DWT-based methodology for detection of seismic precursors on electric field signals in Mexico

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ABSTRACT
This paper presents an analysis of atmospheric electric field signals which were taken on an important seismic activity period from 2012 to 2015 to study its relationship with seismic events. For this purpose, several measurements were acquired every second by using a triaxial electric field monitoring system. Furthermore, the discrete wavelet transform (DWT) was applied to electric field signals with seismic events of magnitudes greater than Mw > 5.5, which occurred in Mexico with different focal mechanisms. The analysed epochs consist of 24 h of observations for a data-set corresponding to 55 different earthquakes (EQs). The time series were processed 12 h before and 12 h after each seismic event. The proposed methodology proves to be an efficient tool to detect signals with relations between electric field and seismic activity. The methodology presented herein shows important anomalies on different time instants according to the focal mechanism. Finally, a statistical post-processing algorithm was performed in order to quantify the data dispersion as a measure of seismic activity. It is found that the variance increases before, during, and after the seismic event about the coefficients D1 to D7 obtained using the DWT.

KEYWORDS
Early warning; seismic zones; earthquake lights; earthquake predictions

1. Introduction

There are many studies that report relations between earthquakes and other physical phenomena. These phenomena mainly include disturbances such as electromagnetic (EM) anomalies associated with the earthquakes. They often encompass a large frequency range, which comes from quasi-dc to high frequencies, being ultra-low-frequency (ULF) range (0.001-1 Hz) the most promising, because it has been associated with anomalies produced in Earth’s EM field before large earthquakes (Johnston 1997; Kushwah et al. 2009). Other physical anomalies related to pre-earthquake disturbances such as an increment in radon emanation from the ground to the atmosphere, water chemistry alterations, haze production and induced changes in the electric field, among others have been reported (Chen et al. 2004; Pulinets et al. 2003; Pulinets and Boyarchuk 2004; Rishbeth 2006; Freund 2013; Depueva et al. 2007; Liu et al. 2006a; Liu et al. 2006b; Karatay et al. 2010; Le et al. 2011; Namgaladze et al. 2012; Devi et al. 2014; Akhoondzadeh 2015; Heki and Enomoto 2015).
Geo-electromagnetic field changes have been widely observed during seismic events (Yen et al. 2004; Chavez et al. 2010). On the other hand, there are electrical phenomena such as electrical currents, which flow between lithosphere and ionosphere that are also related to seismic events (Kuo et al. 2011; Pulinets and Davidenko 2014). Furthermore, there are atmospheric gravity waves that are generated before and after the main shock (Hegai et al. 2006; Koshevaya et al. 2012). They can reach speeds up to 990 m/s, generating the possibility of being detected by the GPS satellite network. Consequently, it is important to mention that these ionospheric effects can be observed about 2000 km away from the main shock (Astafyeva et al. 2009).

It has been reported that the atmospheric electrical phenomena generate EM signals in ULF and very-low frequency (VLF) bands (Hayakawa and Hobara 2010; Athanasiou et al. 2011). In this regard, geomagnetic storms may disturb large territories in the planet due to atmospheric electrical currents that are related to the geo-magnetic field. These pre-seismic phenomena can be observed depending on their type, magnitude, and seismic event depth (Arikan et al. 2012), which generate a limit to distinguish pre-seismic data from EM storm noise (Devi et al. 2014). Other reports show that there exist a relation between a seismic event and the atmospheric electrical current disturbances based on electron density (Ne) and electron temperature (Te) methods. These techniques were implemented on DEMETER satellite located at 630 km altitude (Athanasiou et al. 2011; Liu et al. 2014).

In this paper, the extraction of anomalies in ULF electrical signals associated with seismic activity by means of discrete wavelet transform (DWT) is presented. It is worth noting that DWT is an efficient tool to analyse signals with time shifting frequencies (Alperovich and Zheludev 1997), features that can be found in ULF signals (Han et al. 2014). For this reason, the DWT is used in this work in order to detect and distinguish different transient variations that are superposed on atmospheric electrical field data, as it has been utilized by different authors in the analysis and detection of ULF geo-EM seismic precursors (Chavez et al. 2010; Alperovich and Zheludev 1997; Febriani et al. 2014; Han et al. 2014). Additionally, the variance of electrical signals processed by DWT is also used as a complementary parameter to measure the fluctuations in seismic activity and seismic calm period.

The paper is organized as follows: Section 2 explains the materials and methods employed. The results are described in Section 3. Finally, Section 4 presents the conclusions.

