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Lithosphere-Atmosphere-Ionosphere Coupling Processes for Pre-, Co-, and Post Earthquakes: A case study of Northern Mariana, U.S.A. Earthquake of 31st October, 2007

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Abstract

Using the Plasma analyzer (IAP)and Langmuir Probe (ISL) experiments of the (Detection of Electromagnetic Emissions Transmitted from Earthquake Regions (DEMETER) and Total Electron Content (TEC) from GPS data, lithospheric-atmospheric - ionospheric coupling has been observed before, during and after the magnitude 7.2 Northern Mariana, U.S.A. Earthquake of 31st October, 2007. Both sets of data recorded perturbations within the investigative period.

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The study revealed pre – ionospheric variations on -17 day in the TEC with a value of 3.57 Total electron content unit (TECU) at 8:00 UTC while the IAP and ISL (Electron density) sensors of the DEMETER had 2.83 cm^3 and 3.95 cm^3 respectively on - 4 days. All pre -ionospheric perturbations were recorded in the morning. A co - ionospheric perturbation was revealed by the Electron Density with a value of -2.04 cm^3 during the night time reading on the earthquake day (day 0). Four post - seismic day perturbations were recorded on day 2 (2.35 K and day 3 (2.15 K) from Electron temperature of the ISL experiment and 2.18 cm^3 and 3.98 cm^3 on days 5 and 7 respectively from the IAP sensor. The observed anomalies were screened for false alarm using the geomagnetic indices of Kernnifzer digit (Kp) and disturbance storm time (Dst.) It was however realized that the state of the ionosphere was geomagnetically quiet on these days; hence the observed variations were seismogenic.

Keywords Earthquake; DEMETER; TEC; Perturbations; Seismogenic

Introduction

The agonies caused by earthquake have provoked scientists all over the world to conduct broad-based researches on various phenomena relating to this disastrous event with the sole aim of predicting them. Thus, for many decades, understanding earthquake corollaries and ways of mitigating them have continued to dominate discussions at many scientific and social fora. Earthquakes of various types and magnitudes occur every year. Generally, earthquakes refer to any seismic event originating from either natural or human activities, which generate seismic waves that propagate through the earth's interior. Thus, excepting earthquakes from natural causes, whose occurrences are sometimes more catastrophic, earthquakes can also be induced by human activities like mining (Francesco and Bizzarri, 2014; Bommer *et al.*, 2015), oil exploration and exploitation activities (Davies *et al.*, 2013; McGarr, 2014; Thomas *et al.*, 2020), groundwater over exploitation (Gupta, 1983; Klose, 2013), dam construction (Verdugo and Gonzalez, 2015). However, earthquakes originating from human activities are usually of low magnitudes (tremors/microseisms). In all cases, particularly those of natural origin, the amount of elastic strain energy released during earthquake and their effects have continued to desperately, confer on man dire need to find reliable precursors for it. Thus, common questions of research interest provoked from the resulting scenario are: ''what happened in the weeks, days and even hours before this terrifying event occurred? And were there indicators that such a disaster was on the way? Scientists have, however, acknowledged that all seismic electromagnetic anomalies are hallmark of processes, which started days prior to the main event and persisted few days after it (Akhoondzadeh *et al.*, 2010; Ibanga *et al.*, 2017). This seismic event by itself rarely kills people or animals, but the secondary events triggered by it like collapse of buildings, fires, tsunamis (seismic sea waves) and volcanoes, are actually the main causes of human disaster. Better designs and constructions of dwelling places, safety systems, early warnings and planning, are some ways that could help in mitigating their risk (Celebi *et al.*, 2012). Earthquakes are very complicated physical processes being neither regular nor linear. This has conferred on it a high degree of sophistication such that predicting it from its dynamic relation between its parameters always results in a high degree of uncertainty. Hence, it has become absolutely imperative that we find more reliable approaches of studying, monitoring and understanding the underlying physical and chemical processes that usually precede them. Preparatory to an earthquake activity, a vast amount of energy is usually transferred due to crustal movement and at the instant of the shock, a break down occurs between the source of the energy and the environment. Studies have shown that these alterations before, during and after such events do have different physical and chemical effects on the lithosphere, atmosphere and ionosphere (Hayakawa and Molchanov, 2002; Rapoport *et al.*, 2004; Kamogawa, 2006; Rozhnoi *et al.*, 2009; Chmyrev *et al.*, 2013;), thus making their detection possible. Consequently, perturbations in threshold state of lithospheric, atmospheric and ionospheric parameters can serve as earthquake indicators (precursors). If these ionospheric perturbations are real and systematic, then they could serve as short-term precursor, happening before, between and after the seismic events. All precursors are not expected for all events; hence a single precursor cannot be used alone in forecasting earthquake but an integrated approach employing different precursors from different experiments is the best; such as used in this study.

