

Investigation of Hourly and Daily Patterns for Lithosphere-Ionosphere Coupling Before Strong Earthquakes

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Abstract—The ionosphere can be characterized with its electron density distribution which is a complex function of spatial and temporal variations, geomagnetic, solar and seismic activity. An important measurable quantity about the electron density is the Total Electron Content (TEC) which is proportional to the total number of electrons on a line crossing the atmosphere. TEC measurements enable monitoring variations in the space weather. Global Positioning System (GPS) and the network of world-wide receivers provide a cost-effective solution in estimating TEC over a significant proportion of global land mass. In this study, five earthquakes between 2003–2008 that occurred in Japan with different seismic properties, and the China earthquake in May 2008 are investigated. The TEC data set is investigated by using the Kullback-Leibler Divergence (KLI), Kullback-Leibler Distance (KLD) and L2-Norm (L2N) which are used for the first time in the literature in this context and Cross Correlation Function (CCF) which is used in the literature before for quiet day period (QDP), disturbed day period (DDP), periods of 15 days before a strong earthquake (BE) and after the earthquake (AE). In summary, it is observed that the CCF, KLD and L2N between the neighbouring GPS stations cannot be used as a definitive earthquake precursor due to the complicated nature of earthquakes and various uncontrolled parameters that effect the behavior of TEC such as distance to the earthquake epicenter, distance between the stations, depth of the earthquake, strength of the earthquake and tectonic structure of the earthquake. KLD, KLI and L2N are used for the first time in literature for the investigation of earthquake precursor for the first time in literature and the extensive study results indicate that for more reliable estimates further space-time TEC analysis is necessary over a denser GPS network in the earthquake zones.

Keywords—component; Ionosphere, Total Electron Content, Kullback-Leibler, L2-Norm, Earthquake, Coupling

I. INTRODUCTION

Earth's ionosphere is a dominant factor in space weather and the variability of the ionosphere is important for the ionospheric physics and radio communications. The ionosphere can be characterized with its electron density distribution which is a complex function of spatial and temporal variations, geomagnetic, solar and seismic activity. An important measurable quantity about the electron density is the Total Electron Content (TEC) which is proportional to the total number of electrons on a line crossing the atmosphere. The unit of TEC is given in TECU where 1 TECU = 10^{16} el/m². TEC measurements enable monitoring variations in the space weather. Global Positioning System (GPS) and the network of world-wide receivers provide a cost-effective solution in estimating TEC over a significant proportion of global land mass [1].

Recent studies in the literature indicate that there is a possible coupling between lithosphere and ionosphere before strong earthquakes [2-5]. In these studies, it is suggested that seismic activity causes several disturbances and variations in the ionosphere especially in the frequency and electron and ion compositions. To investigate this interaction, different statistical and physical models have been presented by using some parameters like electron density, Total Electron Content and critical frequency of F2-Layer. In the literature, the statistical tools that are used to investigate the effect of presismic activity on the ionosphere can be grouped into Correlation Analysis [3,4], Inter Quartile Range Analysis [6,7], TEC Difference Analysis [8] and Ionospheric Correction [8,9]. Among these studies, the most dominant and successful to provide pre-earthquake information is shown to be Correlation Analysis.

Kullback-Leibler Divergence (KLI), Kullback-Leibler Distance (KLD) [10,11] and L2-Norm (L2N) [12] are used in various description to define the similarity and the difference between two distributions. In this study, the Cross-Correlation Coefficient (CCF), KLI, KLD and the L2N are applied to TEC data for detailed investigation of lithosphere-ionosphere coupling. KLI, KLD and the L2N are used for the first time in the literature in this context. In addition, sliding window statistical properties of TEC are observed using moving average and standard deviation. In this study, five earthquakes between 2003–2008 that occurred in Japan with different seismic properties, and the China earthquake in May 2008 are chosen. TEC values are estimated for periods of 15 days before a strong earthquake (BE) and after the earthquake (AE) with a time resolution of 2.5 minutes and for all the GPS stations positioned near and far from the earthquake epicenter. TEC values are also obtained for the same GPS station group and with the same time resolution for the days when Ionosphere is under the influence of strong disturbances (disturbed day period-DDP) and also for the periods when there are no significant disturbances, geomagnetic storm or seismic activity in the regions (quiet day period-QDP). The statistical method used in the study and the results on the data are summarized in Section 2 and Section 3 respectively.

