



Pulse ionospheric anomalies before a powerful earthquake in Chile

Ruzhin Yu.Ya.^{1*}, Smirnov V.M.^{2,3}, Smirnova E.V.²

¹*Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Troitsk,*

²*Kotelnikov Institute of Radio Engineering and Electronics RAS, Fryazino*

³*Institute for Scientific Research of Aerospace Monitoring «AEROCOSMOS», Moscow*

*E-mail: ruzhin@izmiran.ru

Abstract

This paper investigates the ionosphere pulse variations of associated with seismic activity in the Chili region on February 27, 2010. Analysis of the ionosphere state was conducted according to the measurements of GPS navigation system. It was demonstrated that immediately prior to the earthquake an instantaneous variation in the rate of change of electron content occurs, which is significantly higher than normal background values. The characteristics of such pulse plasma perturbations and conditions of their formation are determined and discussed.

Keywords: 1. seismic activity; 2. GPS; 3. Ionosphere

1. Introduction

The ionosphere phenomena connected with seismic activity have been discussed for nearly 25 years. The earliest works were different kinds of research of the electromagnetic phenomena, which were observed before and after powerful earthquakes, and on detection of ionospheric harbingers of earthquakes [Liperovsky et al., 1992; Oraevsky et al., 1994; Ruzhin et al., 1996; Hayakawa M. (Eds.) 1999, Devi et al., 2008]. Atmospheric seismic anomalies (possible harbingers) are being actively investigated now and include the generation of electromagnetic radiation in HF and VHF ranges and the emergence of charging (storm) clouds on the eve of earthquakes [Ruzhin et al., 2000; Ruzhin et al., 2007], as well as changing conditions of radio waves VHF distribution [Hayakawa (Eds.) 1999; Ruzhin et al., 2007]. It has also been discovered, that at the propagation of GPS signals near the horizon the effect of an abnormal refraction is manifested over the zone of preparation some days before earthquakes [Devi et al., 2010, Devi et al., 2012].



It is caused by increased humidity and temperature variations, as well as the appearance of seismic events accompanied by flashes of optical radiation in the sky, lightning discharges and glowing objects.

New possibilities in the study of spatial and temporal characteristics of the modification of the ionosphere before earthquakes are offered by the use of the global GPS (Global Positioning System). GPS equipment measures group and phase delays of radio signals at $L1 = 1575$ MHz and $L2 = 1228$ MHz frequencies with a 30-second interval simultaneously for all satellites located within the radio visibility zone for a given GPS station.

The analysis of GPS observations showed that the TEC variations are very sensitive to the change in electronic concentration of the F2 area and can be used for the detection of ionosphere harbingers of earthquakes [Oraevsky et al., 2000; Ruzhin et al., 2002; Liu et al., 2004]. The correlation coefficient between the TEC and f_0F2 reaches a value of 0.9. Since the electron density at the maximum of the F2 layer is one of the most sensitive to seismic activity of the ionosphere parameters, we can use the data to assess the TEC spatial scales and temporal dynamics of seismo-ionospheric effects in almost any seismic active region of the world.

1.1 General information about the Chilean earthquake of February 27, 2010.

This study considers the variations of ionospheric parameters observed during the preparation and passing of a strong earthquake at the coast of Chile on February 27, 2010 at 6:34 UT or 1:34 local time. The magnitude of the earthquake was $M=8.8$. The earthquake epicenter coordinates were 35.846°S , 72.719°W with the depth of an epicenter arrangement of 33 km. A large number of seismic events, which followed the first strongest tremor, characterized the day of the earthquake. On that day, 14 earthquakes of $M \geq 6.0$ were recorded and registered by the geophysical service of the Russian Academy of Sciences on the territory within $-33^\circ - 39^\circ\text{S}$ and $-71,5^\circ - 75,5^\circ\text{E}$. The earthquake epicenters are shown (green circles) in Figure 1. They mostly occurred within a 100-km strip extended along a meridian that indirectly points out the direction of the break in the territory. The asterisk marks the position of the first and strongest shock.