2. Materials and methods

2.1. Electric field data-set

The goal of this work is to propose a signal processing methodology capable of detecting pre-seismic activity into the ULF electric signals. These signals are measured at the Juriquilla seismic station located at Queretaro, Mexico. Its geographic coordinates are: longitude $-100.45$ E, latitude $20.70$ N, and 1946 m a.s.l. (above sea level). The electrical signals are acquired using a Boltek EFM-100C electric field monitoring system. This system is capable of measuring the change in the atmospheric electric field on thousands of Volts per meter. The sensor employs a sampling frequency of 1 Hz within a period of 24 h (12 h before and 12 h after the seismic event), obtaining 86,400 samples. To compare the signal behaviour between seismic and calm data, a set of random signals with seismic calm are also analysed. Table 1 shows the characteristics of the EQs investigated, which occurred in Mexico from January 2012 to August 2015 with a ratio of $D/r < 1$ and $D/r > 1$, where $D$ is the distance between the epicentre and Juriquilla station and $r$ is the radius of the EQ preparation (Dobrovolsky et al. 1979).

The analysis focused within a distance to the station of $r = (1.8) \times 10^{0.45} M$, where $M$ is the magnitude of the EQ according to Chavez et al. (2010). For each seismic event presented in
| Event | Date     | Time (UTC) | Depth (km) | Magnitude (M) | Latitude | Longitude |
|-------|----------|------------|------------|---------------|----------|-----------|
|       |          |            |            |               | D (km)   | r (km)    | D/r      |
| 1     | 20/03/2012 | 17:02:47   | 16         | 7.4           | 16 15 3.6 | 98 31 16 | 533 3848 0.1 |
| 2     | 02/04/2012 | 17:36:42   | 10         | 6             | 16 16 12 | 98 28 12 | 533 902 0.5 |
| 3     | 12/04/2012 | 00:55:10   | 16         | 6.4           | 17 54 60 | 103 4 36 | 414 1365 0.3 |
| 4     | 12/04/2012 | 07:15:49   | 10         | 6.8           | 28 47 48 | 113 26 48 | 1590 2066 0.7 |
| 5     | 01/05/2012 | 16:37:59   | 51         | 5.6           | 18 12 0  | 101 1 36 | 284 596 0.4 |
| 6     | 15/11/2012 | 08:20:22   | 40         | 6.1           | 18 10 12 | 100 31 12 | 280 1000 0.2 |
| 7     | 20/02/2013 | 20:23:11   | 5          | 5.6           | 18 36 0  | 104 2 24 | 287 596 0.4 |
| 8     | 22/04/2013 | 01:16:34   | 10         | 5.8           | 17 52 12 | 102 11 24 | 363 733 0.5 |
| 9     | 16/06/2013 | 05:19:03   | 60         | 5.8           | 18 2 24 | 99 15 0  | 320 733 0.4 |
| 10    | 21/08/2013 | 13:38:30   | 20         | 6             | 16 47 24 | 99 34 36 | 576 733 0.7 |
| 11    | 19/10/2013 | 17:54:55   | 14         | 6.3           | 26 5 24 | 110 28 36 | 1187 1231 1.0 |
| 12    | 09/03/2014 | 23:37:57   | 16         | 5.8           | 15 47 24 | 98 33 60 | 576 733 0.7 |
| 13    | 18/04/2014 | 14:27:23   | 10         | 7.2           | 17 11 48 | 101 11 24 | 395 3128 0.1 |
| 14    | 08/05/2014 | 17:00:16   | 17         | 6.4           | 17 7 36 | 100 52 12 | 398 1365 0.3 |
| 15    | 10/05/2014 | 07:36:01   | 12         | 6.1           | 17 4 36 | 100 57 0  | 403 1000 0.4 |
| 16    | 21/05/2014 | 10:06:15   | 121        | 5.8           | 17 7 36 | 95 4 12  | 691 733 0.9 |
| 17    | 24/05/2014 | 08:24:45   | 18         | 5.7           | 16 13 36 | 98 25 12 | 540 661 0.8 |
| 18    | 31/05/2014 | 11:53:49   | 10         | 6.2           | 18 59 24 | 107 20 48 | 747 1109 0.6 |
| 19    | 07/07/2014 | 11:23:58   | 60         | 6.9           | 14 45 0  | 92 38 48 | 1057 2292 0.4 |
| 20    | 29/07/2014 | 10:46:14   | 117        | 6.4           | 17 42 0  | 95 38 48 | 604 1365 0.4 |
| 21    | 04/09/2014 | 19:22:58   | 10         | 5.9           | 18 38 48 | 106 55 12 | 715 813 0.8 |
| 22    | 08/10/2014 | 02:40:39   | 10         | 6.1           | 23 14 48 | 108 10 36 | 847 1000 0.8 |
| 23    | 21/02/2015 | 13:23:16   | 16         | 6.3           | 18 39 60 | 106 41 24 | 693 1231 0.5 |