II. DESCRIPTION OF THE METHOD

Vertical Total Electron Content (VTEC) is the sum of the free electrons estimated in the direction of the local zenith angle of the GPS receiver location. Let

$$\mathbf{x}_{u;d} = [x_{u;d}(1), \dots, x_{u;d}(n), \dots, x_{u;d}(N)]^T \quad (1)$$

represent the set of VTEC data of length N estimated for day of the d. Here, u indicates the receiver, n is the sample number ($1 \leq n \leq N$) and T is transpose of the operator.

In order to compare the behavior of TEC for the QDP period with those from the DDP, BE and AE periods, an average quiet day TEC estimate (AQDT) for each GPS station is obtained. From the overall amount of N_d days of u^{th} station, AQDT is defined as:

$$\mathbf{x}_{u;d_i-d_s} = \frac{1}{N_d} \sum_{d_n=d_i}^{d_s} \mathbf{x}_{u;d_n} \quad (2)$$

where d_i is the initial day and d_s is the final day of QDP. To eliminate the seasonal and annual effects, the data vectors are normalized. For the day d, the experimental Probability Density Function (PDF), $\hat{\mathbf{P}}_{u;d_i-d_s}$ of the $\mathbf{x}_{u;d_i-d_s}$ vector, can be approximated as follows:

$$\hat{\mathbf{P}}_{u;d_i-d_s} = \mathbf{x}_{u;d_i-d_s} \left(\sum_{n=N_i}^{N_s} x_{u;d_i-d_s}(n) \right)^{-1} \quad (3)$$

where N_i is the initial sample and N_s is the final sample Using this approximation described in Equation 3, the Kullback-Leibler Divergence KLI is defined as:

$$\begin{aligned} \text{KLI}(\hat{\mathbf{P}}_{u;d} \parallel \hat{\mathbf{P}}_{u;d_i-d_s}) &= \sum_{n=N_i}^{N_s} \hat{\mathbf{P}}_{u;d}(n) \ln \left(\frac{\hat{\mathbf{P}}_{u;d}(n)}{\hat{\mathbf{P}}_{u;d_i-d_s}(n)} \right) \\ \text{KLI}(\hat{\mathbf{P}}_{u;d_i-d_s} \parallel \hat{\mathbf{P}}_{u;d}) &= \sum_{n=N_i}^{N_s} \hat{\mathbf{P}}_{u;d_i-d_s}(n) \ln \left(\frac{\hat{\mathbf{P}}_{u;d_i-d_s}(n)}{\hat{\mathbf{P}}_{u;d}(n)} \right) \end{aligned} \quad (4)$$

From the Equation 4, the symmetric Kullback-Leibler Distance KLD can be defined as follows [10,11-15]:

$$\text{KLD}(\hat{\mathbf{P}}_{u;d}; \hat{\mathbf{P}}_{u;d_i-d_s}) = \text{KLI}(\hat{\mathbf{P}}_{u;d} \parallel \hat{\mathbf{P}}_{u;d_i-d_s}) + \text{KLI}(\hat{\mathbf{P}}_{u;d_i-d_s} \parallel \hat{\mathbf{P}}_{u;d}) \quad (5)$$

For the energy normalized TEC distribution, the L2-Norm can be given as [12]:

$$\text{L2N}(\hat{\mathbf{P}}_{u;d} \parallel \hat{\mathbf{P}}_{u;d_i-d_s}) = \sqrt{\sum_{n=N_i}^{N_s} (\hat{\mathbf{P}}_{u;d}(n) - \hat{\mathbf{P}}_{u;d_i-d_s}(n))^2} \quad (6)$$

