Research Paper
J. Astron. Space Sci. 34(1), 1-5 (2017)
https://doi.org/10.5140/JASS.2017.34.1.1

JASS Journal of Astronomy and Space Sciences

Ionospheric F2-layer Perturbations Observed After the M8.8 Chile Earthquake on February 27, 2010, at Long Distance from the Epicenter

Valery V. Hegai†**, Vitaly P. Kim, Anna D. Legen'ka**
Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences (IZMIRAN), Troitsk, Moscow 108841, Russia

The F2-layer critical frequency (foF2) data from several ionosondes are employed to study the long-distance effect of the M8.8 Chile Earthquake of February 27, 2010, on the F2 layer. Significant perturbations of the peak F2-layer electron density have been observed following the earthquake at two South African stations, Hermanus and Madimbo, which are located at great circle distances of ~8,000 and ~10,000 km from the earthquake epicenter, respectively. Simplified estimates demonstrate that the observed ionospheric perturbations can be caused by a long-period acoustic gravity wave produced in the F-region by the earthquake.

Keywords: seismo-ionospheric coupling, ionospheric F2 layer, acoustic gravity wave, ionospheric perturbation

1. INTRODUCTION

The F-region ionosphere is highly variable due to a whole number of influences from below (severe meteorological and seismic events) and from above (solar ionizing EUV flux, solar wind conditions, magnetospheric and auroral activities) (e.g., Forbes et al. 2000; Rishbeth & Mendillo 2001; Laštovička 2006; Kim & Hegai 2015; Chung et al. 2016 ; Kim & Hegai 2016). An ionospheric response to a major earthquake is still far from being fully investigated, although early studies on the subject have been carried out more than 50 years ago when Davies & Baker (1965), Leonard & Barnes (1965), and Row (1966) presented an evidence of perturbations in the F2 layer caused by the M8.4 Alaska Earthquake of March 28, 1964. Row (1967) showed that the ionospheric perturbations could be attributed to the F2-layer electron density of acoustic gravity waves (AGWs) produced by the earthquake in the F-region. A more detailed theoretical treatment of AGWs launched into the ionosphere by seismic shocks was presented by Liu & Yeh (1971) and Yeh & Liu (1974) for the case of an isothermal and dissipationless neutral atmosphere. The data were extrapolated for a realistic neutral atmosphere in a number of studies (e.g., Francis 1973, 1975; Liu & Klostermeyer 1975; Mayr et al. 1984; Maeda 1985; Liang et al. 1998; Sun et al. 2007; Ma 2016). At long distances from an earthquake epicenter, ionospheric perturbations in the F-region due to AGWs of seismic origin are observed as medium- and large-scale traveling ionospheric disturbances (TIDs; Francis 1973, 1975). Seismic TIDs have been registered at distances of more than 3,000 km from epicenters using ionosonde measurements of the F2-layer critical frequency (foF2; Leonard & Barnes 1965; Hegai et al. 2011). The TIDs associated with earthquakes have also been studied using ionospheric total electron content (TEC) data measured by GPS receiver networks (e.g., Calais & Minster 1995; Astafyeva & Afraimovich 2006; Liu et al. 2006; Tsugawa et al. 2011; Cahyadi & Heki 2013).

Another type of ionospheric perturbations detected in the F-region after earthquakes is small amplitude variations in the electron density caused by vertically propagating acoustic waves that were excited by seismic Rayleigh waves traveling along the Earth's surface with respect to an epicenter. Rayleigh wave signatures in the ionosphere following earthquakes have been measured by Doppler sounding (e.g., Yuen et al. 1969; Tanaka et al. 1984; Artru et al. 2004; Chum

Received 21 FEB 2017 **Revised** 5 MAR 2017 **Accepted** 9 MAR 2017
†**Corresponding Author**
Tel: +7-4958-519780, E-mail: hegai@izmiran.ru
ORCID: https://orcid.org/0000-0003-0843-9096

et al. 2016) using TEC measurements (e.g., Ducic et al. 2003; Astafyeva et al. 2009; Rolland et al. 2011) and the inspection of ionograms (Maruyama et al. 2012, 2016a, 2016b).

