



1 **Ionospheric influence on the seismo-telluric current related to electromagnetic**
2 **signals observed before the Wenchuan $M_S=8.0$ earthquake**

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4 Mei Li^{1,2}, Handong Tan² and Meng Cao²

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6 (1) China Earthquake Networks Center, China Earthquake Administration, No.5,
7 Sanlihe Nanhengjie, Xicheng District, 100045 Beijing, China.

8 (2) China University of Geosciences, No.29, Xueyuan Road, Haidian District, 100083
9 Beijing, China.

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11 Corresponding author: Handong Tan, China University of Geosciences, No.29,
12 Xueyuan Road, Haidian District, 100083 Beijing, China. (thd@cugb.edu.cn)

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14 **Abstract.** A three-layer (Earth-air-ionosphere) physical model, as well as a
15 two-layer (Earth-air) model, is employed in this paper to investigate the ionospheric
16 effect on the wave fields for a finite length dipole current source co-located with the
17 main fault of an earthquake when the transmitter-receiver distance is up to one
18 thousand kilometers or even more. The results show that all electrical fields are free
19 of the ionospheric effect for different frequencies in a relative short range, e.g., ~ 300
20 km for $f=1$ Hz, implying the ionospheric influence on electromagnetic fields can be
21 neglected within this range that becomes smaller as the frequency increases. However,
22 the ionosphere can give a constructive interference to the waves passed through and
23 make them decay slowly when an observation is out of this range and the ionospheric
24 effect can be up to 1-2 magnitudes of the electrical fields. For an observed 1.3 mV/m
25 signal at 1,440 km away for the Wenchuan $M_S=8.0$ earthquake, the expected
26 seismo-telluric current magnitude for the Earth-air-ionosphere model is of 5.0×10^4
27 kA, which is of one magnitude smaller than the current value of 3.7×10^5 kA obtained
28 by the Earth-air model free of ionospheric effect. This indicates that the ionosphere
29 facilitates the electromagnetic wave propagation, as if the detectability of the system
30 is improved effectively and it is easier to record a signal even for stations located at
31 distances beyond their detectability threshold.

32 **Keywords.** Ionospheric influence on electromagnetic waves; The Wenchuan
33 earthquake; Seismo-telluric current

34



35 1 Introduction

36 The fact that Electro-Magnetic (EM) emissions accompany every stage of large
37 earthquake preparations seems undebatable although short-term earthquake prediction
38 is still one of the most challenging targets in Earth science today (Eftaxias et al.,
39 (2002). Meanwhile, the Ultra-Low Frequency (ULF) band is of particular interest
40 because only EM signals in the ULF range and at lower frequencies originated in the
41 Earth's crust can be easily recorded at the Earth's surface without significant
42 attenuation comparing with 'high' frequency emissions that might be emitted at
43 epicenter depths at more than 10 km, even several hundreds of kilometers. Recently,
44 ULF electromagnetic anomalous phenomena related to strong earthquakes have been
45 investigated and reported in increasing numbers. Two notable examples are the Loma
46 Prieta $M_s=7.1$ earthquake on October 17, 1989 (Fraser-Smith et al., 1990; Bernardi et
47 al., 1991), as well as the Spitak $M_s=6.9$ earthquake on December 7, 1988 [Molchanov
48 et al., 1992; Kopytenko et al., 1993). It was found that, these two earthquakes have
49 very similar electromagnetic emission fluctuation characteristics. The intensity of the
50 signals began to increase 3-5 days before the earthquake at Spitak and 12 days before
51 that at Loma Prieta. The most important point is the electromagnetic emissions
52 exhibited a maximum 4 h before the Spitak event ($f=0.005-1$ Hz, $D=200$ km, $A=0.2$
53 nT) and 3 h before the Loma Prieta event ($f=0.01-10$ Hz, $D=7$ km, $A=1.5$ nT).

54 A more recent example reported by Li et al. (2013) is the Wenchuan $M_s=8.0$
55 earthquake on May 12, 2008, a typical mid-crust, which resulted in great devastation
56 and 69,000 deaths. This earthquake was preceded by more than one month of
57 increasing anomalous ULF emissions with a climax starting on May 9, three days
58 before the Wenchuan main shock ($f=0.1-10$ Hz, $D=1,440$ km, $A=1.3$ mV m⁻¹).