The cross correlation coefficients (CCF) are determined by an correlation function as:

$$r_{u;d,d_i-d_s} = \frac{1}{N_T \sigma_{u;d} \sigma_{u;d_i-d_s}} \sum_{n=N_i}^{N_s} (\hat{\mathbf{P}}_{u;d}(n) - \bar{\hat{\mathbf{P}}}_{u;d}) (\hat{\mathbf{P}}_{u;d_i-d_s}(n) - \bar{\hat{\mathbf{P}}}_{u;d_i-d_s}) \quad (7)$$

where $\bar{\hat{\mathbf{P}}}_{u;d}$ and $\bar{\hat{\mathbf{P}}}_{u;d_i-d_s}$ denote the average of $\hat{\mathbf{P}}_{u;d}$, $\hat{\mathbf{P}}_{u;d_i-d_s}$ for day d and the period d_i-d_s , respectively N_T is the total number of TEC values, $\sigma_{u;d}$ and $\sigma_{u;d_i-d_s}$ are standard deviations of $\hat{\mathbf{P}}_{u;d}$ and $\hat{\mathbf{P}}_{u;d_i-d_s}$ vectors. Sliding rectangular moving average (MAQDT) and standard deviation (STDQDT) of estimates of the normalized $\hat{\mathbf{P}}_{u;d_i-d_s}$ can be given as [16]:

$$\begin{aligned} \hat{\mu}(n) &= \frac{1}{N_w} \sum_{i=-\frac{N_w-1}{2}}^{\frac{N_w-1}{2}} \hat{\mathbf{P}}_{u;d_i-d_s}(n+i) \\ \hat{\sigma}^2(n) &= \frac{1}{N_w} \sum_{i=-\frac{N_w-1}{2}}^{\frac{N_w-1}{2}} \hat{\mathbf{P}}_{u;d_i-d_s}^2(n+i) - \hat{\mu}^2(n) \end{aligned} \quad (7)$$

where N_w is the sliding window size, which is chosen as an odd number. The normalized MAQDT $\hat{\mu}(n)$ is compared with the normalized TEC estimates for the QDP, DDP, BE and AE periods by using the bounds derived from the STDQDT $\hat{\sigma}^2(n)$.

For station u , the Kullback-Leibler Divergence $KLI(\hat{P}_{u;d} \parallel \hat{P}_{u;d+1})$ and $KLI(\hat{P}_{u;d+1} \parallel \hat{P}_{u;d})$, the Kullback-Leibler Distance $KLD(\hat{P}_{u;d} \parallel \hat{P}_{u;d+1})$ and $KLD(\hat{P}_{u;d+1} \parallel \hat{P}_{u;d})$, L2-Norm $L2N(\hat{P}_{u;d+1} \parallel \hat{P}_{u;d})$ and Cross Correlation Coefficient $r_{u;d,d+1}$ functions are computed between the consecutive d and $d+1$ days in QDP, DDP, BE and AE periods. The results of KLI, KLD, L2N and CCF applications are presented in the next section.

III. RESULTS

In this study, five earthquakes between 2003–2008 that occurred in Japan with different seismic properties, and the China earthquake in May 2008 are investigated. This earthquakes are composed in Table I as date, time (Universal Time-UT), geographical location (latitude, longitude: in degrees), magnitude in Richter Scale (M), depth (z-km) and central station which is chosen as the nearest recording GPS station to the epicenter [17]. The epicenters which are coded as E1, E2, E3, E4, E5 and E6 represent Hokkaido, Honshu, Honshu, Kyushu, Honshu and Sichuan earthquakes, respectively.

TABLE I :Indicator of date, time, geographical location, magnitude and depth of the earthquakes.

	date	UT	°N	°E	M	z	central station ID
E1	25.09 2003	195 0	41	143	8.3	27	mizu
E2	05.09 2004	145 7	33	137	7.4	10	kgni
E3	13.06 2008	234 3	39	140	6.9	10	mizu
E4	11.06 2006	200 1	33	131	6.3	154	usud
E5	23.07 2005	073 4	35	139	5.9	65.6	mtka
E6	12.05 2008	062 8	30	103	7.9	19	kunm

There have been seven GPS stations that used in this study. These stations are given in Table II. The distance between IGS-GPS stations to the epicenter vary from 35 km to 1000 km.

