

Seismic Activities and Ionosphere Reaction

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Abstract

The ionosphere is a part of the Earth's atmosphere specific for the increased concentration of charged particles. By monitoring the reaction of these charges, primarily negatively charged electrons, to various disturbances coming from space or from the Earth's surface, conclusions can be drawn about the intensity, nature and origin of these disturbances. In this paper changes in the ionosphere caused by seismic activity were examined. The carrier of disturbances between the trembling soil and the ionosphere are gravito-acoustic waves.

Keywords: Seismic Activity, Ionosphere, Disturbances, Gravito-acoustic Waves

Introduction

Earthquakes, volcanic eruptions, tsunamis, explosions, and other events on Earth's surface generate waves that travel upwards through the atmosphere [1-3]. Atmospheric waves can be divided into acoustic and gravity waves, depending on their frequency. Acoustic waves are longitudinal waves that propagate upward in the atmosphere at the speed of sound (i.e. approximately 330 m/s at the surface, and about 800 to 1000 m/s at the ionospheric altitude of 250 to 400 kilometers). Acoustic waves take about 7 to 9 minutes to reach the ionosphere. Gravity waves are lower frequency waves. These waves cannot propagate upward vertically but rather obliquely [4, 5]. The vertical component of their velocity is low, so they reach the ionospheric altitudes 45 to 60 minutes after they are generated on Earth's surface. The propagation and evolution of the acoustic and gravity waves in the atmosphere is greatly affected by the propagation medium and its properties. The exponential decrease of atmospheric density with altitude leads to the amplitude growth of both acoustic and gravity waves upon their upward propagation. Consequently, small waves generated at the Earth's surface may provoke significant perturbations in the upper atmosphere and ionosphere.

The ionosphere is the ionized part of the Earth's atmosphere, from about 50 km to more than 600 km altitude. It is ionized primarily by ultraviolet solar radiation and its practical importance is that, among other functions, it influences radio waves propagation to distant places on the Earth [6].

Once disturbances are detected in the ionosphere their spatio-temporal characteristics (such as, arrival time, amplitude,

propagation speed, etc.) can be estimated [7]. From these parameters, it is possible to determine the source of natural hazards. In some cases, we can also obtain the information about the source parameters from the ionospheric disturbances, such as the dimensions of a seismic fault ruptured in an earthquake, the height of a tsunami wave, or the energy of a volcanic eruption. The fact that co-seismic ionospheric disturbance can be detected in the ionosphere only 7 to 9 minutes after an event opens the possibility of using ionospheric measurements for near real-time tsunami warning systems [8, 9]. "Ionospheric seismology" is still a young branch of geophysics. Over the past two decades, thanks to advances in remote sensing and newly developed modeling tools, we have substantially improved our knowledge of the ionospheric signatures of natural hazards [10-12].

However, many features of the coupling between the solid Earth, ocean, atmosphere, and ionosphere remain poorly understood [13]. For instance, it is known that giant earthquakes can generate shock waves, but what about smaller earthquakes? How do variations in the neutral atmosphere affect the propagation of acoustic and gravity waves from the surface to the ionosphere? These and many other questions are still waiting to be answered.

Coupling Mechanism Between Seismic And Gravito-Acoustic Waves

Solid Earth events such as earthquakes, volcanoes and tsunamis can generate atmospheric and ionospheric perturbations by various coupling mechanisms. The focus here is on dynamic coupling: small vertical oscillations of the Earth's surface launch pressure waves in the neutral atmosphere that grow in ampli-

tude by several orders of magnitude as they attain ionospheric heights. These waves are acoustic waves by nature. When the gravity force is included acoustic waves change their features and becomes acoustic waves modified by gravity. On the other hand, gravity waves are governed primarily by buoyancy (gravity) force. In the model of the isothermal atmosphere with exponentially density decrease with the height, dispersion equation for gravito-acoustic waves has a form: $\omega^2 - \omega_a^2 + (\omega_g^2 / (\omega^2 - 1)) k_x^2 - K_z^2 = 0$. (1) Here, k_x and K_z are wavenumbers for propagating waves in the horizontal, i.e. x direction and vertical, i.e. z direction, while ω is their frequency. Gravity force introduces two characteristic frequencies— ω_a is the acoustic cut-off frequency below which acoustic waves cannot propagate and ω_g is the Brunt–Väisälä frequency above which gravity waves cannot propagate. The waves with frequencies between ω_g and ω_a i.e. $\omega_g < \omega < \omega_a$, are evanescent, non propagating waves, Figure

1. Note that the wavenumber K_z can be defined as: $K_z = k_z + ik_{zi}$. This is, in principle, complex number because it should describe the growth or decay of the waves amplitudes with the z coordinate (height) in the vertically unhomogeneous atmosphere. This model of the atmosphere is known as stratified atmosphere [4,5].