59 Many simulating rock-pressure experiments were carried out in order to
60 understand the producing mechanism of the electromagnetic information associated
61 with seismic activities. Laboratory experiments by Qian et al., (1996; 2003) and Hao
62 et al. (2003) demonstrate that, electromagnetic signals are always recorded when rock
63 samples are subjected to dynamic stresses. There is a close relationship between the
64 produced signal and the formation of micro-cracks in the rock. Furthermore, the
65 climax of the signal occurred when the main rupture happened and the magnetic
66 pulses of shorter-period appearing at the last stage of the experiment may be induced
67 by instantaneous electric current of the accumulated charge during the cracking
68 acceleration. Strong electromagnetic signals are generated while rock samples were



69 fracturing (Panfilov, 2014). As rocks upon stressing, dislocations are generated that
70 sweep through the mineral grains and break the peroxy links. The positive holes are
71 activated as charge carriers, and have the remarkable capability to flow out of the
72 stressed sub-volume and spread into the surrounding unstressed rocks. This situation
73 can be considered as analogous to a battery ~~which generates~~ electric currents ~~along~~
74 the stress-gradient direction (Freund, 2002; Freund and Sornette, 2007; Freund, 2009,
75 2010). A gabbro sample ($30 \times 15 \times 10 \text{ cm}^3$) from Shanxi, China, ~~came into~~
76 a 55 nA current recorded about 2 seconds before failure, with the load being at about
77 30,000 lbs and the maximum spike reaches 450 nA when the main failure took place
78 (Freund, 2009). Up to now, no clear explanation has been given although several
79 physical mechanisms have been proposed to interpret the generation of EM emissions
80 and electrical currents observed either during seismic activity or in the laboratory
81 experiments. These include the electrokinetic and magnetohydrodynamic,
82 piezomagnetism, stress-induced variations in crustal conductivity, microfracturing,
83 and so on (Draganov et al., 1991; Park, 1996; Fenoglio et al., 1995; Egbert, 2002;
84 Simpson and Taflove, 2005). Whatever the physical mechanism of electromagnetic
85 generation is, it is well established that, during rock experiments conducted under
86 laboratory conditions, a strong electrical current is produced when rocks are stressed,
87 especially at the stage of the main rupture. So, like what Bortnik et al. (2010) wanted
88 to know, what is the electrical current necessary to produce an observable magnetic
89 signal on the ground, at a given distance from the epicenter and for an assumed
90 ground conductivity? In their work, an infinitesimally short ~~horizontal~~ dipole located
91 at a hypocenter depth in the half-space (Earth) is used to estimate the magnitude of
92 the seismo-telluric current required for the “Alum Rock” $M_W=5.6$ earthquake on
93 October 31, 2007. The observable electromagnetic ground signals ($f=1 \text{ Hz}$, $D=2 \text{ km}$,
94 $A=30 \text{ nT}$) and the results show that for an observed 30 nT pulse at 1 Hz, the expected
95 seismo-telluric current magnitudes fall in the range $\sim 10\text{--}100 \text{ kA}$.

96 Unlike a parameter of the “Alum Rock” $M_W=5.6$ earthquake ($D=2 \text{ km}$), the
97 distance between the epicenter of the Wenchuan $M_S=8.0$ earthquake and the observing
98 station is $D \sim 1,440 \text{ km}$ (Li et al., 2013), i.e. several times ~~higher~~
99 ~~bottom~~ of ionosphere ($h \sim 85\text{--}100 \text{ km}$) (Kuo et al., 2011; Cummer, 2000; Yamauchi et
100 al., 2007). When we investigate electromagnetic emissions induced by an electrical
101 current or a magnetic moment on the surface or beneath the Earth, the effect of the
102 medium air, crustal as well as ionosphere should be taken into account because of

the way peroxy are
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does not instill
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comment separately



103 these three media being of different conductivities and so we need to consider a
104 lithosphere-atmosphere-ionosphere electromagnetic coupling. The ionosphere plays
105 an important role in radio propagation at Extremely Low Frequency (ELF) and Very
106 Low Frequency (VLF), the ground and the ionosphere are good electrical conductors
107 and form a spherical Earth-ionosphere waveguide (Cummer, 2000). In addition, in the
108 magneto-telluric (MT) method, widely used in ~~exploring~~ petroleum or mine, the
109 ionospheric influence on electromagnetic (EM) fields should be considered when the
110 ~~transmitter-receiver~~ distance of a large-scale and large-power fixed ~~resource~~ is up to
111 one thousand kilometers. EM fields can be strengthened in the ionosphere as it is
112 shown when we use analytical solutions of Maxwell equations, as well as numerical
113 ones of the “Earth-ionosphere” mode with a source on the ground or ~~in the air~~ (Fu et
114 al., 2012; Li et al., 2010a; Li et al., 2010b; Xu et al., 2012; Li et al., 2011). Therefore,
115 comparing with an electromagnetic attenuation without ionospheric effect, the point is
116 to evaluate the ionospheric influence on the electromagnetic propagation when the
117 transmitter-receiver distance is up to one thousand kilometers or even more.
118 Furthermore, the comparison between the observation distance ($D=1,440$ km) and the
119 length of the Wenchuan earthquake main rupture $L\sim 150$ km (Zhang et al., 2009)
120 indicates that the length of the dipole source is not negligible. So in this paper, using
121 the work of Key (2009), a three-layer (Earth-air-ionosphere) physical model, as well
122 as a two-layer (Earth-air) model, containing a finite length dipole current source
123 co-located along the fault and beneath the Earth is introduced in Sect. 2. For specified
124 parameters, some simulation results of the dipole source with and without ionospheric
125 effect are given in Sect. 3. In Sect.4, we define and limit our assumed parameter
126 values, present the results for the Wenchuan earthquake case. Discussion and
127 conclusions are given in Sect. 5 and Sect.6, respectively.