With a ratio of $D/r < 1$

| Event | Date     | Time (UTC) | Depth (km) | Magnitude (M) | Latitude | Longitude |
|-------|----------|------------|------------|---------------|----------|-----------|
|       |          |            |            |               | $\circ \circ \circ$ | $\circ \circ \circ$ |
| With a ratio of $D/r > 1$

| Event | Date     | Time (UTC) | Depth (km) | Magnitude (M) | Latitude | Longitude |
|-------|----------|------------|------------|---------------|----------|-----------|
|       |          |            |            |               | $\circ \circ \circ$ | $\circ \circ \circ$ |

Table 1. Earthquakes greater than 5.5 in magnitude occurred in Mexico from January 2012 to August 2015. $D$ is the distance between the epicentre and Juriquilla station. $r$ is the radius of the EQ preparation. The analysis focused within a distance to the station of $r = (1.8) \times 10^{-5} \times M$, where $M$ is the magnitude of the EQ according to Chavez et al., 2010.
Table 2. Determination of the focal mechanism for each analysed seismic event, according with the United States Geological Survey (USGS). $D$ is the distance between the epicentre and Juriquilla station. $r$ is the radius of the EQ preparation.

| Event | Type of focal mechanism | Event | Type of focal mechanism |
|-------|-------------------------|-------|-------------------------|
| 1     | I                       | 2     | T                       |
| 4     | N                       | 3     | T                       |
| 5     | I                       | 6     | T                       |
| 7     | T                       | 9     | I                       |
| 8     | N                       | 10    | I                       |
| 20    | N                       | 11    | T                       |
| 23    | I                       | 12    | T                       |
| 25    | I                       | 13    | T                       |
| 26    | N                       | 14    | N                       |
| 28    | I                       | 15    | I                       |
| 31    | T                       | 16    | T                       |
| 34    | I                       | 19    | I                       |
| 36    | I                       | 21    | N                       |
| 37    | I                       | 22    | T                       |
| 38    | I                       | 24    | N                       |
| 39    | N                       | 27    | I                       |
| 40    | I                       | 29    | N                       |
| 41    | T                       | 30    | I                       |
| 42    | N                       | 32    | N                       |
| 43    | N                       | 33    | I                       |
| 44    | T                       | 35    | T                       |
| 46    | T                       | 45    | N                       |
| 51    | T                       | 47    | I                       |
| 48    | I                       | 49    | N                       |
| 50    | I                       | 52    | N                       |
| 53    | I                       | 54    | N                       |
| 55    | N                       |

Note: I: reverse fault – subduction zone; N: normal fault – subduction zone; T: transcurrent fault.

Table 1, its focal mechanism is presented in Table 2, e.g. event 1 from Table 1 presents a reverse fault (I) as shown in Table 2. Table 2 shows all the focal mechanisms: normal, reverse, and transcurrent faults. Some definitions for these faults are presented by Peacock et al. (2000).

In order to discriminate the geo-EM activity of the magnetosphere due to both the solar activity and cultural noise, the Kyoto Observatory web page information was utilized to compare the analysed EQs data.

### 2.2. Time-frequency analysis

Time-frequency analysis considers both time and frequency domains. It is used when a signal presents a non-stationary and transient behaviour. This property is of vital importance when time or frequency domains are unable to show signal features by using only one domain. For instance, frequency domain techniques such as fast Fourier transform (FFT) are ineffective to show spectral changes of the signal over time (Yue et al. 2014). On the other hand, time domain analysis is also unable to determine which frequency components are present in a transient signal. Therefore, the time-frequency analysis is a mathematical tool that allows distinguishing spectral changes of a transient signal over time (Yue et al. 2014). Among the time-frequency techniques, the short-time FFT (STFT), continuous wavelet transform (CWT), and DWT have demonstrated to be effective tools for time-frequency analysis (Chavez, Amezquita-Sanchez, et al. 2015; Chavez, Valtierra-Rodriguez, ...
et al. 2015). In particular, the DWT is capable of dealing with non-stationary and transient signals, allowing extracting hidden features into analysed signal. Therefore, the DWT was chosen as time-frequency analysis tool to detect differences between calm and seismic activity using ULF signals (Alperovich and Zheludev 1997; Chavez, Amezquita-Sanchez, et al. 2015).