Both acoustic and gravity waves can be launched by solid Earth events due to the continuity of vertical displacement and normal stress across the surface. Because of the imaginary part of K_z , the amplitudes of these waves grow exponentially with height as they propagate upwards, allowing kinetic energy to be conserved while compensating for the exponential decrease in density. Therefore, even a small displacement (typically a fraction of millimetre) due to a seismic wave can lead to vertical oscillations of several tens of metres at ionospheric height.

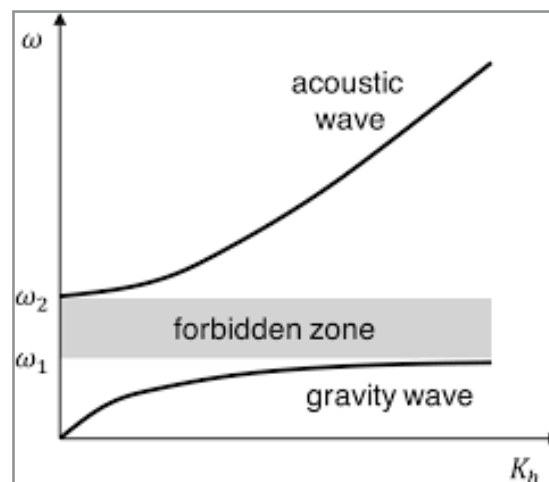


Figure 1: Dispersion relation for gravito-acoustic waves. The frequencies ω_1 and ω_2 are Brunt–Väisälä frequency and acoustic cut-off frequency respectively, while K_h represents the horizontal wavenumber, i.e. k_x in equation (1). Forbidden zone is the zone of non propagating evanescent waves.

Doppler ionospheric Sounding

A high-frequency (HF) wave (3–30 MHz), emitted from the ground, is reflected by the ionosphere at the altitude where the local plasma frequency is equal to the signal frequency. With a wave emitted continuously at a given frequency, it is possible to monitor the motion of the reflecting ionospheric layer through

the Doppler frequency shift of sounding radio wave. This technique is used in France by the Commissariat à l'Énergie Atomique (CEA). The CEA ionospheric network consists of one transmitter site at Francourville (FRC) and three receptor sites (Le Bardon LBD, Bois-Arnault BRN and Bruyères-le-Châtel BLC) 50–80 km away from Francourville, [14].

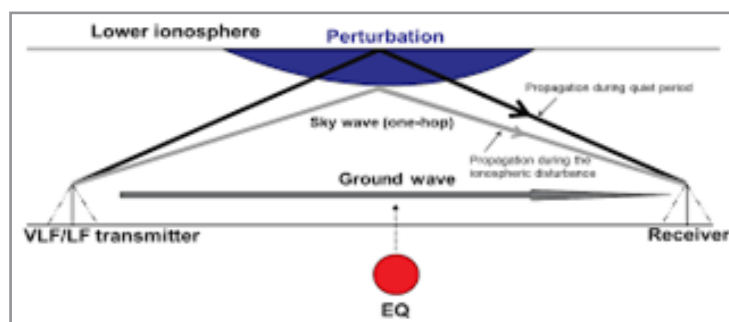


Figure 2: Doppler ionospheric sounding network.

When the earthquake starts, the seismic waves, by the coupling mechanism, generate gravito-acoustic waves. These waves propagate upward through the atmosphere till the reflecting ionospheric layer. There they perturb this layer and make it variable in time. These variations are registered by the signal receivers, Figure 2. Variations contain information about the Doppler shift in the emitted and received wave frequency. This frequency shift can be positive or negative depending on whether the ionospheric reflecting layer is falling or rising when the gravito-acoustic waves reach there. This phenomenon occurs several minutes to 1 hour after the earthquake occurred [15].

GNSS Monitoring

The earthquakes with a magnitude more than 6, $M > 6$, affects the ionosphere layer which is seen through a quantity called the

TEC (Total Electron Content). For the monitoring of the TEC variation can be used data of GNSS (Global Navigation Satellite System) station around the epicenter. TEC is the number of electrons along the satellite signal path that passes through the ionosphere expressed in TECU (TEC Unit). A value of 1 TECU is 1016 electrons/m². Electromagnetic waves transmitted by GNSS satellite signals delay when the signal passes through the ionosphere. These variations are caused by arriving acoustic and gravity waves in the ionosphere. This time delay can be used to detect ionospheric variations through a TEC. The GNSS detection method is a part of the systems for early warning on the strong earthquakes and tsunamis.