In this work, ionosonde foF2 data are utilized to study perturbations of the peak F2-layer electron density following the M8.8 Chile Earthquake of February 27, 2010, at long distances from its epicenter.

2. DATA ANALYSIS AND DISCUSSION

As reported by the U.S. Geological Survey, the major earthquake with a magnitude of 8.8 and depth of 35 km occurred at 06:34:14 UT on February 27, 2010, at a distance of 335 km from Santiago, the capital of Chile. The epicenter of the earthquake was located at a geographic latitude of 35.9°S and longitude of 72.7°W.

We examine the foF2 values [proportional to $(NmF2)^{1/2}$] recorded at several ionospheric stations listed in Table 1. The foF2 data were taken from the NGDC SPIDR website (http://spidr.ionosonde.net/spidr/). The index Kp is used to represent the geomagnetic activity around the earthquake. The solar and geomagnetic activities were low in February 2010; the monthly F10.7 and Ap indices were as small as 82.7 and 5, respectively.

Fig. 1 shows the time variation of the observed critical frequency foF2 (a, b, and c) at three ionosonde stations (Hermanus, Madimbo, and Port Stanley) over the period 00:00 to 24:00 UT on February 27, 2010. The average foF2 (<foF2>) of ten quiet days in February 2010, during which the Kp index did not exceed 2 (February 7, 10, 11, 19, 20, 21, 22, 23, 24, and 28, 2010), is superposed to provide reference curves. The vertical lines consequently indicate the moment of the earthquake onset (t_{EQ}), which means the estimated time of arrival of the seismic atmospheric disturbance traveling in the F-region from the epicenter to the ionosonde site along the great circle path (t_{ar}). The great circle distances from the epicenter of the earthquake to the selected ionosonde stations are given in Table 1. We estimate the arrival times t_{ar} in the simplest way by using the formula $t_{ar} \sim t_{EQ} + L/V$, where L is the value of the great circle distance and V is the speed of the horizontal propagation of the seismic atmospheric disturbance in the F2 layer. The speed of medium- and large-scale seismic atmospheric disturbances, V, is ~800 m/s (e.g., Row 1967; Francis 1973, 1975).

The geomagnetic activity was very low on February 27, 2010, and the Kp index did not exceed 1, while the Kp index did not exceed -3 during the three previous days, which means that the geomagnetic conditions were favorable to identify ionospheric perturbations unrelated to geomagnetic disturbances. After the earthquake, at ~t_{ar}, the foF2 at the South African stations Hermanus and Madimbo started to decrease; soon became smaller than <foF2>, by more than

Table 1. A list of ionospheric stations

Station	Geog. Lat. (°N)	Geog. Long. (°E)	Δt (min)	L (km)
PORT STANLEY	-51.7	302.2	30.0	2,100
HERMANUS	-34.4	19.2	15.0	8,000
NORFOLK IS	-29.0	168.0	60.0	10,400
MADIMBO	-22.4	30.9	30.0	9,700
KWAJALEIN	9.1	167.2	5.0	13,300
WALLOPS IS	37.9	284.5	15.0	8,200
ROME	41.8	12.5	15.0	12,200
WAKKANAI	45.2	141.8	60.0	16,900

Δt is the time interval between ionospheric sounding impulses, L is the great circle distance from the earthquake epicentre to a station.