2.3. DWT-based electric field analysis

Previous works have reported that the first pre-seismic information on geo-electromagnetic information appears about 10-7 days before the main shock, whereas the second pre-seismic burst appears around 12 h before the main shock (Hayakawa and Hobara 2010). In this regard, the second pre-seismic emission is selected as case of study due to its smaller time window around the main shock. Each analysed signal contains information for 12 h before and 12 h after each seismic event, hence the main shock is specified as the central position in time.

Different mother wavelets such as Daubechies, Haar, Morlet, Symlets, Coiflets, and Meyer, among others have been used to perform the DWT algorithm, being Daubechies the most recommended for the analysis of ULF signals (Jach et al. 2006; Huang et al. 2016). Taking this into consideration, Daubechies 10 is selected as mother wavelet function in this work. In order to explore different frequency bands, D1 to D7 DWT levels were selected to extract electric field signal information. Table 3 shows the exact frequency range of each DWT level which were utilized in this work.

### Table 3. Frequency bands per DWT level.

| DWT Level | Frequency band          |
|-----------|-------------------------|
| X(n)      | 0 to 0.5 Hz             |
| D1        | 0.25 to 0.5 Hz          |
| D2        | 0.125 to 0.25 Hz        |
| D3        | 0.0625 to 0.125 Hz      |
| D4        | 0.03 125 to 0.0625 Hz   |
| D5        | 0.015 625 to 0.03 125 Hz|
| D6        | 0.0078 125 to 0.015 625 Hz|
| D7        | 0.00390 625 to 0.0078 125 Hz|

2.4. Variance analysis

In order to evaluate the significance of the results obtained by DWT in ULF electrical signals, a statistical analysis to obtain the variance ($V_{DL}$) of data is applied to each detail, $D_L$, from level 1–7. $V_{DL}$ is defined by Equation (1), where $a$ and $b$ represent the lower and upper limits for the region of interest, respectively. $y_{DL}(n)$ is the input sequence at the detail level and $\bar{y}$ is the mean value of $y_{DL}(n)$.

$$V_{DL} = \frac{1}{b-a} \sum_{n=a}^{b} \left\{ [y_{DL}(n) - \bar{y}]^2 \right\} \quad (1)$$

3. Results and discussions

In order to show the performance of a conventional signal processing technique, the events of Table 1 are also analysed with FFT. In this regard, Figure 1 shows the obtained results. It is worth
noting that the results are divided into three classes as shown in Table 2 (normal fault, reverse fault, and transcurrent fault). Also, two kinds of results are considered, the ones for a ratio of $D/r < 1$ and the ones for a ratio of $D/r > 1$, which are depicted in yellow and blue colours, respectively. These results correspond to the average values. Observing Figure 1, it is evident that significant differences are not remarkable, i.e. the results are very similar, compromising the correct discrimination of the different conditions. This is probably caused because the magnitude of the analysed events is larger than 5.5. On previous works, it is shown the attenuation according to the magnitude of the event (Chavez, Valtierra-Rodriguez, et al. 2015; Han et al. 2014). Unlike FFT, a filtering process using

![Figure 1. FFT-based spectra for events with $D/r < 1$ and $D/r > 1$. Amplitude is on dB.](image)
DWT offers an appreciation of the frequency content in the time domain as shown in Figures 2–6. As abovementioned, the $V_{DL}$ is computed in order to assess the $V_{DL}$ of the frequency content (in red colour), which is also depicted in Figures 2–6. In particular, Figure 2 shows the signals for the events 4 and 11 (Table 1 or 2). On the left, the ratio of $D/r < 1$ is presented and, on the right, the ratio of $D/r > 1$ is presented. For both events, the seven details of the DWT are presented. The main shock is on 0 H. The variance is included as the numerical values depicted by labels on the right.

Figure 2. Different types of focal mechanism: DWT results for events 4 and 11 (Table 1 or 2). On the left, the ratio of $D/r < 1$ is presented and, on the right, the ratio of $D/r > 1$ is presented. For both events, the seven details of the DWT are presented. The main shock is on 0 H. The variance is included as the numerical values depicted by labels on the right.