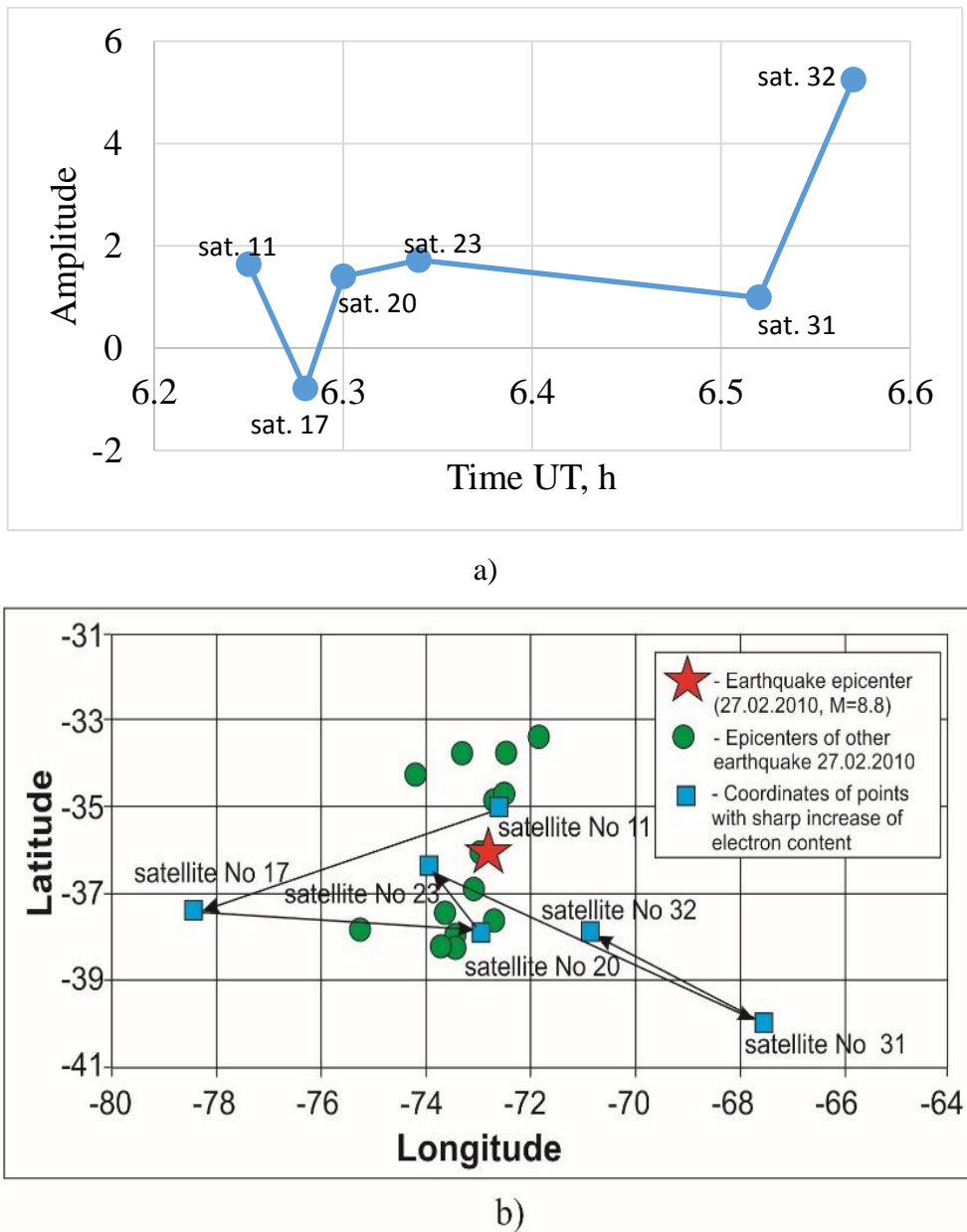


Figure 1: Values of the maximum change speed of electronic contents depending on the time (a) and the place of detecting. The figures specify the numbers of satellite, green circles mark the coordinates of the earthquakes.