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129 **2 Description of the modeling methodology**

130 In order to study the electromagnetic fields emitted by a long dipole current
131 source, the approach used here follows the magnetic vector potential formulation
132 described in Wait (1982) and developed by Key (2009), who generalized the
133 formulation to allow for multiple layers above the transmitter (in addition to multiple
134 layers below). He used exponential forms for the recursions rather than hyperbolic
135 functions in isotropic media, which consists of N layers of isotropic conductivity σ_i
136 where $i = 1, \dots, N$, and which uses a right-handed coordinate system with the z axis



137 pointing down. Assuming a time-harmonic source with $e^{-i\omega t}$ time dependence,
 138 negligible magnetic permeability μ variations, and angular frequencies ω that are
 139 low enough so that displacement currents can be neglected, Maxwell's equations are

$$\nabla \times \mathbf{E} = i\omega \mathbf{B}, \quad (1)$$

141 and

$$\nabla \times \mathbf{B} = \mu\sigma \mathbf{E} + \mu \mathbf{J}_s. \quad (2)$$

143 Expression $\mathbf{J}_s = \mathbf{I}\delta(\mathbf{r} - \mathbf{r}_0)$ is the imposed electric dipole source at position \mathbf{r}_0 with
 144 vector moment \mathbf{I} , and here is restricted to an infinitesimal dipole with unit moment.

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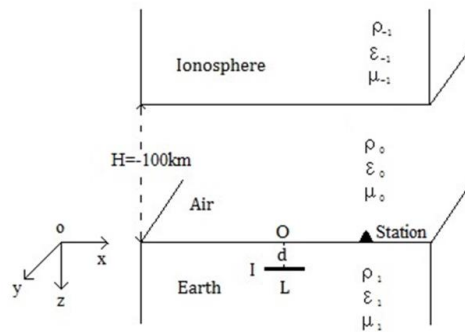
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this figure would make intuitively more sense if the available space on the page were used to increase the horizontal distance between O and "Station" to several times the vertical distance H=100km. This would allow visualize propagation of the EM wave in the waveguide

156 **Fig.1.** An x-directed dipole current source, with its central coordinate $(0, 0, d)$, is placed in the
 157 bottom medium (Earth) of a three layer modeling (Earth-air-ionosphere model), where z is defined
 158 positive in the downward direction.

159

160 Based on the model set up by Key (2009), some modifications will be done in
 161 this study in order to answer the questions illustrated above. A physical model is
 162 specified. It has three layers, Earth, air and ionosphere, which is called
 163 Earth-air-ionosphere model. Its coordinate system is denoted in Fig.1 with z -direction
 164 being downward. An x-directed dipole of a length L and a current I is placed in the
 165 bottom medium (Earth: $z > 0$), which is homogeneous and has the electrical
 166 properties: magnetic permeability μ_1 , permittivity ϵ_1 , and conductivity σ_1 . The
 167 middle medium (air: $-100 \text{ km} < z < 0$) is described by its electrical properties μ_0 ,
 168 $\epsilon_0 (= 8.854 \times 10^{-12} \text{ Farad m}^{-1})$ and $\sigma_0 (= 10^{-14} \text{ S m}^{-1})$. The top medium
 169 (ionosphere: $z < -100 \text{ km}$) is characterized by electrical properties μ_{-1} , ϵ_{-1} and
 170 $\sigma_{-1} (= 10^{-5} \text{ S m}^{-1})$.



Something is wrong here: according to Figure 1 the Earth medium is at $z < 0$ and the air medium is at $z > 0$.

171 As a comparison, a two-layer model (Earth-air model) including in Earth
 172 medium ($z > 0$), as well as air medium ($z < 0$), is also established during the study.
 173 All the corresponding parameters described are the same as these of
 174 Earth-air-ionosphere model.