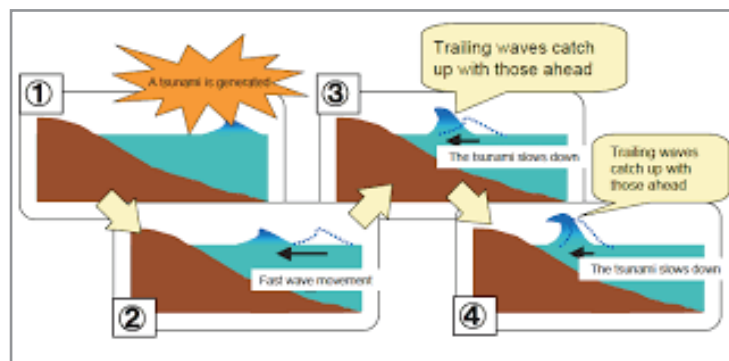


Figure 3: Evolution of the tsunami wave induced by the earthquake.

Detection of Gravity Waves Induced by Tsunami

Tsunamis, driven by strong earthquakes, are long surface gravity waves that propagate for great distances in the ocean, Figure 3. They are usually triggered by submarine earthquakes, landslides or eruptions. Tsunami waves are expected to induce a coupling with the atmosphere: despite their small amplitude compared to ocean swell, they can generate atmospheric gravity waves because of their long wavelengths. The gravity wave created at the sea surface propagates obliquely upward. As it reaches the ionosphere, the gravity wave should then perturb the local plasma, and induce some detectable signals on radio sounding. The detection can be made using GPS (Global Positioning System) network. This opens exciting perspectives for the study of tsunamis up to several hundred kilometres from the coastline. Tsunami waves are extremely difficult to observe in the open ocean: the associated gravity waves in the upper atmosphere might prove to be a valuable signature [8].

Infrasound Monitoring

Only long-period infrasound, with periods longer than approximately 10 s, can reach the ionosphere; the shorter periods (higher frequencies) are significantly damped below the ionosphere. The infrasound observed in the ionosphere mostly originated from strong earthquakes, with a magnitude more than 7, $M > 7$, [16, 17]. The coseismic infrasound is mainly generated by the vertical movement of the ground surface. As the seismic waves propagate at supersonic speeds, the infrasound generated outside the epicenter propagates nearly vertically. Infrasound in the

ionosphere is usually detected as perturbations of the total electron content (TEC) measured by dual-frequency GPS receivers or as changes of Doppler shift observed by continuous Doppler sounders. The GPS TEC represents an integrated value measured along the signal path between the GPS receiver and the satellite. The GPS TEC perturbations observed by dense networks of GPS receivers are often used to study ionospheric responses to earthquakes. Contrary, the continuous Doppler sounding provides information about variations at a specific altitude, at which the sounding radio signal reflects. The height of reflection varies during the day and season. The principle of Doppler sounding is based on measurements of the Doppler shift that experiences the sounding radio signal during its reflection from the ionosphere if the reflection level moves or if the electron density changes in the reflection region. Owing to geomagnetic field, radio waves actually propagate in two modes in the ionosphere: in the ordinary (L-O) and extraordinary (R-X) modes. The vertically propagating L-O mode reflects at the height where the local plasma frequency, given by the electron density, matches the frequency of the sounding signal. In the case of oblique sounding or in the case of extraordinary wave mode (R-X), the signal is reflected at lower altitudes compared to vertically propagating L-O mode.

Conclusion

The coupling between seismic hazards and ionosphere is an important topic in research field. The perturbation in ionosphere due to earthquake is an example of seismo-ionospheric coupling.

The perturbation can be analyzed through the various channels of a mechanism called Lithosphere-Atmosphere-Ionosphere Coupling (LAIC). The three channels are thermal, electromagnetic and gravito-acoustic channel. Gravito-acoustic wave is the most reliable parameter to predict the ionospheric perturbation due to earthquake. It should be noted that it is easier to detect the waves in the ionospheric plasma, rather than the neutral atmosphere due to the radio propagation properties (plasma dispersive properties). It should be pointed out that the development of accurate modeling tools is crucial for the future application of seismo-ionospheric methods for other planets than Earth, which is another exciting perspective for this branch of geophysics. Seismometers are the traditional instruments used for studying the seismic and volcanic activities of a planet. Whereas, the newly introduced atmospheric/ionospheric seismology/volcanology via remote atmospheric/ionospheric monitoring is a novel way to explore the planetary seismicity and to learn about the formation and evolution of a planet.

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