Data

DEMETER Data

DEMETER is a microsatellite launched by the French Space Agency: *Centre National D'etudes Spatiales* (CNES) in operation between 2004 and 2010 on a polar and circular sun-synchronous orbit with an altitude of 710 km (reduced to 660 km in 2005). Among the six experiments of the scientific payload was the Plasma analyzer (IAP) instrument which was carefully designed to record the parameters of the thermal population, which are the densities of the main ionospheric ions: hydrogen (H+), helium (He+) and oxygen (O+) (within a range of 10^2 –5.10^5 ions/cm^3), their temperatures (from 500 – 5000 K) and the ion flow velocity in the earth's frame of reference (Berthelier *et al.*, 2006). The electron density and temperature were in situ measured by a Langmuir (ISL) probe sensor (Lebreton *et al.*, 2006). Due to technical reasons data are only recorded at invariant latitudes less than 65°. The DEMETER satellite mission ended on 9th December, 2010 but its data are archived at Centre de Données de la Physique des Plasmas (CDPP) and can be accessed through the web server (http://demeter.cnrs-orleans.fr//). The data are organized and plotted in half orbits. CDPP offers vast array of data to investigate variations in electromagnetic emissions; production of plasma inhomogeneities and other ionospheric phenomena linked with seismic events. Its high sensitivity promotes the reliability of its data. In this research, data from the IAP and ISL sensors in the burst mode were used (Parrot, 2012; Ibanga, *et al.*, 2017).

GPS Data

The Global Positioning System (GPS) satellites are now prime sensors to measure signatures related with natural hazards such as earthquake. This GPS is a group of satellite that orbits the earth twice daily at an altitude of about 20,000 km. The huge network of GPS receivers (a few thousands all over the planet) explains simultaneous coverage in universal scale with high temporal resolution. From a list of International Global navigation satellite system service (IGS) station code, the IGS station within the seismogenic area (radius of 1,247.38 km) at GUUG lying 604 km from the epicenter was selected. The observation file was requested 30 days before and 10 days after the earthquake. Applying the RINEX Gopi software, total electron content was calculated from the observation data. Thus, total electron content variations are often investigated for seismo-ionospheric precursors due to TEC data global analysis, continuous observation and satisfactory time- and space resolution plus enormous amount of the data available. TEC is defined as the total number of electrons integrated along the path from the receiver to each GPS. The GPS satellites transmit two frequencies of signals (LI = 1575.42 MHz and L2 = 1227.60 MHz). These GPS receivers are capable of detecting ionospheric TEC perturbations caused by surface-generated Rayleigh, acoustic and gravity waves. TEC can be used to estimate spatial sizes and temporal dynamics of pre-earthquake ionospheric effects in any seismogenic region. TEC factor is predominantly associated with density in the F-layer which is greater than in the other layers (Sunil *et al.*, 2015); providing an opportunity to detect any acoustic, gravity, or both types of waves perturbations in the upper atmosphere. This technique has been used to identify perturbations due to an earthquake by Calais and Minster (1995). Zaslavski *et al.* (1998) have employed a statistical approach with TEC data from TOPEX – POSEIDON to check connections between ionospheric perturbations and seismic event. Liu *et al.* (2002), equally used a statistical technique to obtain the ionospheric TEC from data measured by a network of the GPS in Taiwan. Thomas *et al.* (2020), investigated Earth tremors in parts of Nigeria using TEC. As a part of the earthquake process, the Earth's surface is being deformed due to the accumulation of strain and slips over time. GPS is used to monitor this movement by measuring precisely the position (within 5 mm or less) of stations near active faults relative to each other. TEC data based on the date and geographic location of seismic event from about 30 days before to 10 days after the main seismic event have been processed in this study. The GPS station nearest to the epicenter of this event had a code of GUUG (Guam of latitude 13.433 and longitude 144.803).