CONZ and LPGS GPS stations were used to research the TEC variations of the ionosphere during earthquake preparation and passing at the Chile coast caused by the influence of seismological effects. The CONZ station is located near the Pacific coast in the epicentral zone, and the LGPS station is approximately 1,350 km away from the epicenter and is located near the Atlantic coast. The size of the ionosphere disturbance zone for an earthquake of M=8.8 can be over 6,000 km.

2. Determination of parameters of ionosphere TEC pulse response

The parameters of an ionosphere response were determined by radio translucence method along “satellite – the Earth” line. The methodical aspects of applying this method are described herein in detail [Andrianov et al., 1993]. The data of code and phase measurements received by the receivers of IGS network stations were used to determine the TEC parameters of an ionosphere. The change speed of the total electron content or its increment on an observed time interval is the most sensitive parameter of an ionosphere to the influence of external factors. The time interval for the regular IGS stations as a rule makes 30 seconds. The results of calculations (in terms of TECU/c, 1 TECU=10¹⁶ m⁻²) for the specified satellites are made according to the following formula

$$DTEC(t) = \frac{1.81}{T} \{ \lambda_1 [\Phi_1(t) - \Phi_1(t-T)] - \lambda_2 [\Phi_2(t) - \Phi_2(t-T)] \}$$

Here, T=30 s is an observation interval, λ_1, λ_2 are wavelengths of navigation satellites signals, Φ_1, Φ_2 is the data of phase measurements for the specified wavelengths.

The detailed analysis of change speed of total electron content, which was carried out for the satellites observed at the time of the emergence of seismic shock, has shown the existence of a violent change of this parameter. The maximum values of this parameter depending on the time of supervision and the place of its detection for 6 satellites observed during this period of time are given in Figure 1. It is noteworthy that the absolute maximum in the change speed of the electron content was recorded at 6:34 UT, which practically corresponds to the timepoint of the earthquake emergence. The negative value corresponds to the observation on satellite No. 17, the trajectory of whose subionospheric point was above sea surface. Such course of the change speed for the electron content can testify to a tsunamigenic nature of the earthquake. The absolute maximum was observed in the point with the latitude of 37,94° and the longitude of 71,33° that practically corresponds to the earthquake epicenter: 35.846°S, 72.719°W.

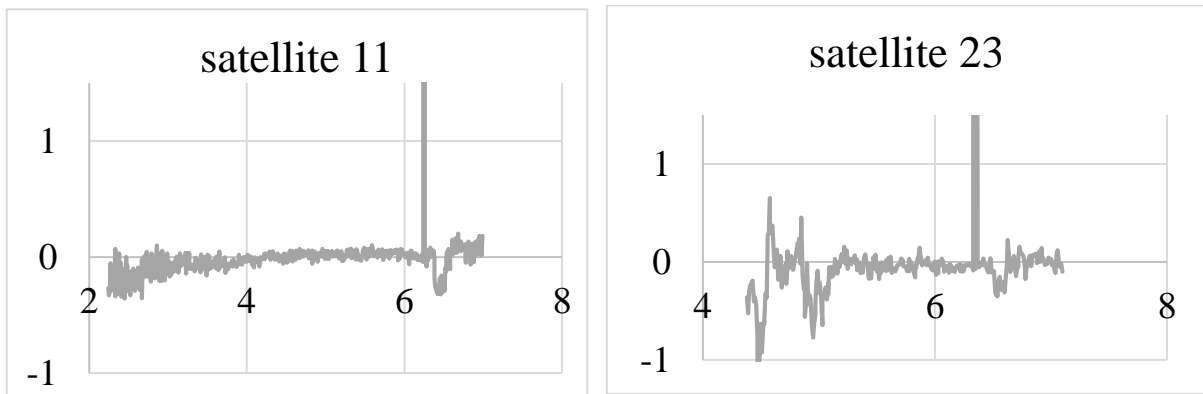


Figure 2: Example of pulses in change speed of an electron content for two of the six observed satellites over time (UT time, in hours).

