Journal of Atmospheric and Solar-Terrestrial Physics 134 (2015) 1–8

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Near-field co-seismic ionospheric response due to the northern Chile M_w 8.1 Pisagua earthquake on April 1, 2014 from GPS observations

C.D. Reddy [a,*], A.S. Sunil [a], G. González [b,c], Mahesh N. Shrivastava [c], Marcos Moreno [d]

[a] *Indian Institute of Geomagnetism, Navi Mumbai, India*
[b] *Universidad Católica del Norte, Antofagasta, Chile*
[c] *National Research Center for Integrated Natural Disaster Management, Santiago, Chile*
[d] *GFZ Helmholtz Centre Potsdam, German Research Centre for Geosciences, Germany*

A R T I C L E I N F O

Article history:
Received 14 January 2015
Received in revised form
2 September 2015
Accepted 4 September 2015
Available online 6 September 2015

Keywords:
GPS TEC
Pisagua earthquake
Acoustic waves

A B S T R A C T

Large earthquakes can induce near and far-field ionospheric perturbations by direct/secondary acoustic and gravity waves through Lithosphere–Atmosphere–Ionosphere (LAI) coupling. We analyze co-seismic induced ionospheric TEC perturbations following the northern Chile M_w 8.1 Pisagua earthquake occurred on April 1, 2014. The continuous Global Positioning System (GPS) data at 15 sites from the Integrated Plate Boundary Observatory Chile (IPOC) and International GPS Service (IGS) GPS networks have been used in the present study. The nearest GPS site iqqe, ~98 km away from the epicenter, recorded the ionospheric disturbance 12 min after the event. The maximum co-seismic induced peak-to-peak TEC amplitude is ~1.25 TECU ($1\,\text{TECU}=10^{16}$ electrons/m^2), and the perturbations are confined to less than 1000 km radius around the epicenter. The observed horizontal velocity of TEC perturbations has been determined as ~1180 m/s. We could also discern the signatures of acoustic gravity waves (AGW) with velocity ~650 m/s and frequency ~2 mHz. The ionospheric signal components due to Rayleigh and/or Tsunami waves could not be observed. This contribution presents characteristics of near-field co-seismic ionospheric response due to the 2014 Pisagua earthquake.

1. Introduction

Ionospheric disturbances associated with the earthquakes have been detected by many researchers (e.g. Reddy and Seemala, 2015; Sunil et al., 2015; Cahyadi and Heki, 2015; Chum et al., 2012; Rolland et al., 2011a,b; Tsugawa et al., 2011; Galvan et al., 2011; Saito et al., 2011; Heki, 2011; Astafyeva et al., 2009). These ionospheric perturbations carry traceable information about the earthquake itself that generated them. Therefore understanding the connection between the solid earth (lithosphere), atmospheric and seismo-ionospheric perturbations can potentially complement the earthquake reporting systems and provide a useful tool for seismic hazard mitigation. Some of the well established techniques for monitoring ionospheric perturbations caused by large earthquakes include observations from both ground and satellite based advanced radio techniques, such as HF Doppler sounding (Chum et al., 2012; Ogawa et al., 2012; Liu et al., 2006; Artru et al., 2004), DEMETER (Parrot et al., 2006), Over The Horizon (OTH) radar (Occhipinti et al., 2010), and Faraday rotation measurements using linearly polarized EM signals from geostationary satellites (Davies, 1980) and GPS (Ducic et al., 2003; Heki, 2011; Saito et al., 2011). In particular, most modern and affordable GPS receivers provide an integrated value called Total Electron Content (TEC).

Lognonné et al. (2006) and Jakowski et al., (2012) provided reviews on detection, imaging, monitoring and forecasting of ionospheric perturbations from ground based Global Navigation Satellite System (GNSS) (e.g. GPS, GLONASS, GALILEO). Using Doppler sounding system, Chum et al. (2012) examined seismic generated infrasound (acoustic waves < 20 Hz) wave packets at 210–220 km height and showed that for waves longer than 30 s period, about 1/10 of the infrasound energy flux excited at the ground reached at these heights. Further, using cross-correlation between the seismic and ionospheric signal, they studied the velocity of upward propagating atmospheric waves. Perevalova et al. (2014), analyzed the seismo-ionspheric response from a set of earthquakes between 1965 and 2013 and demonstrated that only those earthquakes with $M_w \geq 6.5$ will have significant wave response in the ionosphere. The tendency of TEC to be larger for the earthquakes of lager magnitudes was first reported by Astafyeva et al. (2013). Furthermore, they demonstrated that shallow earthquakes with magnitudes M_w 7.2–7.8 will cause co-seismic

---

* Corresponding author.
E-mail address: cdreddy@iigs.iigm.res.in (C.D. Reddy).

http://dx.doi.org/10.1016/j.jastp.2015.09.006
1364-6826/

perturbations with near-field amplitude of 0.2–0.4 TECU (lasting 4–8 min), while mega earthquakes of $\sim M_w$ 9.0 produce extremely large perturbations of $\sim$1–3 TECU (lasting 30–40 min). Cahyadi and Heki (2015) provide a scaling law, which represents the relation between induced TEC and moment magnitude of the earthquake. In addition to the magnitude of the earthquake and focal depth, there is some evidence that the earthquake focal mechanism (Astafyeva and Heki, 2009), atmospheric acoustic resonance conditions (e.g. at 3.7 and 4.4 mH$_z$, Nishida et al., 2000; Rolland et al., 2013; Sunil et al., 2015; Tahira, 1995), directivity and apparent velocity (Heki and Ping, 2005), geomagnetic latitude, and other factors, can influence the intensity of ionospheric responses. While some of these aspects are addressed by Cahyadi and Heki (2015) using 21 earthquakes between M_w 6.6 and 9.2, TEC response amplitudes during quiet and disturbed geomagnetic conditions have been compiled by Perevalova et al. (2014), which can serve as ready reference to seismo-ionospheric studies.

