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Probing Earth's Ionosphere: Understanding Seismo-Ionospheric Connection Via Total Electron Content (TEC) Analysis

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Abstract— This investigation focuses on analysing the Total Electron Content (TEC) as a vital parameter of the ionosphere to understand its relationship with seismic activities and pre-earthquake phenomena. Focused on the Earth's ionosphere, the research utilises data from Japan's GPS Earth Observation Network (GEONET), employing sophisticated analysis tools like FORTRAN and MATLAB. This research investigates how seismic stress can lead to a positive charge in the Earth's crustal formations, focusing on the impact this has on Total Electron Content (TEC) disruptions as observed via GPS signals. The methodology involves calculating TEC using phase delay measurements, revealing alterations in the ionosphere. The study's significance lies in its multidimensional approach, encompassing seismic events and alternative sources of ionospheric disturbances. This study adds significantly to the comprehensive grasp of TEC fluctuations, highlighting its importance in gaining insights into ionospheric behaviours' complexities extending past seismic activities' impacts.

Keywords— Total Electron Content, TEC, ionosphere, seismic influences, seismo-ionospheric, GPS signals.

I. INTRODUCTION

In contrast to the prevalent trend of concentrating on solar-earth studies within the field of ionospheric research, this particular investigation shifts its focus toward examining the ionospheric anomalies associated with seismic activity to forecast earthquakes. At the heart of our study lies the focus on a critical ionospheric measure: the Total Electron Content (TEC). TEC is meticulously determined through dual-frequency Global Positioning System (GPS) receivers sourced from multiple Global Navigation Satellite System (GNSS) platforms, enabling comprehensive ionospheric data collection. The historical backdrop of earthquake prediction through seismo-ionospheric abnormalities traces back to the Alaska earthquake in 1964, sparking sustained scientific interest in studying seismo-ionospheric phenomena as potential earthquake precursors. Contemporary investigations have illuminated connections between earthquake occurrences and unexpected changes in ionospheric profiles. Various experimental and theoretical approaches have been employed to measure the impact on the ionosphere during seismic processes, revealing anomalies 1-10 days before earthquakes within the ionosphere's D, E, and F layers. Our study advances knowledge by analysing ionospheric anomalies' time and location patterns around earthquake epicentres. Using sophisticated statistical methods, we identify significant trends and relationships. Recent advancements in GNSS technology and data processing algorithms have significantly enhanced the accuracy of TEC measurements, thus improving earthquake predictions' reliability. Integrating geophysics and atmospheric science enables the interdisciplinary approach to contribute to earthquake forecasting and enriches our comprehension of the complex interactions between the Earth's crust and the ionosphere.

The research examined discrepancies in the total electron content above active geological faults. Earlier studies have suggested a significant link between these fault systems and variations in TEC, pointing to their potential as indicators of seismic-ionospheric disturbances. TEC disruptions are attributed to the accumulation of positive charges along tectonic faults, leading to atmospheric potential differences and subsequent disturbances in ionospheric electron content. This disruption, driven by positive charge accumulation on rock surfaces, presents a potential earthquake precursor.

Ongoing observation of TEC fluctuations and anomalies is essential for improving earthquake early warning systems and thus has the potential to protect and preserve countless lives. By tracking TEC, scientists can detect changes in the ionosphere triggered by seismic movements or pre-seismic events, offering crucial insight into Earth's underlying processes. The hypothesis posits that the stressed Earth's crust, radon gas emanation along active faults, and the production of electrified clouds influencing the ionosphere may lead to TEC disruptions, serving as potential earthquake indicators.