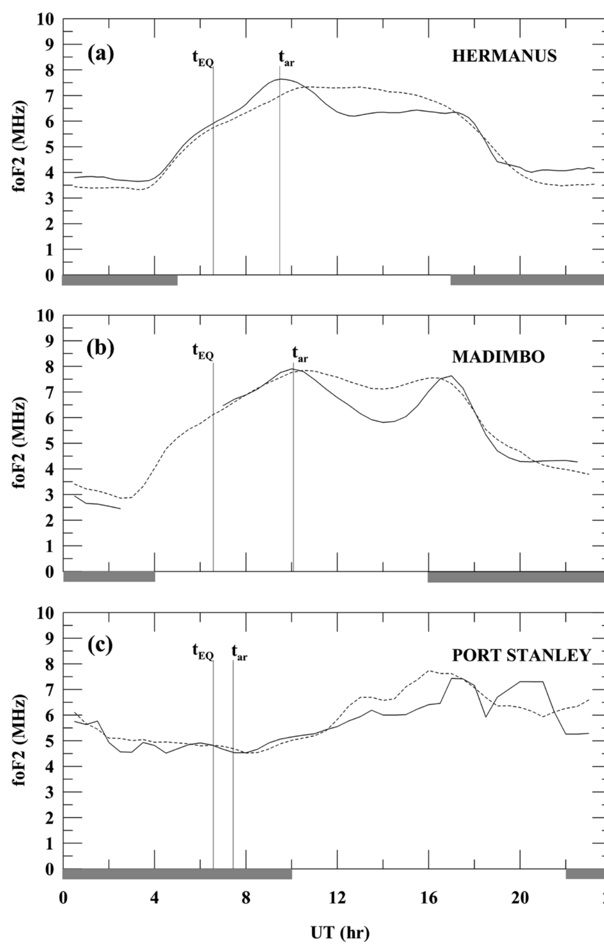

Fig. 1. Time variation of the observed critical frequency foF2 (a, b, and c) at the three ionosonde stations (Hermanus, Madimbo, and Port Stanley) over the period from 00:00 to 24:00 UT on February 27, 2010. The average foF2 (<foF2>) of ten quiet days in February 2010 during which the Kp index did not exceed 2 is superposed to provide reference curves. The vertical lines consequently indicate the moment of the earthquake onset (t_{EQ}), which means the estimated time of arrival of the seismic atmospheric disturbance traveling in the F-region from the epicenter to the ionosonde site along the great circle path (t_{ar}). The gap in the foF2 curve for Madimbo is due to the unavailability of appropriate data.

20 %; and recovered to <foF2> in approximately 8 and 5 hr, respectively. Note that the observed depression of foF2 occurred during daytime hours. Fig. 1(c) shows no meaningful negative perturbation in the F2 layer over the South American station Port Stanley at ~t_{ar}, although this station is located much closer to the epicenter than the South African stations Hermanus and Madimbo. The other stations listed in Table 1 did also not demonstrate any significant perturbations in foF2 around the estimated time of arrival of large-scale seismic AGWs. It is reasonable to suggest that the negative perturbations in foF2 observed at Hermanus and Madimbo shortly after t_{ar} are associated with large-scale long-period AGWs produced in the F2 layer during the Chile Earthquake. The frequency of the predominant seismic AGW near the F2 layer peak at large distance from an earthquake epicenter can be estimated using a simplified theoretical formula (Row 1967; Liu & Yeh 1971; Yeh & Liu 1974), $\omega \sim \omega_b(L/\mathrm{hmF2})$, where ω is the AGW frequency, ω_b is the Brunt–Väisälä frequency (the mean value of $\omega_b/2\pi$ in the F2 layer is ~0.001 Hz), and hmF2 is the height of the F2 layer peak at the point of observation. In the case of Hermanus, we obtain $\omega/2\pi \sim 3.6\times10^{-5}$ Hz (for hmF2 taken from the IRI-2016 model: http://omniweb.gsfc.nasa.gov/vitmo/iri2016_vitmo.html/), which means that the AGW period is approximately 7.7 hr. To our knowledge, this is the first evidence of significant perturbation in foF2 produced by seismic AGWs at such a long distance (> 8,000 km) from the epicenter of an earthquake that stipulated the AGWs in the F-region ionosphere. At the same time, the theoretical treatment by Francis (1973) indicates that seismic AGWs with periods between 30 sec and 2 hr are attenuated by a factor of $1/e$ at a distance of ~5,000 km from the earthquake epicenter. This could explain the absence of any seismic AGW effect on foF2 at other stations located at distances much larger than 5,000 km from the epicenter. Previously, Maruyama et al. (2016) reported a long-distance effect of the Chile Earthquake on the ionospheric F-region based on another mechanism, unrelated to seismic AGWs. They observed short-period (tens of seconds) wavy fluctuations of the virtual height in the daytime F1 region after the earthquake at the European ionospheric station Kazan (L ~ 15,150 km), which were attributed to infrasound waves due to Rayleigh waves excited by the earthquake and propagated to Kazan.