The change speed of the electron content in a period 20 minutes, preceding a seismic event, exceeded the usual course of this parameter by orders of magnitude. All registered events are chaotically distributed near the epicenter on the area of 1,000 km across and 500–600 km along a meridian. It should be noted that the closest in terms of time (2 min.) and space (200 km) phenomena, are registered for satellites 20 and 23. Furthermore, there are no simultaneously registered events. Figure 2 shows examples of a pulse anomaly against continuous registration within several hours.

2.1 Thunderstorm activity on the eve of an earthquake

The received violent changes of the ionosphere TEC with big amplitude (Figure. 1, left panel) are the result of the sudden emergence of additional ionization on the way of radio beams from the corresponding satellite to the land receiver. The explosion-like emergence of ionization spots, which are chaotically located in the ionosphere near a future epicenter, can be connected with pulse sources. New ionization is possible when powerful pulses in electromagnetic radiation or when streams of energetic particles emerge in an ionosphere, which is capable to ionize neutral components of the lower ionosphere, causes the radiation of an ionosphere. Such ionizing sources are present in lightning discharges in the atmosphere.

The emergence of a lightning activity before an earthquake in the range of altitudes up to 10 km and over was discussed for the first time in the works [Ruzhin, et al., 2000; Ruzhin et al., 2007] where the model of the processes resulting in lightning activity in the atmosphere and radiation within the VHF range is offered. Figure 3 shows the dependence of the minimum altitude of the VHF (53 MHz) of the radiating sources on

the range for three earthquakes (A, B, C) according to the stations of the network (island of Crete [Ruzhin, et al., 2000]). The figure makes it clear that the altitude of radiators can reach 5 to 10 km above sea level to receive VHF signals at the distance of 300–400 km (without attracting the effect of atmospheric refraction anomalies). As monitoring of seismogenic VHF radiation has been carried out continuously and for a long time, the analyzed material is received for all possible events, which took place for almost a three-year period of observations.

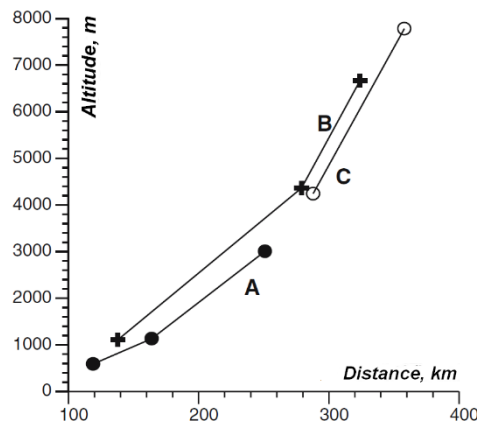


Figure 3: Dependence of altitude on range for radiating sources VHF

A theory [Sorokin et al., 2011] of generating a high-frequency earthquake precursor, which is based on the assumption, that the formation of charged clouds in the atmosphere over an area of the earthquake preparation and subsequent electric discharges, which are the source of radiation in the UHF band, is proposed and substantiated. A possible candidate was soon found and is being intensively investigated now [Jacobson and Light, 2012]. The so-called compact intracloud categories (CID) are a special class of manifestations of lightning activity. Compact discharges happen significantly above usual lightnings in the range of altitudes from 8 to 17 km. Also the power (up to tens of gigawatt) radiated by them in the radio frequency range is unusual – these categories are considered to be the most intensive natural sources of radio emission in HF/VHF ranges on Earth. Independent optical and radio measurement of CID effects on the FORTE satellite allowed for the estimation of the effective power of radiation VHF (ERP – Effective Radiated Power) within the frequencies of 26–49 MHz, which exceeded 140 kW. The main part of the radiated electromagnetic energy is within the VLF range.