175 We assume that the total space is non-magnetic and that the magnetic
 176 permeability μ variations are negligible in the different layers, i.e. $\mu_1 = \mu_0 = \mu_{-1} =$
 177 $4\pi \times 10^{-7}$ Farad m^{-1} . However, the ionosphere as the electrically conducting
 178 section of the upper atmosphere ~~play a so~~ important role ~~on~~ the electromagnetic
 179 propagation that we set $\epsilon_{-1} = 5\epsilon_0$ when an ionospheric effect on electromagnetic
 180 transmission is taken into consideration. On the same manner we have $\epsilon_1 = \epsilon_0 =$
 181 8.854×10^{-12} Farad m^{-1} , i.e. ϵ_i is not considered as zero during all calculations.
 182 Under these conditions, the formula listed above are still suitable and more
 183 explanations about the potential formulation of a horizontal electric dipole can be
 184 found in the Appendix A of Key (2009) and related programs are available with an
 185 access to the website (<http://marineemlab.ucsd.edu/>). The horizontal finite length
 186 dipole source can be ~~seen~~ as an integral of an infinite small horizontal dipole during
 187 related calculations.

188

189 3 Simulation results

190 According to these two models ~~built~~ above, several free parameters must be
 191 specified in order to investigate the attenuation characteristics of the electromagnetic
 192 fields emitted by a long x-directed dipole current source. As for the parameters of the
 193 dipole current source, we select $L=150$ km, the Wenchuan earthquake main rupture
 194 stage within 30 s out of 90 s (~ 300 km) based on Zhang et al., (2009, Fig.1), the
 195 depth $d=19$ km (Xu, 2009), the hypocenter depth of the Wenchuan case and the
 196 current is set to be $I=1$ A temporarily. Here, the Earth is considered to be an isotropic
 197 media with an average conductivity σ_1 , and we assume $\sigma_1 = 1.0 \times 10^{-3}$ S m^{-1} at
 198 this time, i.e. $\rho_1 = 10^3$ ohm \cdot m, although the ground conductivity depends not only
 199 on the local petrology, but also on the porosity, temperature, and pressure (e.g., Wait,
 200 1966). All these parameters are common to two models. ~~While the~~ parameter
 201 $\epsilon_{-1} = 5\epsilon_0$ is of most importance during the calculation in three-layer model in that it
 202 potentially can affect the transmission of electromagnetic waves produced by the
 203 dipole beneath the Earth, and possibly ~~induces~~ the Earth-atmosphere-ionosphere
 204 electromagnetic coupling.



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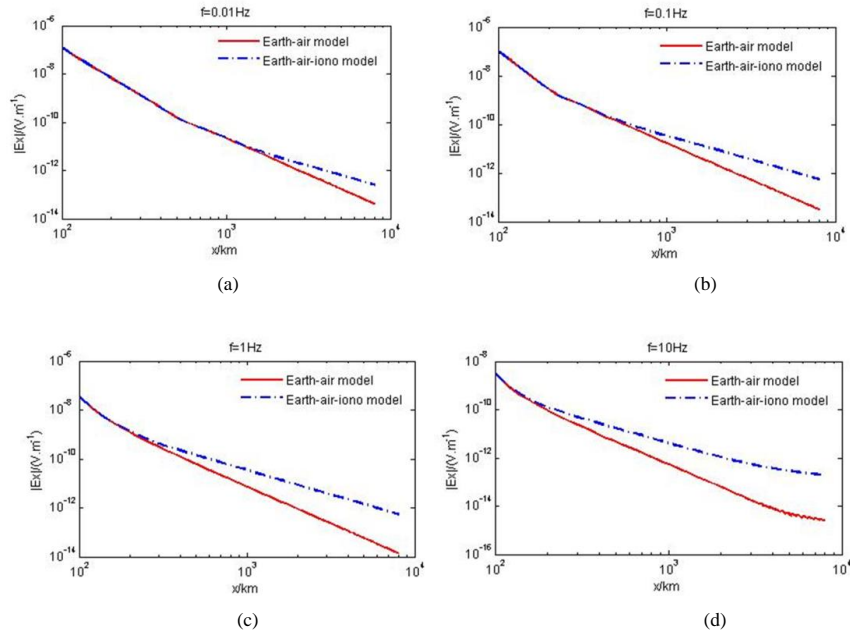
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Fig.2. Electric field $|E_x|$ decay curves along x-axial direction as a function of the observing distance for the Cartesian coordinate system with different frequencies. Red solid lines stand for electric field curves for Earth-air model and blue dot lines denote electric field curves with the ionospheric effect for Earth-air-ionsphere model.