It is important to understand why the nearest station to the earthquake epicenter, Port Stanley (L ~ 2,100 km), did not notably indicate the impact of seismic AGWs on foF2. This could likely be attributed to the fact that the seismic AGWs arrived at Port Stanley at night when the height of the F2 layer peak over Port Stanley was ~320 km, reflecting unfavorable conditions for the seismic AGWs to change the foF2 because a superposition of the seismic AGWs produces perturbation in the ionospheric electron density at long distance, predominantly between altitudes of 180 and 280 km, which is in agreement with Francis (1973).

3. CONCLUSIONS

The present study showed that the M8.8 Chile Earthquake of February 27, 2010, likely produced a long-distance impact on the ionospheric F2 layer at a distance > 8,000 km from the epicenter. Seismic perturbations (reduction) of foF2 have been observed for several hours at the South African stations Hermanus and Madimbo. They exceeded 20 % with respect to quiet time values. We suggest that the mechanism responsible for these perturbations is associated with large-scale AGWs excited in the F-region ionosphere by the earthquake.

ACKNOWLEDGMENTS

We acknowledge the Space Physics Interactive Data Resource (SPIDR) for providing the foF2 data. This work was supported by a research grant from the Russian Academy of Sciences.

REFERENCES

Artru J, Farges T, Lognonné P, Acoustic waves generated from seismic surface waves: propagation properties determined from Doppler sounding observations and normal-mode modelling, Geophys. J. Int. 158, 1067-1077 (2004). https://dx.doi.org/10.1111/j.1365-246X.2004.02377.x

Astafyeva EI, Afraimovich EL, Long-distance traveling ionospheric disturbances caused by the great Sumatra-Andaman earthquake on 26 December 2004, Earth Planets Space 58, 1025-1031 (2006). https://dx.doi.org/10.1186/BF03352607

Astafyeva EI, Heki K, Kiryushkin V, Afraimovich EL, Shalimov S, Two-mode long-distance propagation of coseismic ionosphere disturbances, J. Geophys. Res. 114, A10307 (2009). https://dx.doi.org/10.1029/2008JA013853

Cahyadi MN, Heki K, Ionospheric disturbances of the 2007 Bengkulu and the 2005 Nias earthquakes, Sumatra, observed with a regional GPS network, J. Geophys. Res. 118, 1777-1787 (2013). https://dx.doi.org/10.1002/jgra.50208

Calais E, Minster JB, GPS detection of ionospheric perturbations following the January 17, 1994, Northridge earthquake, Geophys. Res. Lett. 22, 1045-1048 (1995). https://dx.doi.org/10.1029/95GL00168

Chum J, Liu JY, Laštovička J, Fišer J, Mošna Z, et al., Ionospheric signatures of the April 25, 2015 Nepal earthquake and the relative role of compression and advection for Doppler sounding of infrasound in the ionosphere, Earth Planets Space 68, 24 (2016). https://dx.doi.org/ 10.1186/s40623-016-0401-9