Geomagnetic data

Regional but significantly large-scale changes in atmospheric electricity over seismically active zones before the seismic shock are transformed to the ionosphere by means of a large-scale electric field. From the penetration of this electric field into the ionosphere, electron concentration anomalies are observed when the region affected has an area with a diameter larger than 200 km^2 (Dobrovolsky *et al.*, 1979). However, the disparities in the ionospheric parameters are not only due to earthquakes as there are numerous possibilities of ionospheric distresses that can originate from other sources (solar activity, acoustic gravity waves, traveling ionospheric disturbances, plasma dynamics, and large meteorological phenomena). Consequently, the observed parameters may exhibit variations in the absence of seismic activity; hence, it is difficult to isolate pre-seismic ionospheric phenomena from the ionospheric turbulences due to the solar-terrestrial activities (Ondoh, 2008). Thus, to differentiate the seismo-ionospheric perturbations from geomagnetic instabilities, the geomagnetic indices Dst and Kp were checked. The Kp index screens the planetary activity on a universal scale whereas the Dst index registers the equatorial ring current variations (Mayaud, 1980). The ionospheric influence of a geomagnetic storm has a global effect being observed all over the world while the seismogenic impact is observed only by places within the radius (R) of the earthquake preparation zone ($R = 10^{0.43M}$ where M is the earthquake's magnitude), Dobrovolsky *et al.* (1979).

Methodology

The earthquake used in this study, had relevant information including time of occurrence, geographic location and magnitude of event, orbits closest to the epicenter (at a resolution of 20^0 for longitude and 10^0 for latitude) were selected 30 days before and 10 days after the earthquake. This time period was carefully chosen to allow enough time in monitoring of the ionospheric plasma parameter from its natural to perturbed state, enhancing separation of seismic anomalies from the background of natural variations, expecting the former to appear at the end of the period. Different time windows ranging from five days to two months have been used to monitor the ionosphere but principally, reports on seismo-electromagnetic variations are observed three weeks or less to the earthquake day (Rong *et al.*, 2008; Píša *et al.*, 2011; Parrot, 2012, Thomas, *et al.*, 2021). The total ion density (Oxygen, Hydrogen and Helium ions from the IAP Sensor) was obtained by downloading data files from the DEMETER website. Data from each orbit were confined to the two modes but only the burst mode data were used in this research. The median and the inter-quartile range of the data were used to obtain their upper and lower limits in order to distinguish seismic variances from the background of regular variations. A reference value k was selected to be 2.1 (Akhoondzadeh *et al*., 2010; Ibanga, *et al*., 2017). Any perturbations outside these bounds were anomalous. These involved computation of upper and lower boundaries, median value and inter-quartile range using Eqs. (1) – (3) below:

$$x_{high} = M + k \times IQR \qquad (1)$$

$$x_{low} = M - k \times IQR \qquad (2)$$

$$x_{low} < x < x_{high} \Rightarrow -k < \frac{x-M}{IQR} < k, D_x = \frac{x-M}{IQR} \qquad (3)$$

Where x, x_{high}, x_{low} M, IQR and Dx are parameter values, upper bound, lower bound, median of the data, inter-quartile range and differential of x respectively. From Eq. (3), if the absolute value of Dx is greater than k, (i.e., |Dx| > k), then the behaviour of x is considered to be anomalous. k values must be selected to be proportional to earthquake magnitude and therefore, for large events with Magnitude > 7.0, values greater than 2 may be used. Variations of the ionospheric parameters depend on the local time (Akhoondzadeh *et al.*, 2010).