2.2 Effects in ionosphere from lightning discharges and accompanying VLF radiations

Historically these phenomena were discovered and actively investigated in connection with short-term disturbances of communication on long routes [Inan et al., 1991; Johnson et al., 1999]. This is direct (i.e. heating, sprites, etc.) and indirect influence (through dropouts of energetic particles of radiation belts, induced by lightning VLF emissions). The distortion in a signal phase within the VLF range usually occur very slowly, but sometimes the amplitude and the phase of a signal can undergo fast changes for a short period of time (1–2 seconds) owing to so-called Trimp effect ((short-time variation in the amplitude and phase of the VLF signal). The figure shows one such example of an abrupt rise of the amplitude of VLF signal. The time of restoration is dozens of seconds. The "affection" area of the ionosphere is within 100–300 km.

The ionization produced by the dropouts of trapped energetic electrons (with energies up to 500–600 keV) due to scattering caused by whistles in the magnetosphere is the first type Trimp. This kind of Trimp event appears after a second or a little later after the cause, which is a lightning discharge. Such whistles induced rashes directly measured by satellites and rockets.

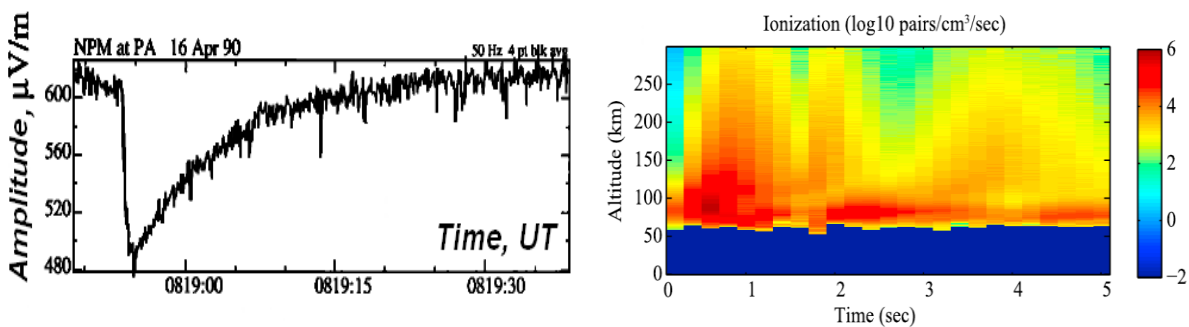


Figure 4: Restoration amplitude of VLF signals in time ("Trimp effect" to the left). To the right – calculations outcome of ionization speed by Monte Carlo's method for a typical Trimp event (adapted from [Marshall et al., 2011]).

The Trimp effect of the second type appears in 0.1–0.2 seconds (along with precipitation) after the discharge. This is a direct or a fast effect. The figure shows the result of a model calculation of [Bortnik et



al., 2006; Marshall et al., 2011] ionization speeds of an ionosphere for a typical range of energetic electrons of the radiation belt (LEP) which is a source of the observed Trimpi effect in the UWL range (to the right). It is obvious that the earliest ionization happens within the first second in the range of altitudes from 80 to 160 km due to a more vigorous range component. The process continues for several seconds at first due to the soft part of the dropping out particles range (see altitudes up to 300 km).

As a result, based on the above parameters and pulse anomalies characteristics of TEC, we can assume that in the final stages of preparation for the earthquake, a few minutes before the main shock took place, intense lightning discharges happen in the atmosphere, accompanied by dropouts of energetic particles from the inner radiation belt of the Earth. These abrupt changes of ionization in the way of GPS rays in the ionosphere occurring randomly over a large area (80–300 km high and 150–300 km wide) above the epicenter caused the anomalies detected TEC. These findings are supported by the analysis of the DEMETER satellite data for a few orbits in the neighborhood, on the day of the earthquake and the day before.