The complex relationship between the Earth's geological activities and atmospheric conditions has captivated scientists striving to uncover the processes leading up to earthquakes. This research explores the complicated relationship between faults, ionisation processes, and ionospheric anomalies as potential precursors to significant earthquakes. In recent studies, ionisation at the ground-air interface has been proposed as a crucial factor in understanding ionospheric anomalies. While previous investigations explored the connection between electric currents generated by battery systems and fluctuations in magnetic fields, this research focuses on the potential impact of rising ionised air on ionosphere anomalies, specifically in the context of seismic activities. Central to this study is exploring the piezoelectric effect, where trapped pebbles within faulted geological structures may act as sources of electric current. A laboratory experiment involving the application of pressure to a granite block revealed intriguing electron flows, suggesting the block's potential to function as an electrochemical battery with an open circuit. The ensuing ionisation in fault cracks may contribute to the observed anomalies in the ionosphere. As we delve into the geophysical processes underlying earthquakes, fault types emerge as a critical factor. Normal faults, thrust faults, and strike-slip faults each exhibit distinct characteristics in the displacement of blocks. The correlation between fault types and ionospheric Total Electron Content (TEC) anomalies becomes a focal point for categorising earthquakes.

This research aims to bridge the gap between geophysics and atmospheric science, shedding light on the intricate processes beneath the Earth's surface that may be precursors to seismic events. By categorising earthquakes based on fault types and examining ionospheric TEC anomalies, we strive to further the comprehensive understanding of the complex interactions between geological structures and atmospheric conditions, ultimately enhancing the capability to predict and mitigate the impact and consequences of high-magnitude earthquakes.

This research further explores TEC data from Kumamoto, Japan, aiming to assess the connections between TEC variations and seismic activities around the time of earthquakes, focusing on the Japan earthquake. Recognising that precursory alterations are not immediately discernible, the study examines environmental changes associated with seismic events, acknowledging that geological or atmospheric factors may influence these impacts. The compression of the Earth's rocks during seismic events, which releases electrically charged carriers and positive holes, is explored as a mechanism behind TEC disruptions. If validated, this research may pave the way for employing TEC disturbances as indicators for seismic warnings, contributing significantly to earthquake prediction and preparedness efforts.

Also, the research utilises cutting-edge data analysis techniques to examine vast amounts of TEC data meticulously. This approach helps to uncover nuanced yet crucial patterns that may signal seismic events. This approach enhances the precision of earthquake prediction models and opens avenues for real-time monitoring and rapid response strategies. By integrating these technological advancements, the research underscores the potential of ionospheric studies in revolutionising our approach to earthquake forecasting and disaster management.

II. METHODOLOGY

This research focuses on the significance of total electron content (TEC) in comprehending ionospheric activities and seismic events. The following methodology outlines the steps to collect, process, and analyse TEC data, utilising GPS measurements from Japan's GPS Earth Observation Network (GEONET). Investigating Total Electron Content (TEC) in the ionosphere is paramount in understanding the intricate relationship between seismological phenomena and ionospheric conditions. Contemporary research efforts are intensifying in their quest to understand the relationship between seismic events and the ionosphere's condition, identifying Total Electron Content (TEC) as a critical factor for in-depth investigation.

Figure 1 visually represents the measurement system for TEC, highlighting the role of a GPS spacecraft and a ground-based receiver in accurate TEC calculations:

$$TEC(r,\theta,\phi,t) = \int_{rx}^{st} d(r,\theta,\phi,t)dp \qquad (1)$$

The TEC, quantifying the number of electrons passing through the Earth's surface to a GPS spacecraft orbiting in space, is expressed mathematically as a line integral involving parameters such as range (r), latitude (θ), longitude (ϕ), and time (t).

Seismic activities and the early stages of earthquakes exert pressure on the crustal rocks of the Earth, which in turn become positively charged. It leads to the TEC acting as a crucial signifier of changes within the ionosphere attributed to these geophysical events. By leveraging GPS signals, disruptions in TEC are identified, revealing correlations between TEC variations and seismic events. The phase delay in electromagnetic signals travelling from a ground-based receiver to a GPS satellite due to ionospheric effects further underscores the intricate interplay between seismic activities and ionospheric conditions. This study explores the complex relationships between these occurrences, enhancing our comprehension of how the ionosphere reacts to seismic activities and the precursors of earthquakes. There are the following points for a better understanding of work.

III. DATA COLLECTION

Our study extensively utilised Japan's GEONET to gather TEC information. The process involved extracting the data from the Receiver Independent Exchange Format (RINEX) files containing vital measurements of phase delays in GPS signals. The data covered a specific period, and each receiver contributed various data points over time.