Table II : GPS Stations that are used in the content of the study.

GPS Station	Station ID	Latitude	Longitude
Koganei, Japan	kgni	35.5 °N	139.4° E
Kashima, Japan	ksmv	35.7 °N	140.6° E
Mizusawa, Japan	mizu	38.9 °N	141.1° E
Mitaka, Japan	mtka	35.4 °N	139.5° E
Tsukuba, Japan	tskb	35.9 °N	140.0° E
Usuda, Japan	usud	35.9 °N	138.3° E
Yuzh.-Sakh, Russia	yssk	46.8 °N	142.7° E

Kunminimung, China kunm 24.8 °N 102.8° E

The TEC is estimated using the Reg-Est method as IONOLAB-TEC [18,19,20]. There are no significant disturbances in the AE and BE periods [21]. 14 October-02 November 2003 and 23 August-21 September 2005 periods are chosen as DDP. 14 October-03 November 2006 and 27 April-21 May 2006 periods are chosen as QDP [21].

In the first group of the study, in order to compare the behavior of IONOLAB-TEC for the QDP period with those from the DDP, BE and AE periods, an average quiet day TEC estimate (AQDT) for each GPS station is obtained by Equation 2. Equations 4, 5, 6 and 7 are applied AE, BE, QDP and DDP data of seven stations in Table II. It is observed that days of the DDP and AQDT are highly correlated. In the both of the AE and BE periods (EA) and QDP, the correlation coefficients vary between 0.2 and 0.7. The values of EA – AQDT and QD-AQDT are lowly correlated. Difference between minimum and maximum values of KLI, KLD and L2N (D) are larger when the distance of the station decreases and the magnitude of the earthquake increases. If the distance of the station is less far from 150 km, the KLD and the L2N methods select the EA days from the QDP. At the distance less from 150 km, D difference of the KLD, KLI and L2N of DDP-AQDT is greater although there are highly correlation coefficients. For the kunm, KLD, L2N and CCF variations of E6-AQDT, QDP-AQDT and DDP-AQDT are shown at the Figure 1a, 1b, 1c, respectively. For the mizu, KLD, L2N and CCF variations of E3-AQDT, QDP-AQDT and DDP-AQDT are shown in the Figure 1d, 1e, 1f, respectively. At the E6, which is the greater earthquake than the E3, it is shown that KLD and L2N values of EAP have greater scale than the E3 and KLD and L2N values of both E6 and E3 are greater than the QDP and the DDP.

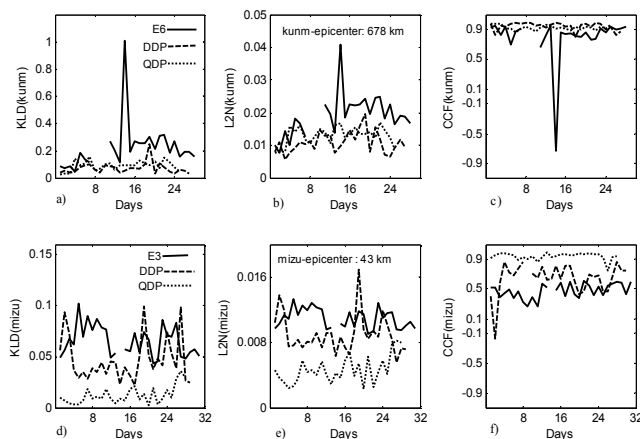


Figure 1. E6-AQDT, DDP-AQDT and QDP-AQDT of kunm for: a) KLD b) L2N c) CCF and E3-AQDT, DDP-AQDT and QDP-AQDT of mizu for: a) KLD b) L2N c) CCF.