Chung JK, Yoo SM, Lee W, The first measurement of seasonal trends in the equatorial ionospheric anomaly trough at the CHUK GNSS site during the solar maximum in 2014, J. Astron. Space Sci. 33, 287-293 (2016). https://dx.doi.org/10.5140/JASS.2016.33.4.287

Davies K, Baker DM, Ionospheric effects observed around the time of the Alaskan earthquake of March 28, 1964, J. Geophys. Res. 70, 2251-2253 (1965). https://dx.doi.org/10.1029/JZ070i009p02251

Ducic V, Artru J, Lognonné P, Ionospheric remote sensing of the Denali Earthquake Rayleigh surface waves, Geophys. Res. Lett. 30, 1951 (2003). https://dx.doi.org/10.1029/2003GL017812

Forbes JM, Palo SE, Zhang X, Variability of the ionosphere, J. Atmos. Sol. -Terr. Phys. 62, 685-693 (2000). https://dx.doi.org/10.1016/S1364-6826(00)00029-8

Francis SH, Acoustic-gravity modes and large-scale traveling ionospheric disturbances of a realistic, dissipative atmosphere, J. Geophys. Res. 78, 2278-2301 (1973). https://dx.doi.org/10.1029/JA078i013p02278

Francis SH, Global propagation of atmospheric gravity waves: a review, J. Atmos. -Terr. Phys. 37, 1011-1054 (1975). https://dx.doi.org/10.1016/0021-9169(75)90012-4

Hegai VV, Legen'ka AD, Kim VP, Georgieva K, Wave-like perturbations in the ionospheric F2-layer observed after the M_s8.1 Samoa earthquake of September 29, 2009, Adv. Space Res. 47, 1979-1982 (2011). https://dx.doi.org/10.1016/j.asr.2011.01.011

Kim V, Hagai V, Response of the midlatitude F2 layer to some strong geomagnetic storms during solar minimum as observed at four sites of the globe, J. Astron. Space Sci. 32, 297-304 (2015). https://dx.doi.org/10.5140/JASS.2015.32.4.297

Kim V, Hegai V, On the variability of the ionospheric F2-layer during the quietest days in december 2009, J. Astron. Space Sci. 33, 273-278 (2016). https://dx.doi.org/10.5140/JASS.2016.33.4.273

Laštovička J, Forcing of the ionosphere by waves from below, J. Atmos. Sol. -Terr. Phys. 68, 479-497 (2006). https://dx.doi.org/10.1016/j.jastp.2005.01.018

Leonard RS, Barnes Jr. RA, Observation of ionospheric disturbances following the Alaska earthquake, J. Geophys. Res. 70, 1250-1253 (1965). https://dx.doi.org/10.1029/JZ070i005p01250

Liang J, Wan W, Yuan H, Ducting of acoustic-gravity waves in a nonisothermal atmosphere around a spherical globe, J. Geophys. Res. 103, 11229-11234 (1998). https://dx.doi.org/10.1029/98JD00424

Liu CH, Yeh KC, Excitation of acoustic-gravity waves in an isothermal atmosphere, Tellus 23, 150-163 (1971). https://dx.doi.org/10.1111/j.2153-3490.1971.tb00558.x

Liu CH, Klostermeyer J, Excitation of acoustic-gravity waves in realistic thermosphere, J. Atmos. -Terr. Phys. 37, 1099-1108 (1975). https://dx.doi.org/10.1016/0021-9169(75)90155-5

Liu JY, Tsai YB, Chen SW, Lee CP, Chen YC, et al., Giant ionospheric disturbances excited by the M9.3 Sumatra earthquake of 26 December 2004, Geophys. Res. Lett. 33, L02103 (2006). https://dx.doi.org/10.1029/2005GL023963

Ma JZG, Atmospheric layers in response to the propagation of gravity waves under nonisothermal, wind-shear, and dissipative conditions, J. Mar. Sci. Eng. 4, 25 (2016). https://dx.doi.org/10.3390/jmse4010025