IV. TEC CALCULATION

The Total Electron Content was determined by employing differential pseudo-range calculations derived from the data on phase delays. The formula

$$P_n = 40.3 \times \left(\frac{1}{f_1} - \frac{1}{f_2}\right) \times TEC + DCB \qquad (2)$$

Where:

Pn Represents differential pseudo-range measurements.

1/f_1 1/f_2 is the GPS measurement frequencies 1,575.42 and 1,227.60 MHz

TEC is Total Electron Content (m/s^2)

DCB is the bias in the measurements.

V. SOFTWARE ANALYSIS

The analysis of RINEX observation data files, leading to the extraction of TEC data over time, was conducted using FORTRAN software, initially overseen and credited to Professor Kosuke Heki from Hokkaido University. We examined the adjustment of seismo-ionospheric parameters by analysing Total Electron Content (TEC) by employing FORTRAN software. The study involves understanding the operational aspects and data formats used and created by the software, organising input data (including ionosphere measurements), running the FORTRAN program with this data, and then extracting TEC information from the resulting output files. This extraction step may require parsing text or binary files to isolate the TEC data for further analysis. Subsequently, researchers can analyse the TEC data statistically, visualise it, and compare it with other datasets or models to gain insights into seismo-ionospheric interactions. Close attention to software documentation and potential expert guidance is critical throughout the process to ensure accurate interpretation and meaningful results. This step involved processing the GPS measurements to obtain the required TEC values for each receiver.

VI. Spatial Interpolation and Visualisation

MATLAB software facilitated the analysis and visualisation of TEC data across a designated time frame. By computing average values for each location and time, it produced a singular data point at 30-second intervals for each site, matching the GPS receivers' sampling frequency. A grid of interpolated data covering Japan was generated every 30 seconds using the linear triangulation method. These grids were transformed into curves, and each curve plot contributed a frame to the resulting video.

VII. ALTERNATIVE SOURCE EXPLORATION

We also investigated alternative factors that might affect the ionosphere. It included analysing the solar flux, counting sunspots (SSN) and examining the intensity of geomagnetic storms on Earth throughout March 2011. This study utilised data provided by the Space Physics Interactive Data Resource (SPIDR), courtesy of the National Oceanic and Atmospheric Administration (NOAA). We undertook a comparative analysis with previous studies to evaluate the potential impact of solar or geomagnetic activities on ionospheric irregularities.

Visual representations of the total electron content (TEC) in Mode 1 and 2 were created using MATLAB, a powerful software application frequently used for such computations. The methodology began with acquiring TEC data from relevant repositories or collected through specialised instruments. Following this, the spectrogram function in MATLAB was utilised, harnessing its inherent features for time-frequency analysis. This function applied the Short-Time Fourier Transform (STFT) method, which entailed dividing the TEC time series into brief, overlapping segments and calculating the Fourier Transform for each segment. Before Fourier Transform computation, a windowing function was applied to each segment to mitigate spectral leakage and enhance frequency resolution. The resulting spectrograms were then generated, displaying time along the horizontal axis, frequency along the vertical axis, and colour-coded magnitude to represent the spectral content at each time-frequency point.

This comprehensive methodology ensures a systematic approach to investigating the TEC and its connections to ionospheric and seismological phenomena, employing state-of-the-art tools and techniques for data analysis and interpretation.

TABLE I: List of Kumamoto Earthquakes

Region	Depth	Magnitude	UTC Time
Kumamoto Earthquake (32.791˚N- 130.754˚E)	10 Km	6.2	14/04/2016 21:26:39
Kumamoto Earthquake (32.791˚N- 130.754˚E)	12.0 Km	7.0	16/04/2016 01:10:49