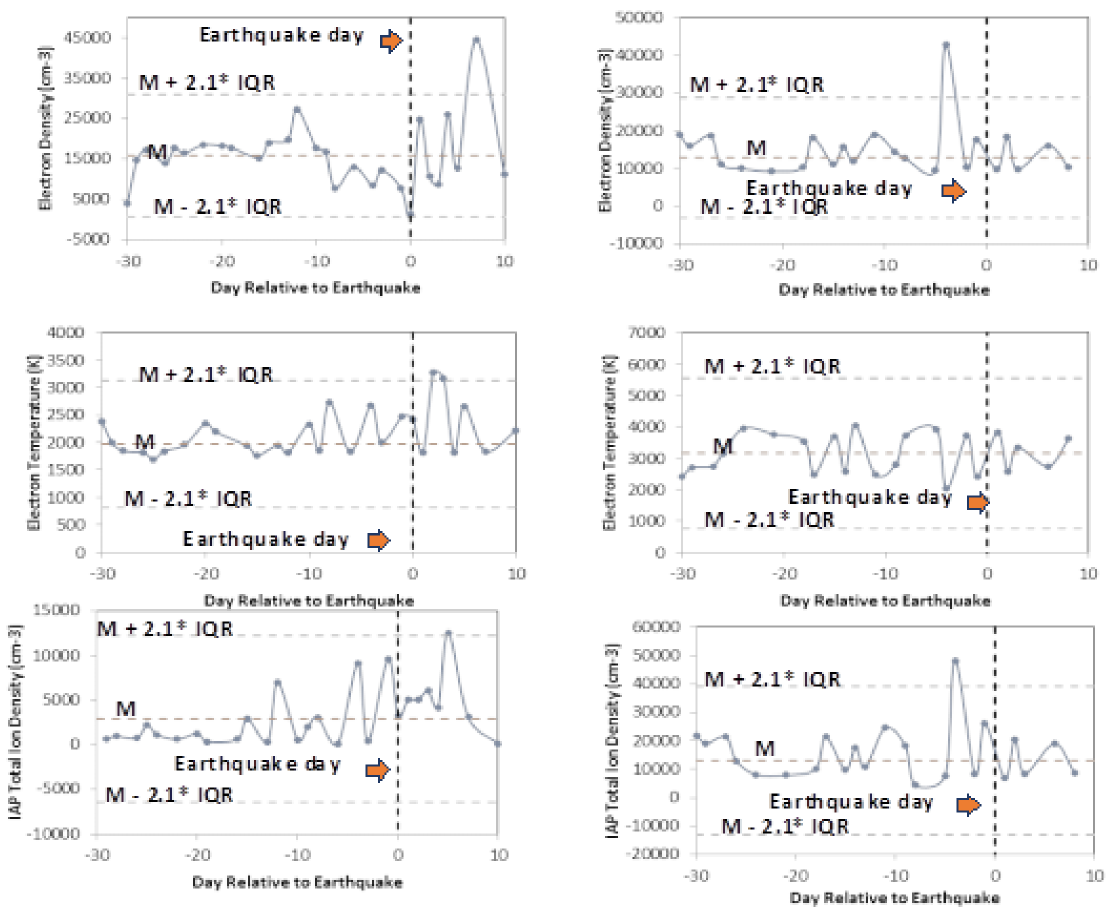
Results and discussion

Pre-, co-, and post - Perturbations in the plasma parameters of the ionosphere obtained by DEMETER and GPS data obviously presented itself during the period of investigation within the seismogenic area of the Northern Mariana Earthquake of 31st October, 2007. A comprehensive report on the anomalies detected from these data sets is shown in Table 1. All times are in universal time coordinate. Days are relative to the earthquake day (0) with negative and positive indicting pre and post days. Figure 1, shows the analysis of DEMETER data. The vertically dotted line shows the earthquake day and the ordinate of each panel indicates days relative to and after the earthquake day. Median, upper and lower bounds are indicated with red and green horizontal lines, respectively. The abscissa (y-axis) represents various parameters including **(i)** electron density derived from the measurements of the ISL experiment, **(ii)** electron temperature derived from the measurements of the ISL experiment **(iii)** total ion density derived from measurements of the IAP experiment during (a) night and (b) day.

By visual inspection of Fig. 2(a), the studies revealed pre – ionospheric variations on -17 day in the TEC with a value of 3.57 TECU at about 8:00 hours calculated from equation (3). In the same vein, IAP and ISL (Electron density) sensors of the DEMETER (fig. 1) had 2.83 cm^3 and 3.95 cm^3 respectively on -4 day being anomalies computed from equation (3). All pre - unusual perturbations were recorded in the morning. Also, using equation (3), a co-ionospheric perturbation was revealed by the Electron Density with a value of -2.04 cm^3 during the night time reading of the said day (earthquake day (day 0)). Four post -seismic day perturbations were recorded on day 2 (2.35 K) and day 3 (2.15 K from Electron temperature of the ISL experiment and 2.18 cm^3 and 3.98 cm^3 on days 5 and 7 respectively from the IAP sensor. The co and post anomalies were measured in the night time half orbits readings. Fig. 2 displays the DTEC (2a) together with the geomagnetic indices. In other to discriminate these perturbations from geomagnetic activities, the geomagnetic indices of kp and Dst were checked (Fig. 2b and c). These presented a quiet geomagnetic activity on all perturbed days. It is worthy to note that about 71% of the detected irregularities were detected in the night time half orbits (Fig. 1) showing that the signals were better depicted in the night. This is consistent with the report of Pulinets and Boyarchuk (2004) and Ibanga, *et al.* (2017) which showed that the efficiency of the anomalous electric field penetration into the ionosphere at night is higher than in daytime. The unusual variations observed in the investigated parameters from the GPS and DEMETER data had both positive and negative signs.