2.3 DEMETER satellite data

DEMETER satellite has been launched into a circular orbit for the diagnostics of ionosphere disturbances connected with earthquakes, eruptions of volcanoes and electromagnetic manifestations of human activity. Its characteristics are elaborated upon in a series of articles of a special issue of the journal [First results of the DEMETER micro-satellite, 2006]. Figure 5 shows the results of measurements obtained by DEMETER satellite equipment (at the altitude of ~ 660 km) on February 27, 2010 when the satellite flew eastward from the epicenter. 4 hours prior to the earthquake at the minimum distance of ~ 400 km from the epicenter (to the left). The top panel is the power range of energetic electrons (up to 500 keV), and the lower panel represents the measured streams of energetic electrons with energies up to 0.1 MeV, 1.0 MeV and 2.5 MeV respectively. The vertical arrow is the moment when the DEMETER orbit crosses the magnetic field line (see the panel to the right).

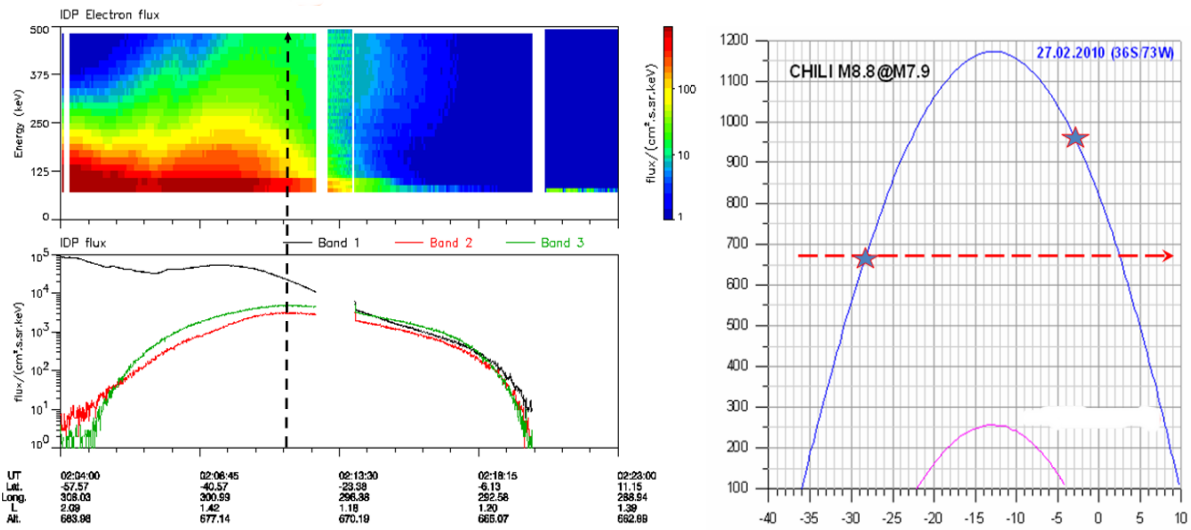


Figure 5: Measurements made onboard the satellite (to the left) and the magnetic field line (to the right) corresponding to the epicenter projection to the altitude of 100 km (axes: altitude/latitude)

The presented spectra and fluxes of energetic particles (a few hours before the earthquake) are, in this case, the basis for a pulse source of ionizing night ionosphere (local time around midnight). The chart on the right presents the magnetic field lines and the trajectory of the satellite. The magnetic equivalent levels of reflection (pitch angle of about 90°) are marked with an asterisk over the area of the earthquake preparation as well as in the opposite magnetically conjugate region. The particles are seen to drop out only in the zone of the earthquake due to the magnetic field gradient near the Brazilian anomaly (the ratio of the magnetic fields along the orbit (for altitudes of 670 km) is 1.2375).

3. Discussion

The pulses of TEC speed change happen within dozens of seconds. The pulses appear chaotically in space (near the epicenter) and in time, 20 minutes prior to the main tremor (see Figure 1). With this in mind, we offer the following sequence of events (Figure 6).

After a powerful discharge 1 in the atmosphere the large portion of the VLF radiation pulse leaks into the magnetosphere and causes dropouts of energetic electron radiation belts. The streams of particles (LEP

phenomenon indicated by a large arrow in Figure 6) reach the bottom of the ionosphere (80–90 km), creating intense ionization in the ionosphere on the way 2 to GPS: zone 3 (below the altitude of 250–300 km).