VIII. Results and Discussion

Our research meticulously examined the intricate domain of measurement inaccuracies, focusing on the Total Electron Content (TEC) data mismatch, specifically Differential Code Biases (DCB). Utilising data obtained from the GPS Earth Observation Network System (GEONET) in Japan through RINEX observation data files, this study has comprehensively investigated the perturbations in TEC caused by seismic activities. FORTRAN software significantly simplifies extracting Total Electron Content (TEC) data, owing to its specialised functions and superior numerical processing abilities. This software facilitates the practical analysis of ionospheric observations and satellite information, guaranteeing precise computation of TEC values. MATLAB stands out as an essential platform for further study and visual representation, equipped with extensive capabilities for managing data, conducting statistical analyses, and employing visualisation methods. The synergy between FORTRAN and MATLAB provides researchers a fluid workflow, facilitating effortless progression from data extraction to comprehensive analysis and visualisation when examining TEC phenomena.

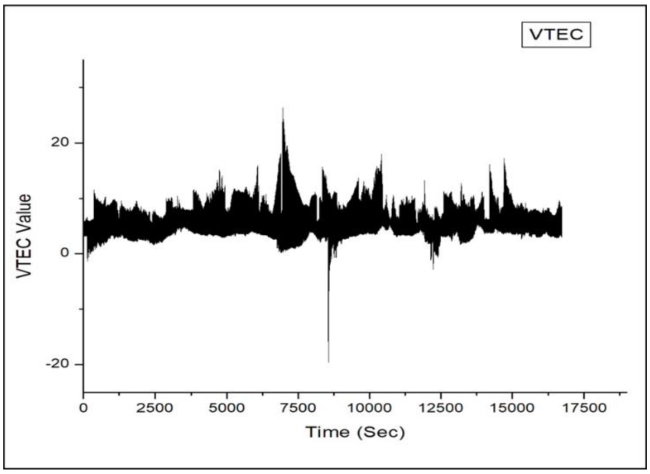

Figure 1: Vertical Total Electron Content (VTEC) during Kumamoto Earthquakes, Japan

Broadening our analysis to encompass seismic activities and other factors affecting the ionosphere, we focused on leveraging the extensive datasets available through the Space Physics Interactive Data Resource (SPIDR), operated by NOAA (National Oceanic and Atmospheric Administration). This approach enhanced our understanding of how solar activity and geomagnetic occurrences contribute to the complexities of ionospheric disturbances. By scrutinising SPIDR's comprehensive data archives, we discerned correlations between solar activity, geomagnetic storms, and fluctuations in ionospheric behaviour. These findings broaden our understanding of the intricate dynamics shaping Earth's ionosphere, shedding light on the multifaceted influences that extend beyond seismic triggers.

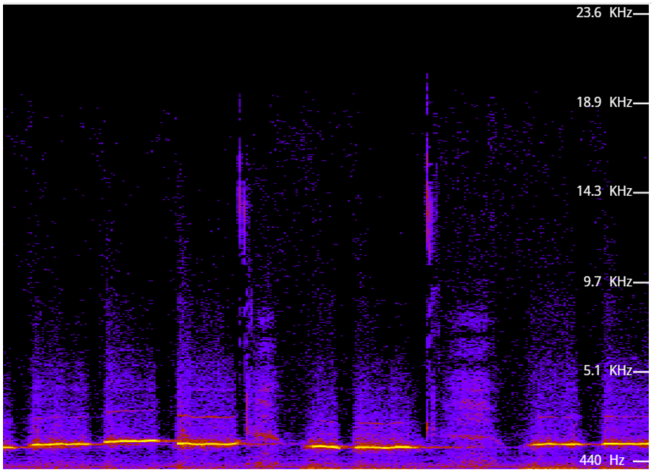

Figure 2: Spectrogram Mode 1 of Vertical Total Electron Content during Kumamoto Earthquakes, Japan