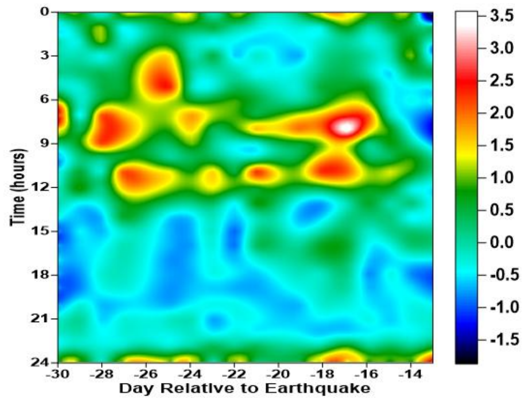
Table 1: List of Earthquake and detected anomalies (Day is relative to Earthquake Day)

EARTHQUAKE			GPS			DEMETER					GEOMAGNETIC	
NAME	DATE	TIME	DAY	TIME	VALUE	DAY	VALUE	SENSOR	PARAMETER	TIME	kp	Dst
Northern Mariana	31/10/07	3:30	-17	8:00	3.57	-4	2.83	IAP	Total ion density	10:30	-28	-27
U.S.A.						-4	3.95	ISL	Electron density	10:30	-27	-6
						0	-2.04	ISL	Electron density	22:30	-13	-5
						2	2.35	ISL	Electron Temperature	22:30	-12	-1
						3	2.15	ISL	Electron Temperature	22:30	-11	
						5	2.18	IAP	Total ion density	22:30	-6	
						7	3.98	ISL	Electron density	22:30	-5	

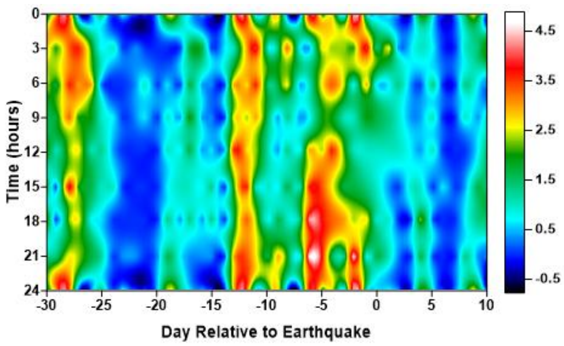


(a) (b)

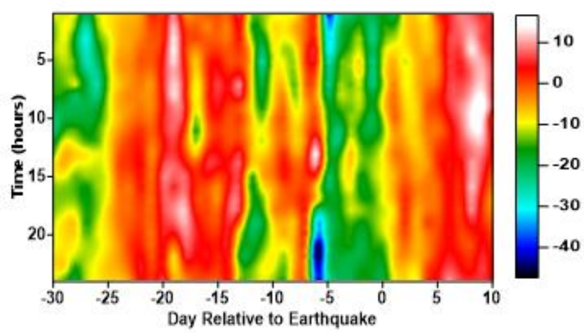
Fig. 1: Results of DEMETER data analysis for Northern Mariana, U.S.A. earthquake (31st October, 2007).



(a) DTEC



(b) kp



(c) Dst

Fig. 2: Results of (a) DTEC (b) kp geomagnetic index (c) Dst geomagnetic for Northern Mariana earthquake of 31-10-2007

Also, by virtual inspection on -17 around 8:00 UTC, the DTEC showed anomalous behaviours. Correlating these perturbations with the Kp and Dst plots, these indices of geomagnetic activities were quiet about this time, suggesting a seimo-induced perturbation. In fact both indices of geomagnetic activities used pictured strong activities two days to the earthquake. However, from Table 1, both GPS and DEMETER data revealed only pre-, co- and post seismic anomalies.

Conclusion

Ionospheric data investigated at the height of the satellite have been processed together with TEC data (density integrated along the total ionosphere) at the time of a major earthquake. In this study, the effectiveness of DEMETER IAP and ISL devices to identify striking anomalies in total ion density, Electron density and temperature parameters have been displayed. Also, GPS data have been employed to detect anomalies in total electron content variations, in the neighborhood of strong earthquake epicenter some days before its occurrence. A total of 8 anomalies were recorded from both datasets having both positive and negative signs. Since geomagnetic activity was very quiet throughout the days around the studied earthquake date, the identified anomalies can be inferred as pre-, co-, post-seismic ionospheric variations. Nonetheless, it is essential to bear in mind, that the ionosphere exhibits complicated behavior even under quiet geomagnetic condition and the measured parameters sometimes display variations in quiet seismic condition that can be associated with other unknown factors. The seismo ionospheric anomalies represented in this paper are promising for the short-term prediction but attention has to be paid to further investigation required to obtain a very precise regional model of quiet time for ionosphere to classify seismic precursors from the background of daily variations.

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