Figure 2a, and 2b show KLD variations of station mizu for DDP 23 August-21 September 2005, and QDP 14 October-11 November 2006, respectively. It is observed that even on QDP, KLD variation has low ranged scattered distribution. Even on DDP, KLD variation is different from QDP but has smaller level than AE and BE.

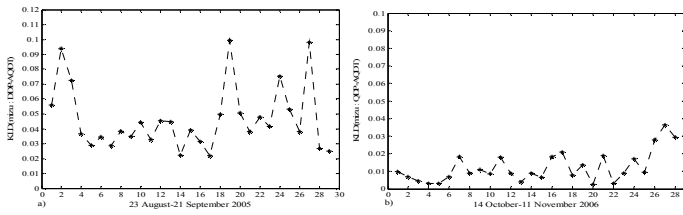


Figure 2. KLD variations of mizu a) DDP-AQDT b) QDP-AQDT.

In the second group of study, the Kullback-Leibler Divergence $KLI(\hat{P}_{u;d} \parallel \hat{P}_{u;d+1})$ and $KLI(\hat{P}_{u;d+1} \parallel \hat{P}_{u;d})$, the Kullback-Leibler Distance $KLD(\hat{P}_{u;d} \parallel \hat{P}_{u;d+1})$ and $KLD(\hat{P}_{u;d+1} \parallel \hat{P}_{u;d})$, L2-Norm $L2N(\hat{P}_{u;d+1} \parallel \hat{P}_{u;d})$ and Cross Correlation Coefficient $r_{u;d,d+1}$ functions are applied to the d and $d+1$ consecutive days of QDP, DDP, and BE and AE (EAP) periods for each earthquake given at the Table I and each GPS station given at the Table II. For the consecutive days, all of the CCF values of the QDP days vary between 0.8 and 1 and so consecutive QDP days are highly correlated. Consecutive EAP days become low correlated at the nearest stations to the epicenter. At the consecutive days, the values smaller than the 0.8 are %4 at E1, %17 at E2, %3 at E3, %1 at E5, %1 at E6, %5 at QDP and %6 at DDP. The effects of the EAP are observed better than DDP with CCF method for consecutive days. Difference between minimum and maximum values of KLI, KLD and L2N (D) are greater when the distance of the station decreases and the magnitude of the earthquake increases. D values of DDP are similar to the QDP, so KLI, KLD and L2N methods are less sensitive for the consecutive DDP days. Figure 3 shows the KLD and L2N variations of mizu and tskb for the E3. It is shown from Figure 3a and 3b that KLD values for mizu, which has 43 km distance to the epicenter and tskb which has 358 km distance to the epicenter, are very similar. It is also shown from Figure 3c and 3d, L2N values of both stations vary very similar level.

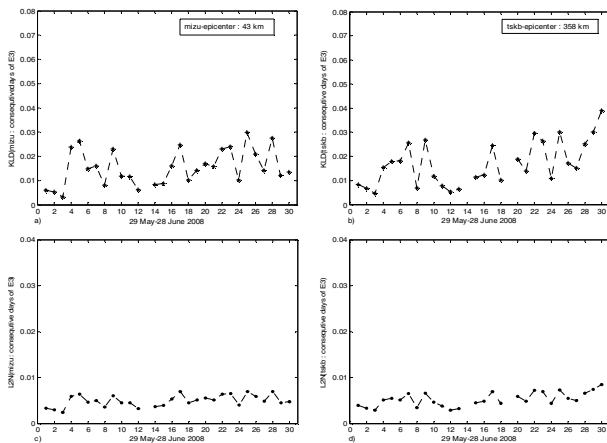


Figure 3. KLD variations of a) mizu b) tskb and L2N variations of c) mizu d) tskb. for consecutive days of E3.