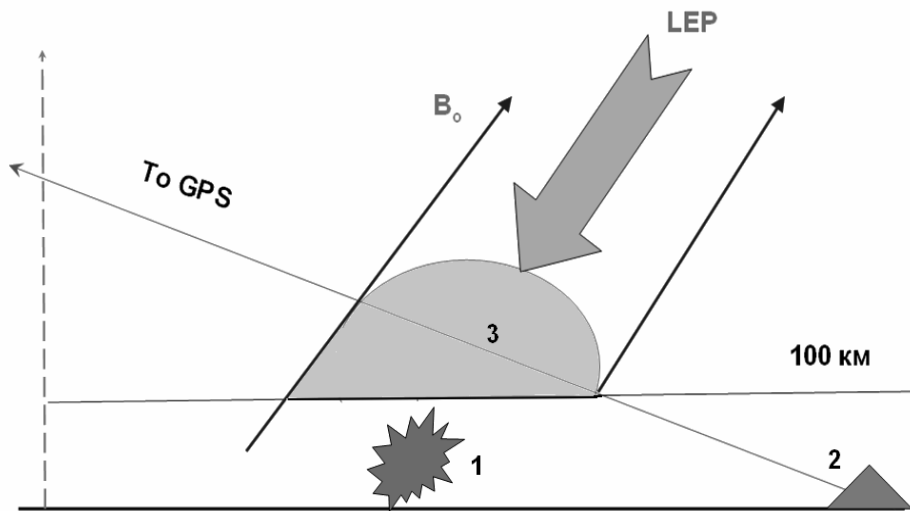


Figure 6: Scheme of events for estimates of pulse anomalies of TEC variation.

Let us estimate the TEC variations based on the ionization rate data (Figure 4) and the possible size of the area of the ionosphere affected Trimpi - effect. The ionization rate is taken within $5 \cdot 10^4 - 10^5 \text{ cm}^{-3} \text{ s}^{-1}$ and the size of the area along the radio wave beam is 200 km (sampling from 150–300 km), the result is the following:

$(5 \cdot 10^4 - 10^5) \times 200 \times 10^5 = 10^{12} - 2 \times 10^{12} \text{ cm}^{-2}$ or 1-2 TECU, which is equivalent to the amplitude in Figure 1, if the ionization time is less than 1 second.

Such variations are accurately registered by radio transluence satellite signals. Thus, due to the proposed variant of a pulse ionization source, which is the dropout of energetic particles induced by lightning discharges, it is possible to observe ionization flashes in the ionosphere, recorded 20 minutes before the earthquake in Chile on February 27, 2010.



4. Conclusion

Instant changes of change speed of the electron contents exceeding its usual background course were noted immediately before the earthquake, according to all satellites observed at that time. At the same time, the maximum value was registered in the point, which almost coincides with the earthquake epicenter and time of its occurrence.

It has been shown that lightning discharges and the conditions for the induced dropout of energetic particles could lead to a pulse change in the concentration of ionosphere plasma within the altitudes of 250–300 km, which were the reason of the discovered pulse anomaly in the change of TEC precipitation speed.

Acknowledgement:

The work is partially supported by the Russian Foundation for Basic Research (Grant No. 17-55-45094)

References

1. Andrianov, V.A. and Smirnov V. M. Definition of a high-rise profile of electronic concentration of an ionosphere of Earth on two-frequency measurements of radio signals of artificial satellites of Earth. *The Radio technician and the electronic engineer*. T.38, No. 7, 1326-1335, 1993.
2. Bortnik, J., Inan, U. S. and Bell, T. F. Temporal signatures of radiation belt electron precipitation induced by lightning-generated MR whistler waves. *J. Geophys. Res.*, 111, A02, 205, 2006.
3. Devi, M., A.K. Barbara, A. Depueva., V. DEPUEV. Preliminary results of TEC measurements in Guwahati, India. *Advances in Space Research*, 42. 753-756, 2008.
4. Devi M., Barbara A. K., Depueva, A. H., Ruzhin, Yu.Ya., Depuev, V., Anomalous Total Electron Content (TEC) and atmospheric refractivity prior to very strong China earthquake of May 2008, *International Journal of Remote Sensing*, 31, 3589-3599, 2010.
5. Devi, M., Barbara, A. K., Ruzhin, Ya. Yu., Hayakawa, M. Over-the-Horizon Anomalous VHF Propagation and Earthquake Precursors. *Surv. Geophys.* DOI 10.1007/s10712-012-9185-z, 2012.
6. First results of the DEMETER micro-satellite. *Planetary and Space Sci.*, Vol. 54, No. 5 (special issue), 2006.