It is evident that dense GPS arrays such as Southern California Integrated GPS Network (SCIGN) (Calais et al., 2003), Japanese GPS Earth Observation Network (GEONET, operated by GSI, Japan, Sagiya, 2004; Ogawa et al., 2012) Sumatra GPS Array (SuGAr) (Sunil et al., 2015; Cahyadi and Heki, 2013; Cahyadi and Heki, 2015) provide an opportunity to investigate ionospheric perturbations and their spatio-temporal characteristics at higher resolution than any other currently available techniques (Saito et al., 2001). For earthquakes with magnitude $M_w \sim 6$, the signal-to-noise ratio of these perturbations is small and may show up just above the noise level. However, by virtue of the associated waveforms being remarkably coherent over a wide region and the noise being incoherent, it is possible to retrieve the propagation direction and velocity of these perturbations. The imaged ionospheric perturbations from dense GPS arrays could, in principle, can be used as a proxy to study the coupling and energy transfer processes in the Lithosphere–Atmosphere–Ionosphere (LAI) coupled system (Calais et al., 2003). Numerical modeling of these waveforms (Rolland et al., 2011a, Kherani et al., 2012) could potentially lead to a better understanding of LAI coupling mechanisms.

Heki et al., (2006) demonstrated that, the near-field co-seismic ionospheric disturbances can be used in providing information on focal processes, such as rupture speed and relative magnitudes of multiple asperities. Astafyeva and Heki (2009) further suggest that studying co-seismic ionospheric disturbances has the potential to infer focal mechanisms, similar to seismic studies in solid Earth. These studies are referred to as seismic remote sensing.

From seismic gap theory, and the slip deficit accumulated along the northern segment of the Andean subduction zone (Chlieh et al. 2011; Schurr et al. 2014) it is likely that the next mega thrust earthquake in this region could still have a magnitude of M_w 8.9, and could occur to the north of the M_w 8.1 2014 Iquique earthquake sequence. In this context, near real-time global TEC monitoring network that can detect the acoustic and gravity waves generated by the earthquake and tsunami (e.g. Galvan et al., 2011) could potentially serve as a plug-in to enhance existing early warning systems at this subduction margin segment. This study will focus on the characteristics of near-field co-seismic ionospheric response due to the M_w 8.1 Iquique earthquake of April 1st 2014.

2. Vertical deformation modeling

The 2014 Pisagua Earthquake occurred near the coast of northern Chile (lat-19.610° lon −70.769° depth 25 km; time 23:46:47 UTC) located on the primary plate boundary interface

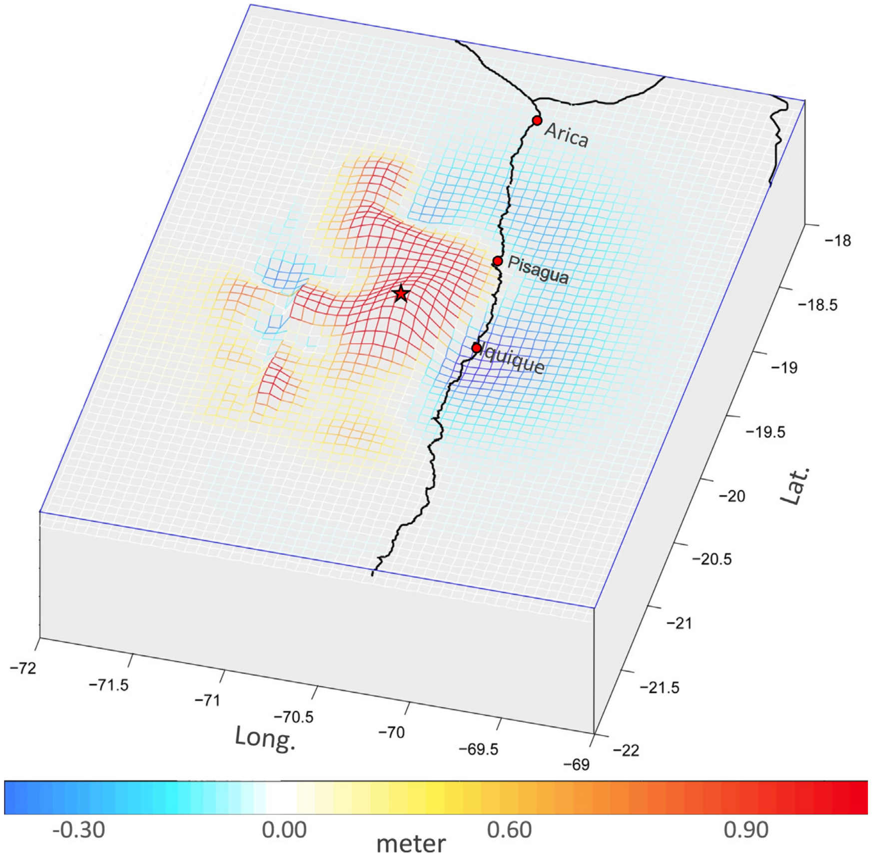

Fig. 1. Modeled vertical deformation due to Pisagua earthquake on April 1, 2014. The fault parameters (strike, dip, rake; 358° 12° 107°) are provided by USGS. The star indicates location of the earthquake. The focal mechanism is shown in Fig. 2.