For the tskb, KLD, L2N and CCF variations of E6, QDP and DDP are shown at the Figure 3a, 3b, 3c, respectively. For the mizu, KLD, L2N and CCF variations of E6, QDP and DDP

are shown at the Figure 3d, 3e, respectively. It is shown for mizu that there is no significant difference for the KLD and L2N values of E5, DDP and QDP periods. For the mizu, KLD and L2N values of both E1 and E3 and QDP periods vary very similar level. Both E1 and E3 are the large scaled earthquakes and distances of mizu to the E1 and E3 are 392 km and 43 km, respectively. There are no important difference on the KLD and L2N values of E1, E3 and QDP periods. For storm days in the DDP, KLD and L2N values are larger for mizu.

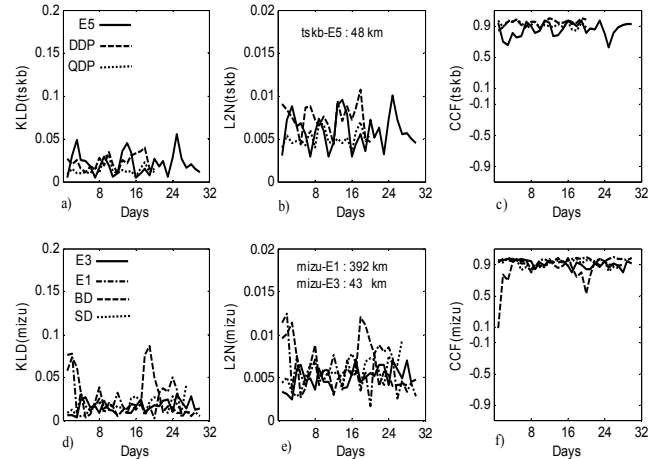


Figure 3. Variations of a) KLD b) L2N c) CCF for consecutive days of E5, DDP and QDP of tskb and variations of a) KLD b) L2N c) CCF for consecutive days of E1 E3, DDP and QDP of mizu.

Finally, in group four, the normalized MAQDT is compared with the normalized TEC estimates for QDP, DDP and EAP by using the bounds derived from SQDT in Equation 7 for each earthquake given at the Table I and each GPS station given at the Table II. It is observed that for the MAQDT comparisons and the EAP TEC estimates that are not bounded by STDQDT, especially for those stations that are closer to the epicenter. For the EAP, QDP and DDP of a station, TEC estimates can not be categorized by statistical differentiation because of abundance unbounded values in both of the EAP, DDP and QDP.

IV. CONCLUSION

In this study, the relation between earthquakes and the TEC obtained from GPS is examined. Five earthquakes between 2003-2008 occurred in Japan with different properties and China earthquake in May 2008 are chosen for the purpose. For the statistical analysis, the cross correlation function (CC) which is used in the literature before, and the Kullback-Leibler Divergence (KLD) with L2-Norm (L2N) methods which are used for the first time in this context, are applied to the data sets. It is observed that the CCF, KLD and L2N between the neighbouring GPS stations cannot be used as a definitive earthquake precursor due to the complicated nature of earthquakes and various uncontrolled parameters that effect the behaviour of TEC such as distance to the earthquake epicenter, distance between the stations, depth of the earthquake, strength of the earthquake and tectonic structure of the earthquake. The investigation of CCF, KLD and L2N for the consecutive days for each station indicates that when

similar disturbances occur for days in a row, these methods are inadequate in identifying the disturbance due to earthquakes. The most promising results are obtained for the analysis of Kullback-Leibler divergence between the AQDT and the TEC estimates for the BE. For this group of study, it is observed that the seismic activity before the strong earthquakes have a diurnal disturbance structure which can be distinguished from the ionospheric disturbances due to geomagnetic storms or solar flares. The increasing levels of KLD for preseismic activity is also a promising candidate for further investigation in this direction, especially for those GPS stations that are closer to the epicenter. Similar results are also observed for the MAQDT comparisons and the BE TEC estimates that are not bounded by STDQDT, especially for those stations that are closer to the epicenter. KLD, KLI and L2N are used for the first time in literature for the investigation of earthquake precursor for the first time in literature and the extensive study results indicate that for more reliable estimates further space-time TEC analysis is necessary over a denser GPS network in the earthquake zones.

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