(a) Total $|E_x|$ for $f=0.01$ Hz; (b) Total $|E_x|$ for $f=0.1$ Hz;

(c) Total $|E_x|$ for $f=1$ Hz; (d) Total $|E_x|$ for $f=10$ Hz;

Fig.2a-d displays electric field component amplitude $|E_x|$ decay curves along the x-axial direction with the frequencies $f=0.01$ Hz, $f=0.1$ Hz, $f=1$ Hz, and $f=10$ Hz respectively for the Cartesian coordinate system up to $\sim 10,000$ km on the Earth's surface.

It can be seen from Fig.2a-d, first, the electrical field with “high” frequency has a big attenuation although all curves for both Earth-air model (red solid lines) and Earth-air-ionsphere model (blue dot lines) decay rapidly as the distance increases. Second, each group of curves run at the same level for one fixed frequency, e.g., $f=1$ Hz, when an observing point is located at a relative near distance, ~ 300 km for $f=1$ Hz (Fig.2c) for example. That is to say, the ionospheric influence on electromagnetic field transmissions can be neglected within this range. However this range changes



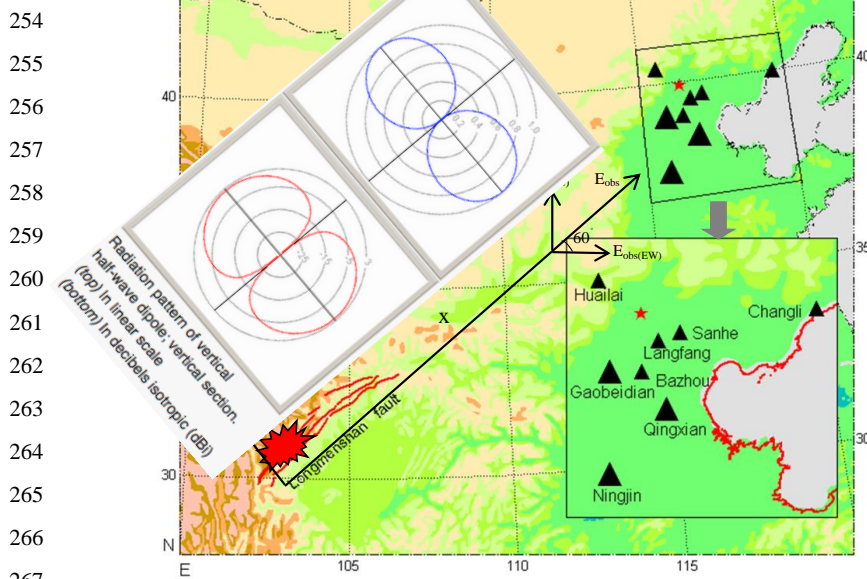
239 for different frequencies and it becomes smaller as the operating frequency of the
 240 current source increases (e.g., more than 1000 km for $f=0.01$ Hz (Fig.2a) and only
 241 ~ 200 km for $f=10$ Hz (Fig.2d)). Third, the most important result is, as the distance
 242 increases, field curves with an ionospheric effect (blue dot lines) run by a different
 243 way from that of curves without an ionospheric effect (red solid lines) and the
 244 ionospheric lines attenuate more slowly. Now, this kind of ionospheric influence
 245 cannot be neglected at this time anymore. The ionospheric difference is about 1
 246 magnitude ($\times 10$) for all the frequencies listed and even once up to 2 magnitudes for
 247 $f=10$ Hz within the range shown in Fig.2. For example, the ionospheric difference
 248 value shows 1 magnitude from ~ 840 km, up to 2 magnitudes from $\sim 3,700$ km for
 249 $f=10$ Hz (Fig.2d).

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251 4 The Wenchuan $M_S=8.0$ earthquake as a sample

252 4.1 Estimating the seismo-telluric current magnitude

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with the geometry shown
 the intensity of the EM
 emission perpendicular to
 the Longmenshan fault
 should be much higher as
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 Any comment?

268 **Fig.3.** Distribution of the Wenchuan earthquake epicenter and observation stations. Black solid
 269 triangles present the related locations of observation stations in Hebei electromagnetic observation
 270 network, bigger ones indicate the stations where abnormal information was recorded and the red
 271 star denotes Beijing (Li et al., 2013, Fig.1). A ground surface coordinate system is added.

272



273 On the base of the work of rock experiments conducted under laboratory
274 conditions, there is a reason to believe that a giant seismo-telluric current is generated
275 when the main rupture took place during the Wenchuan earthquake on 12 May 2008
276 and that this current mainly propagates along the Longmenshan fault. At the same
277 time a strong electrical field induced by this current suddenly increased. This
278 electrical field was recorded at the ground-based Gaobeidian observing station, 1440
279 km away from the epicenter of the shock, with a SN maximum amplitude of 70 mm,
280 i.e. 1.3 mV m^{-1} (Li et al., 2013), that is $E_{\text{obs(SN)}} = 1.3 \text{ mV m}^{-1}$ in the following
281 statement (Fig. 3).

what does "SN"
mean? Signal-to-
Noise?