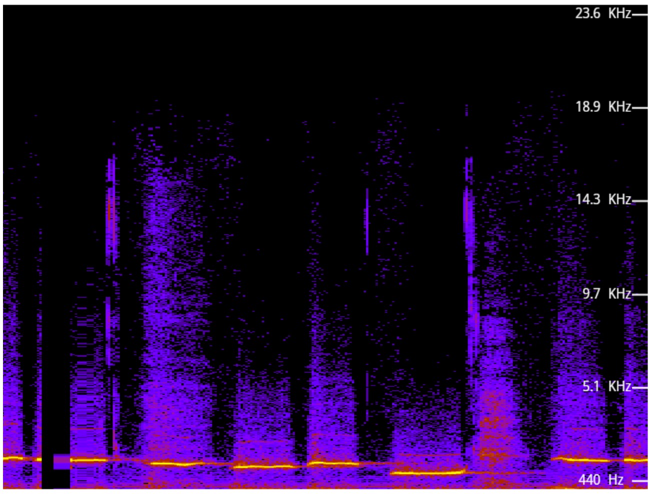

Figure 3: Spectrogram Mode 2 of Vertical Total Electron Content during Kumamoto Earthquakes, Japan

The discernible patterns in TEC disruptions associated with seismic tasks affirmed the impact of seismic and pre-earthquake activities on the ionosphere. They underscored the utility of TEC as an indicator of such phenomena. Furthermore, the comprehensive analysis considered the interplay of solar and geomagnetic variables, offering a holistic perspective on the factors contributing to TEC variations.

In this research, spectrograms for Total Electron Content (TEC) in Mode 1 and 2 were drawn using advanced time-frequency analysis techniques. The spectrograms were constructed by applying the Short-Time Fourier Transform (STFT) to segmented TEC data. Each segment was subjected to windowing using a suitable window function to minimise spectral leakage and enhance frequency resolution. Subsequently, the Fourier Transform was computed for each windowed segment to convert the time-domain TEC signal into the frequency domain. The magnitude of the Fourier Transform was then calculated to capture the spectral content of each segment. By arranging the magnitude spectra over time, spectrograms were generated, with time represented on the horizontal axis, frequency on the vertical axis, and magnitude depicted by colour or intensity. This approach allowed for a comprehensive visualisation of ionospheric disturbances in Mode 1 and Mode 2, enabling a detailed analysis of temporal and frequency characteristics associated with seismic events and other ionospheric phenomena.

The interdisciplinary nature of this research contributes valuable insights into understanding DCB within seismic and ionospheric contexts. By laying the groundwork for further exploration, this study advances our comprehension of the intricate relationship between seismic activity, ionospheric disturbances, and the biases inherent in TEC measurements. Overall, this research enhances our understanding of ionospheric behaviour and paves the way for future investigations in this complex and interconnected field.

References

[1] Trigunait, A, Parrot, M, Pulinets, S.A., Li, F.(2004): Variations of the ionospheric electron density during the Bhuj seismic event, Ann. Geophys, 22, pp 4123–4131.

[2] Parrot, M., Berthelier, J. J., Lebreton, J. P., Sauvaud, J. A., Santolik, O., and Blecki, J. (2006): Examples of unusual ionospheric observations made by the DEMETER satellite over seismic regions, Phys. Chem. Earth, 31, pp 486–495.

[3] Pulinets, S.A., Legen'ka, A.D.(2003): Spatial–temporal characteristics of large-scale distributions of electron density observed in the ionospheric F-region before strong earthquakes, Cosmic Res., 41(3), pp 221–229.

[4] Akhoondzadeh, M., Parrot, M. and Saradjian, M.R.(2010): Electron and ion density variations before strong earthquakes (M>6.0) using DEMETER and GPS data, Nat. Hazards Earth Syst. Sci., 10, pp 7–18.

[5] Carolina, A., Corrado, R., Carolina, F., Genzano, N., Pergola, N. and Tramutoli, V.(2008): Robust TIR satellite techniques for monitoring earthquake active regions limits, main achievements and perspectives, Annals of Geophy., 51, pp 303-318.

[6] Sarkar, S. and Gwal, A.K.(2010): Satellite monitoring of anomalous effects in the ionosphere related to the great Wenchuan earthquake of May 12, 2008, Nat Hazards, 55, pp321–332.

[7] Pulinets, S.A., Liu, J.Y., Safronova, I.A.(2004): Interpretation of a statistical analysis of variations in the foF2 critical frequency before earthquakes based on data from Chung-Li ionospheric station (Taiwan). Geomagn. Aeronom. 44: pp102–106.