Maeda S, Numerical solutions of the coupled equations for acoustic-gravity waves in the upper thermosphere, J. Atmos. -Terr. Phys. 47, 965-972 (1985). https://dx.doi.org/10.1016/0021-9169(85)90074-1

Maruyama T, Tsugawa T, Kato H, Ishii M, Nishioka M, Rayleigh wave signature in ionograms induced by strong earthquakes, J. Geophys. Res. 117 A08306 (2012). https://dx.doi.org/10.1029/2012JA017952.

Maruyama T, Yusupov K, Akchurin A, Interpretation of deformed ionograms induced by vertical ground motion of seismic Rayleigh waves and infrasound in the thermosphere, Ann. Geophys. 34, 271-278 (2016a). https://dx.doi.org/10.5194/angeo-34-271-2016

Maruyama T, Yusupov K, Akchurin A, Ionosonde tracking of infrasound wavefronts in the thermosphere launched by seismic waves after the 2010 *M*8.8 Chile earthquake, J. Geophys. Res. 121, 2683-2692 (2016b). https://dx.doi.org/10.1002/2015JA022260

Mayr HG, Harris I, Varosi F, Herrero FA, Global excitation of wave phenomena in a dissipative multiconstituent medium: 1. Transfer function of the Earth's thermosphere, J. Geophys. Res. 89, 10929-10959 (1984). https://dx.doi.org/10.1029/JA089iA12p10929

Rishbeth H, Mendillo M, Patterns of F2-layer variability, J. Atmos. Sol. -Terr. Phys. 63, 1661-1680 (2001). https://dx.doi.org/10.1016/S1364-6826(01)00036-0

Rolland LM, Lognonné P, Munekane H, Detection and modeling of Rayleigh wave induced patterns in the ionosphere, J. Geophys. Res. 116 A05320 (2011). https://dx.doi.org/10.1029/2010JA016060

Row RV, Evidence of long-period acoustic-gravity waves launched into the *F* region by the Alaskan earthquake of March 28, 1964, J. Geophys. Res. 71, 343-345 (1966).

https://dx.doi.org/10.1029/JZ071i001p00343
Row RV, Acoustic-gravity waves in the upper atmosphere due to a nuclear detonation and an earthquake, J. Geophys. Res. 72, 1599-1610, (1967). https://dx.doi.org/10.1029/JZ072i005p01599
Sun L, Wan W, Ding F, Mao T, Gravity wave propagation in the realistic atmosphere based on a three-dimensional transfer function model, Ann. Geophys. 25, 1979-1986 (2007). https://dx.doi.org/10.5194/angeo-25-1979-2007
Tanaka T, Ichinose T, Okuzawa T, Shibata T, Sato Y, et al., HF-Doppler observations of acoustic waves excited by the Urakawa-Oki earthquake on 21 March 1982, J. Atmos. -Terr. Phys. 46, 233-245 (1984). https://dx.doi.org/10.1016/0021-9169(84)90150-8
Tsugawa T, Saito A, Otsuka Y, Nishioka M, Maruyama T, et al., Ionospheric disturbances detected by GPS total electron content observation after the 2011 off the Pacific coast of Tohoku Earthquake, Earth Planets Space 63, 66 (2011). https://dx.doi.org/10.5047/eps.2011.06.035
Yeh KC, Liu CH, Acoustic-gravity waves in the upper atmosphere, Rev. Geophys. 12, 193-216 (1974). https://dx.doi.org/10.1029/RG012i002p00193
Yuen PC, Weaver PF, Suzuki RK, Furumoto AS, Continuous traveling coupling between seismic waves and the ionosphere evident in May 1968 Japan earthquake data, J. Geophys. Res. 74, 2256-2264 (1969). https://dx.doi.org/10.1029/JA074i009p02256