282 In order to establish a relationship between the seismo-telluric current during the
283 main event and the observable ground electrical signals registered at Gaobeidian
284 station, we consider that a finite length current dipole source, with the length being
285 the main rupture $L=150 \text{ km}$ of the Wenchuan earthquake and the current I , is
286 co-located with the Longmenshan main fault (x-direction), with the depth being $d=19$
287 km. Then one can refer to Fig.1 with ionospheric effect.

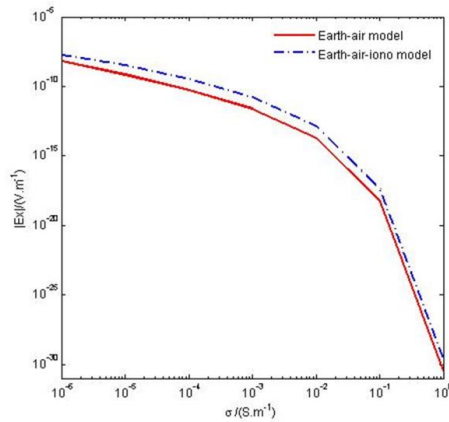
288 A coordinate system on the Earth's surface (see Fig.3) is set up to calculate the
289 observable electrical field along the x-direction E_{obs} according to the electrical value
290 $E_{\text{obs(SN)}}=1.3 \text{ mV m}^{-1}$ recorded at the Gaobeidian station. The Gaobeidian station lies in
291 the extended line of the Longmenshan fault, which trends northeast and dips about
292 60° west (Xu, 2009). Other locations of stations are shown in Fig.1 of Li et al. (2013)
293 and here they are shown in Fig.3 which includes a ground surface coordinate system.
294 From Fig.3, we see that the electrical field component intensity along the x-direction
295 is about $|E_x|=E_{\text{obs}}=1.5 \text{ mV m}^{-1}$ ($E_{\text{obs(SN)}}=\sin 60^\circ \times E_{\text{obs}}=1.3 \text{ mV m}^{-1} \rightarrow E_{\text{obs}}=1.5 \text{ mV}$
296 m^{-1}).

297 As the observing frequency of the electromagnetic observation system is 0.1-10
298 Hz and the recorder belongs to a real-time analog record, it is not easy to finger out
299 the right frequency of the signals registered at the Gaobeidian station during the
300 maximum stage prior to the Wenchuan earthquake. We set the main frequency $f=1 \text{ Hz}$
301 during our calculations although the information is of a short period $\sim 0.1-0.3 \text{ s}$ and a
302 large amplitude $\sim 1.3 \text{ mV m}^{-1}$ (Li et al., 2013) and frequency bands (0.4-3 s and
303 0.05-0.1 s) with various amplitudes were observed (Guan et al., 2003). At the same
304 time, the results of 2D MT inversion in the Longmenshan fault show that the apparent
305 resistivity logarithm is $\sim 1-4.8$ (Zhu et al., 2008) and it is a wide range.

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319 **Fig.4.** The calculated value of $|E_x|$, expected at the observation location (1,440 km, 0, 0) due to a
 320 dipole source of $L=150$ km, $I=1$ A, $f=1$ Hz and $d=19$ km (Fig.1), as a function of the typical
 321 crustal materials conductivity σ both in Earth-air model (red line) and in Earth-air-ionsphere
 322 model (blue dot line).
 323

324 Fig. 4 shows the calculated values of $|E_x|$, expected at the observation location
 325 (1,440 km, 0, 0) due to a dipole source of $L=150$ km, $I=1$ A and $d=19$ km (Fig.1), as a
 326 function of the typical crustal materials conductivity σ . Comparing with the red line
 327 with the blue dot one, the ionospheric effect is clearly displayed throughout the
 328 variation of the crustal conductivity. A rapid attenuation (exceed 20 orders) of the
 329 field values indicates the importance of the conductivity σ . It is difficult to specify the
 330 average conductivity σ (referred to as σ_1 in the context) of the homogeneous Earth
 331 medium, even for the typical Wenchuan area. However, combined with $f=1$ Hz here,
 332 the skin-depth depends on the conductivity σ , given by the formula $\delta = (\pi f \mu_0 \sigma)^{-\frac{1}{2}}$.
 333 Taken the depth $d=19$ km into account, here $\delta = d = 19$ km and the calculated σ_1
 334 is attained, i.e. $\sigma_1 = 7.0 \times 10^{-4} \text{ S m}^{-1}$, which is advantageous to radiate
 335 electromagnetic waves within this depth.

