes of relative STEC
 443 derivatives in the southern hemisphere are represented by blue triangles.



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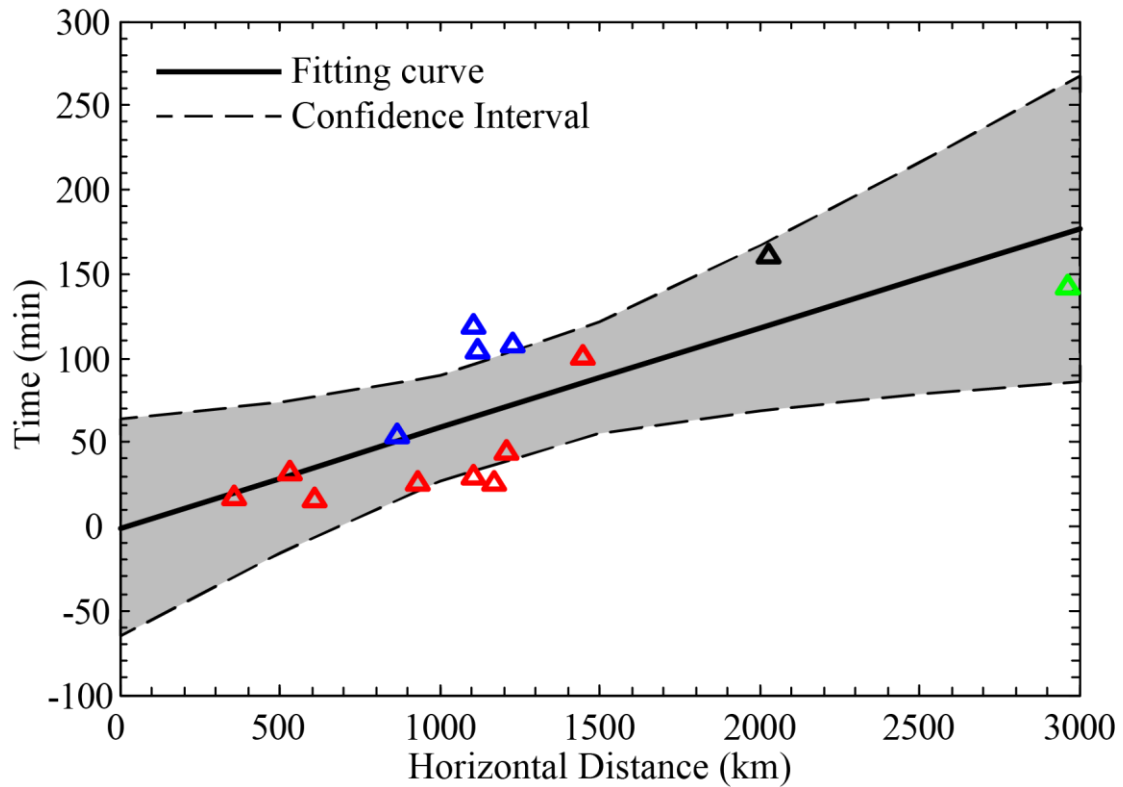
445 **Figure 6.** Results of Swarm B ionospheric current data analysis for the 2017 UNE:

446 (a), (c), and (e) are the FAC, (b), (d), (f) are the IRC. From top to bottom, they

447 indicate observations of Swarm B on 19 August 2017 (quiet time), 3 September 2017

448 (UNE time), and 18 September 2017 (quiet time), respectively. The ionospheric

449 current disturbances in response to UNE are represented by the red rectangles.



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Figure 7. Horizontal distance-time data for the UNE-generated ionospheric disturbances. The black line indicates the fitting curve obtained by the least square method. The gray lines represent the boundaries of 95% confidence intervals. The red and blue triangles indicate same meanings as in Figure 5. The black triangle represents the position of ionospheric current disturbances in the northern hemisphere.

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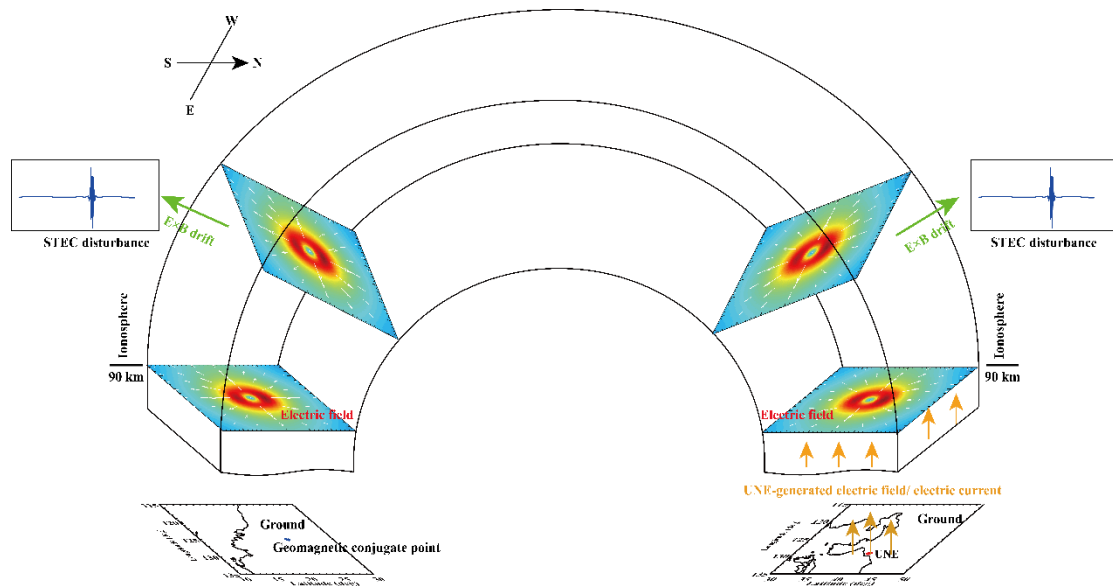
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The green triangle represents the geomagnetic conjugate position of ionospheric current disturbances in the southern hemisphere.

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Figure 8. A sketch of geomagnetic conjugate effect related to UNE in the region of the nuclear test site nearby and the corresponding geomagnetic conjugate region.