DWT offers an appreciation of the frequency content in the time domain as shown in Figures 2–6. As abovementioned, the $V_{DL}$ is computed in order to assess the $V_{DL}$ of the frequency content (in red colour), which is also depicted in Figures 2–6. In particular, Figure 2 shows the signals for the events 4 and 11 (Table 1), which correspond to normal and transcurrent faults (Table 2). Also, the DWT results for the details, $D_L$ with $L = 1, 2, ... , 7$, are depicted. This figure is only presented to show that different focal mechanisms present different values of $V_{DL}$ according to the analysed detail. This behaviour could be used as starting point in a new research to discriminate between different focal
mechanisms. It should be pointed out that the signals with the same kind of focal mechanism may present different behaviours since they have different features such as depth, magnitude, and $D/r$ ratio (see Table 1).

In Figure 3, the DWT results for the events denoted by 20 ($D/r < 1$) and 21 ($D/r < 1$) from Table 1, being a normal fault on a subduction zone, are presented. As can be observed, the values of $V_{DL}$ change before and after the main shock in all details, $D_L$. These changes occur in a time window from 11 to 5 h before and after the main shock, between these time windows it is observed a non-
significant increment of the $V_{DL}$, indicating that the aforementioned changes may be used as precursors of seismic activity. In a similar way, Figure 4 presents the results for the events denoted by 38 ($D/r < 1$) and 48 ($D/r > 1$) from Table 1, being reverse fault on subduction zone. Unlike the results for normal fault, the changes of $V_{DL}$ are presented 5 h before and after the seismic event. For transcurrent faults, events denoted by 51 ($D/r < 1$) and 22 ($D/r > 1$) from Table 1, the $V_{DL}$ of $D_L$ apparently increases only after the main shock as shown in Figure 5. On the other hand, Figure 6 shows...
the results for the analysis of signals with absence of a seismic event, i.e. signals with $M < 5.5$, on the ratio earthquake preparation. Although small values of $M$ are considered, the ratio of $D/r$ can be also calculated. The results for a ratio of $D/r < 1$ (left side of Figure 6) show non-significant changes of $V_{DL}$ since no seismic activity is detected. On the right side, the results consider a signal with a solar event ($Dst = 72$). $Dst$ (disturbance storm-time) represents the geomagnetic activity (data obtained from http://wdc.kugi.kyoto-u.ac.jp/dstdir/) (Chavez, Amezquita-Sanchez, et al. 2015). Finally, Figure 7 shows a summary of the obtained $V_{DL}$ values for the different types of faults. The depicted

Figure 5. Transcurrent fault: DWT results for events 51 and 22 (Table 1 or 2). On the left, the ratio of $D/r < 1$ is presented and, on the right, the ratio of $D/r > 1$ is presented. For both events, the seven details of the DWT are presented. The main shock is on 0 H. The variance is included as the numerical values depicted by labels on the right.
signals are the average of the $V_{DL}$ values for events with the same focal mechanism. As can be observed, important changes in amplitude occur before and after the main shock.

4. Conclusions

A methodology based on DWT and variance ($V_{DL}$) for the analysis of the geomagnetic data acquired at Juriquilla station is described herein. Electric field behaved in different ways. Signals associated with seismic event data are reported, where the observation time depending on the particular electric

Figure 6. DWT results: On the left, a random analysis without seismic event on the ratio $D/r < 1$ is presented and, on the right, the signal analysis within a solar event, $D_{st} = 72$ and the ratio $D/r > 1$, is presented. For both events, the seven details of the DWT are presented. The variance is included as the numerical values depicted by labels on the right).
and the focal mechanism are implied. Accordingly, the proposed signal processing methodology consists of applying a detail level 1–7 DWT filter using a DB10 wavelet mother function to the existing data in order to obtain frequency components associated to seismic anomalies into the geomagnetic signal. Information in other bandwidths is obtained but with different statistical basis. As demonstrated, \( V_{DL} \) provides information before and after the main shock in the analysed details or bandwidths. According to the obtained results, this methodology can extract the abnormal signals in the ULF range of the electric anomalies related to different stages of the EQ preparation, in a ratio that depends on the focal mechanism.

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![Figure 7. Average of the variance \( V_{DL} \) values obtained according to the fault type: On the left, the results for the ratio of \( D/r < 1 \) are presented and, on the right, the results for the ratio of \( D/r > 1 \), are presented. The main shock is on 0 H.](image-url)
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