336 Using the same parameters as above, the simulation results show that the
 337 seismo-telluric current along the main fault needed to produce an electrical ground
 338 signal $E_{\text{obs(SN)}} = 1.3 \text{ mV m}^{-1}$ at the Gaobeidian station when the Wenchuan event
 339 occurred, is about 5.3×10^4 kA with the ionospheric effect and 3.7×10^5 kA without the
 340 ionospheric effect. As it is expected, these two results have one order ($\times 10$)



341 difference from each other. While the former is more reasonable under this conditions
342 because the seismo-telluric current produced by the Wenchuan main rupture is
343 specified.

344 4.2. Detectability under the ionospheric effect

345 Now according to the Wenchuan earthquake example, the seismo-telluric current
346 source ($f=1$ Hz, $d=19$ km, $L=150$ km, and a current $I=5.3\times 10^4$ kA considering the
347 Earth-air-ionosphere model) is thought of as a powerful finite length dipole source.

348 Fig.5 displays the fluctuations of the surface electrical fields with and without
349 ionospheric effect for the Wenchuan source along x-axial direction. It shows no
350 obvious ionospheric effect within 300 km, while this effect is roughly up to 1
351 magnitude from ~ 800 km. The gap becomes larger as the distance extends, 2
352 magnitudes from ~ 4000 km, and then it keeps this gap till 10,000 km. Under this
353 condition, considering the observable signal 1.5 mV m^{-1} at Gaobeidian station before
354 the Wenchuan epicenter, the distance recorded such a signal must be ~ 1500 km
355 (blue arrow) with ionospheric effect, or it is only ~ 800 km (red arrow) without
356 ionospheric effect. So the ionosphere facilitates the electromagnetic wave propagation,
357 as if the detectability of the system is improved effectively and it is easier to record a
358 signal even for stations located at distances beyond their detectability threshold.

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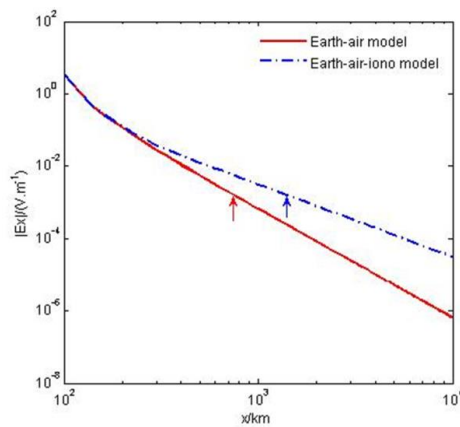
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371 **Fig.5.** The Wenchuan source producing electric field $|Ex|$ decay curves as a function of the
372 distance along x-axial direction with ionospheric effect (blue dot line), as well as without
373 ionospheric effect (red line). The electric field $|Ex|=1.5 \text{ mV m}^{-1}$ is labeled by a red arrow and a
374 blue one respectively.



375 5 Discussion

376 In very recent years, there is an increasing amount of evidence that during some
377 last stages of the long term process of preparation, there could be a transfer of energy
378 between lithosphere and the above layers of atmosphere and ionosphere, so as to
379 introduce the concept of a lithosphere–atmosphere–ionosphere coupling (LAIC)
380 among the three involved layers of the Earth system (Pulinets et al., 2000; Hayakawa
381 and Molchanov, 2002; Molchanov et al., 2004; Pulinets and Ouzounov, 2011). On
382 one hand, the ‘energy source’ is usually thought to be beneath the Earth and related
383 with tectonic activities in the lithosphere. On the other hand, numerous rock-pressure
384 experiments and electromagnetic observations associated with seismic activities have
385 already proved that a giant electrical current and an abrupt increase of electromagnetic
386 signals are motivated when the main rupture occurs for stressed-rocks. These
387 phenomena happened on May 9 2008, 3 days before the Wenchuan event, which
388 hypocenter lies in mid-crust. The strong seismo-telluric current is thought to run
389 mainly along the Longmenshan fault and electromagnetic oscillations, induced by the
390 current and predominated by ULF frequency band, propagate up to ionosphere and
391 give rise to perturbations of ionospheric parameters. Some of these parameters have
392 been investigated, such as GPS TEC and f0F2 (Yu et al., 2009; Xu et al., 2010;
393 Akhoondzadeh et al., 2010), DEMETER satellite O+ density (Zhang et al., 2009),
394 electron density and electron temperature (Zeng et al., 2009), and so on. Fortunately,
395 all these study results present a climax on May 9 and this indicates a lithosphere–
396 atmosphere–ionosphere coupling or interaction aroused by these electromagnetic
397 signals prior to the Wenchuan event.

398 Unfortunately, at present, most of investigations put emphases on the effect of
399 earthquakes upon the ionosphere and few of them pay attention to an inverse problem,
400 that is the ionospheric influence on the electromagnetic waves passed through.