[8] Pulinets, S.A., Boyarchuk, K.A., Hegai, V.V., Kim, V.P., Lomonosov, A.M.(2000): Quasielectrostatic model of atmosphere–thermosphere–ionosphere coupling. Adv. Space Res. 26 (8): pp 1209–1218.

[9] Parrot, M. and Mogilevsky, M.M. (1989): VLF emissions associated with earthquakes and observed in the ionosphere and the magnetosphere, Phys. Earth Planet. Inter., 57, pp 86-99.

[10] Serebryakova, O.N., Bilichenko, S.V., Chmyrev, V.M., Parrot, M., Rauch, J.L., Lefeuvre, F., Pokhotelov, O.A.(1992): Electromagnetic ELF radiation from earthquake regions as observed by low-altitude satellite. Geophys. Res. Lett. 19(2): pp 91-94.

[11] Aggarwal Y.P., Sykes L.R., Simpson D.W. and Richards D.G., (1975), Spatial and temporal variation variations in ts/tp and in P

wave residuals at Blue Mountain Lake, New York: Application to earthquake prediction, J. Geophys. Res., 80, pp 718-732.

[12] Antselevich, M.G., (1971), the influence of Tashkent earthquake on Earth's magnetic field and the ionosphere, Tashkent earthquake 26 April 1966. FAN publ., Tashkent, pp 187-188.

[13] Birfeld Y.G., (1973), The Earth's Seismicity Effect on the Ionosphere via Acoustic Waves, Otkrytiya Izobret. Promyshl Obraztsy Tovarn. Znaki, No. 42.

[14] Boskova J., Shmilaur J., Jiricek F. and Triska P., (1993), Is the ion composition of outer ionosphere related to seismic activity, J. Atmos. Terr. Phys., Vol. 55, pp 1689-1695.

[15] Cha C., Proceedings: Lectures by Seismological Delegation, NASA, 1976, pp 5.

[16] Liu J.Y., Chen Y.I., Jhuang H.K. and Lin Y.H., (2004), Ionospheric foF2 and TEC anomalous days associated with M=5.0 earthquakes in Taiwan during 1997-1999 TAQ, 15, pp 371-383.

[17] Singh B., Kushwah V., Singh O.P., Lakshmi D.R. and Reddy B.M., (2004), Ionospheric perturbations caused by some major earthquakes in India, Physics and Chemistry of Earth, 29, pp 537-550.

[18] Sobolev, G. A. and Husamiddinov, S. S., (1985), pulsed electromagnetic Earth and ionosphere field disturbances accompanying strong Earthquakes, Earthquake Prediction Res., 3, pp 33–41.

[19] Pulinets S.A., Boyarchuk K.A., Lomonosov A.M., Khegai V.V. and Liu J.Y., (2006), Ionospheric precursors to earthquakes: a preliminary analysis of the foF2 critical frequencies at Chung-Li ground based station for vertical sounding of the ionosphere (Taiwan Island), Journal of Geomagnetism and Aeronomy, 42, pp 508-513.

[20] Pulinets S., (2004), Ionospheric precursors of earthquakes: recent advance in theory and practical applications, TAQ, 15 (3), pp 445-467.

[21] Freund, F.T., I.G. Kulahci, G. Cyr, J. Ling, M. Winnick, J. Tregloan-Reed and M. M. Freund(2009), Air ionisation at shake surfaces and pre-tremor signals, J. Atmos. Sol. - Terr. Phys., 71, pp 1824-1834.

[22] Pulinets, S. An.; Ouzounov, D.; Karelin, A. V.; Boyarchuk, K. A.; Pokhmelnykh, L. A.;. (2006).The physical nature of warm abnormalities saw before solid seismic tremors.

[23] Qiang, Z.; Chang-gong, D.; Lingzhi, L.; Min, X.; Fengsha, G.; Tao, L.; Yong, Z.; Manhong, G.;. (1999). Satellite warm infrared brilliance temperature oddity picture - present moment and looming tremor forerunners. Sci. China, 42, pp 313-324.