7. Hayakawa M. (Eds.). Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. Terra Scientific Publishing Company, Tokyo, Japan. 996, 1999.
8. Inan, U. S., Bell, T. F., Rodriguez, J. V. Heating and ionization of the lower ionosphere by lightning. *Geophys. Res. Lett.*, 18, 705–708, 1991.
9. Jacobson R. and Light. T. E. L, Revisiting “Narrow Bipolar Event” intracloud lightning *Ann. Geophys.*, 30, 389–404, / doi:10.5194/angeo-30-389-2012, 2012.
10. Johnson, M. P., Inan, U. S. and Lauben, D. S. Subionospheric VLF signatures of oblique (nonducted) whister - induced precipitation, *Geophys. Res. Lett.*, 26(23), 3569–3572, 1999.
11. Liperovsky, V.A., Pokhotelov, O. A., Shalimov, S. A. Ionospheric harbingers of earthquakes. *M. Science*, 304 pages, 1992.
12. Liu, J.Y., Chuo, Y.J., Shan, S.J., Tsai, Y.B., Chen, Y.I., Pulinets, S.A., Yu, S.B. Pre-earthquake ionospheric anomalies registered by continuous GPS TEC measurement. *Annales Geophysicae*, Vol. 22. P. 1585-1593, 2004.
13. Marshall, R. A., Bortnik, J., Lehtinen, N., Chakrabarti, S., Optical signatures of lightning-induced electron precipitation. *J. Geophys. Res.*, 116, A08214, doi:10.1029/2011JA016728, 2011.
14. Oraevsky, V.N., Ruzhin, Yu.Ya., Depueva A.Kh. Seismo-ionospheric precursors and atmospheric electricity // *Turk. J. of Physics*. Vol.18. No.11, 1229-1234, 1994.
15. Oraevsky V.N., Ruzhin Yu.Ya., Shagimuratov I.I. Anomalies of ionospheric TEC above Turkey before two strong earthquakes at 1999 .*Proceed. 15th Wroclaw EMC Symposium*, 2000.
16. Ruzhin Yu.Ya, Depueva A. Kh. Seismoprecursors in space as plasma and wave anomalies, *Journ. Atmospheric Electricity*, Vol.16, No. 3, 271-288, 1996.
17. Ruzhin, Yu.Ya., Nomicos, C., Vallianatos, F. High frequency seismoprecursor emissions. In: *Proceedings of 15th Wroclaw EMC Symposium*, 512–517, 2000.
18. Ruzhin, Yu.Ya. Oraevsky, V.N., Shagimuratov, I.I., Sinelnikov, V.M., Ionospheric precursors of earthquakes revealed from GPS data and their connection with “sea-land” boundary, *Proceed, 16th Wroclaw EMC Symposium*, pp. 723-726, 2002.
19. Ruzhin, Yu. Nomicos, C. Radio VHF precursors of earthquakes. *Natural Hazards*. Vol. 40. 573-583. DOI 10.1007/s11069-006-9021-1, 2007.
20. Sorokin V.M., Ruzhin, Yu.Ya. Kuznetsov, V.D. Yaschenko. A.K., Generation of VHF radio emissions by electric discharges in the lower atmosphere over a seismic region. *Journal of Atmospheric and Solar-Terrestrial Physics*, 73, N5-6, 664–670, 2011.