401 The ionosphere, as a part of the electrical conducting region of the upper
402 atmosphere, can enhance electromagnetic fields and make the decay slow when an
403 observation is within ionospheric range and the ionospheric effect can be up to 1-2
404 magnitudes of the electrical fields in our simply three-layer model for some specified
405 parameters we select.

406 Considering the Wenchuan event, the electrical signals from the lithosphere
407 interact with the ionosphere and are improved simultaneously and then registered at
408 1440km Gaobeidian station with the amplitude of 1.3 mV m^{-1} . This electrical field is



409 used to simulate the seismo-telluric current produced by the Wenchuan main rupture
410 in an Earth-air-ionosphere model together with an Earth-air model. The results present
411 that, the seismo-telluric currents with and without ionospheric effect must be about
412 5.3×10^4 kA and 3.7×10^5 kA, respectively. Compared with the expected seismo-telluric
413 current ~ 10 – 100 kA of the “Alum Rock” $M_w=5.6$ earthquake for an observed 30 nT
414 pulse at 1 Hz and $D=2$ km (Bortnik et al., 2010), this result is probably in a reasonable
415 range.

416 However, firstly, the total rupture of the Longmenshan fault ~~concerned with the~~
417 Wenchuan main shock is extremely complicated ~~that contains~~ tenths rupture stages
418 and several pauses, totaled 90 s for the whole rupture process (~ 300 km), according
419 to Zhang et al.,(2009). Thus the total surface rupture ~ 300 km is nevertheless not
420 used here. While performing the analysis on only the primary 30 s, a main stage of the
421 Wenchuan earthquake, out of 90 s as we have selected $L=150$ km above, is expected
422 to be representative of the majority of the rupture to generate a seismo-telluric current.
423 Secondly, three medium are thought of as a homogeneous isotropic medium in our
424 models and with the same average conductivity value for each one, especially for the
425 wenchuan area. However, the Earth conductivity plays ~~a so~~ important role that can
426 predominately affect the fluctuations of the electrical fields as shown in Fig.4
427 although no one exactly knows the right conductivity of the bottom medium. The
428 value $\sigma_1 = 7.0 \times 10^{-4} \text{ S m}^{-1}$ taken part in all analysis is estimated when the
429 observing frequency range $f=0.1$ - 10 Hz and the hypocenter depth $d=19$ km of the
430 Wenchuan main event are taken into account for the skin-depth formula. One must
431 also mention that we use $f=1$ Hz in our calculations because we cannot distinguish the
432 ~~right frequency of~~ the recorded analog signals. All these can underscore our
433 simulation results.

434 While these disadvantageous selections maybe are not so important at the same
435 time because the key point of this paper is of ionospheric influence on
436 electromagnetic waves and our investigation attains advantageous results.

437

438 6 Conclusions

439 In this paper, a three-layer (Earth-air-ionosphere) physical model, as well as a
440 two-layer (Earth-air) model, is employed to investigate the ionospheric effect on the
441 wave fields for a finite length dipole current source co-located with the main fault of
442 an earthquake when an observing location distance is up to one thousand kilometers



443 or even more. For a dipole source with specified parameters of the length $L=150$ km,
444 the current $I=1$ A, and the depth $d=19$ km, the results show that all fields are free of
445 the ionospheric effect for different frequencies in relative short ranges, e.g., ~ 600
446 km for $f=0.1$ Hz, which implies the ionospheric influence on electromagnetic field
447 transmissions can be neglected within this range. However, the ionosphere can
448 ~~strengthen~~ the field amplitude and ~~make~~ the decay ~~slow~~ when an observation is out of
449 this range and the ionospheric effect can be up to 1-2 magnitudes of the electrical
450 fields.

451 This is ~~suitable for~~ the 12 May 2008 Wenchuan $M_S=8.0$ earthquake during which
452 a strong electromagnetic signal with an amplitude of ~ 1.3 mV m^{-1} , is recorded by the
453 Gaobeidian ULF ($f=0.1-10$ Hz) observing station 1440 km ~~away~~ from the epicenter.
454 The main fault rupture producing a current is equivalent to a finite length dipole
455 current source, with a nucleation depth of 19 km and a length of 150 km. Considering
456 the Earth-air-ionosphere model, the expected current for the most typical properties of
457 Wenchuan area is of ~~5.3×10^4 kA~~, which is of one magnitude smaller than the current
458 value of ~~3.7×10^5 kA~~ obtained with the Earth-air model free of ionospheric effect. On
459 the contrary, a signal introduced by a seismic activity can be advantageously recorded
460 by a remote station under the ionospheric effect as if the detectability of the system is
461 improved effectively.

462

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468

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