Geodetic evidence on segmentation of Cascadia subduction zone based on episodic tremors and slips using multivariate harmonic analysis of GPS time series

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ABSTRACT

Episodic tremor and slip (ETS) events with different recurrence intervals have been observed in abundance all along the Cascadia subduction zone margin. Analysis of seismic records as well as Global Positioning System (GPS) time series of the Pacific Northwest Geodetic Array (PANGA) has suggested three distinct coherent zones for the occurrence of these events. In this paper multivariate harmonic estimation has been deployed for further analysis of the segmentation in this area. Raw time series of 43 permanent GPS stations have been used for this purpose. The GPS stations have been geographically divided into three distinct groups including those in the northern, middle and southern parts of the study area. After the reduction of time series for the linear trend as well as annual and semiannual effects, the data series of each group has been analyzed using the multivariate harmonic estimation technique. Subsequently, different combinations of GPS stations including the stations located in the southern, northern and middle zones have been analyzed. Furthermore, the northern and middle, southern and middle as well as the northern and southern zone pair combinations have also been analyzed. The statistical measure devised for identifying the significant frequencies suggests common periods that are consistent with the recurrence intervals of the ETS events already reported for each of the above three geographic zones. Moreover, the method can provide geodetic evidence, in addition to geophysical ones, on the segmentation of ETSs, provided that the adopted time series are of a sufficient length. The geodetic evidence obtained in this research is consistent with the recurrence intervals as well as the boundaries obtained by the analysis of seismic records. Contrary to univariate harmonic estimation, multivariate approach using spatio-temporal correlation of the GPS time series is capable to detect those ETSs whose impacts on the time series are weak.

Keywords: slow earthquakes, multivariate analysis, segmentation, GPS data

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1. INTRODUCTION

Episodic tremor and slip (ETS) is the name of a plate boundary phenomenon recently discovered in northern Cascadia (e.g., *Rogers and Dragert, 2003*). It is a repeated, transient ground motion at a plate margin, opposite to the direction of longer-term inter-seismic deformation, accompanied by low-frequency, emergent, semi-continuous seismic signals. Because of three essential components of these events, i.e., transient ground motion, tremor-like seismic signals, and the episodic occurrences, detailed ETS studies require continuous seismic and geodetic observations from a dense network over a long period of time.

Every ETS event consists of two parts: tremor and slip. For investigating tremors one must focus on seismic data; however, the evaluation of a slip requires geodetic measurements (e.g. *Rogers and Dragert, 2003*; *Kao et al., 2005, 2009*; *Ito et al., 2007*; *Szeliga et al., 2008*; *Haltkamp and Brudzinski, 2010*; *Mousavian and Hossainali, 2013*).

The Source-Scanning Algoritm (*Kao and Shan, 2004*) and the Tremor Activity Monitoring System (TAMS) (*Kao et al., 2007, 2008*) are two methods which are used for identifying their approximate distribution in time and space. However, various methods have been developed for identifying the corresponding duration of slip events. *Rogers and Dragert (2003)* identified approximate dates for slip transients by applying a sawtooth function that was correlated with the de-trended coordinate time series. They established the maxima for cross-correlation function as the midpoint of slip events. *Szeliga et al. (2008)* applied wavelet transformation for detecting the onset time of ETSs in the geodetic time series of some stations located throughout the length of the Cascadia subduction zone. They have also estimated the recurrence range of these events in the northern, middle and southern parts of Cascadia. Independently of seismic tremor records, *Haltkamp and Brudzinski (2010)* have used a hyperbolic tangent curve fitting technique for the identification of slow slip duration and displacement magnitudes within the GPS time series along Cascadia margin. *Mousavian and Hossainali (2013)* have also detected these slips using univariate least squares harmonic estimation (LS-HE). Moreover, based on the analysis of the recurrence intervals of ETSs in this region, different coherent zones have been suggested for this area; for example, according to *Brudzinski and Allen (2007)*, Cascadia can be divided into 3 distinct coherent zones located at the northern, middle and southern parts of this area.

Clustering the ETSs in terms of their recurrence intervals could be the first step for understanding how continental blocks could be responsible for the differences in the period of the ETS events. For example, using the intriguing hypothesis that different terrane composition affects the rheology of the upper plate and hence the plate interface suggests that longer periods between slow slip episodes can be assigned to the strength of upper plate in accumulating strain in a longer period of time (*Kohlstedt et al., 1995*).

The paper is the first attempt in approaching the two problems of detecting the mean period of the ETS and providing geodetic evidence on the segmentation character of the study area simultaneously using a multivariate analysis technique. For this purpose, after removing semiannual, annual and linear effects from all of the time series, multivariate harmonic estimation is used for constructing the existing common signals in the study area. This independent approach to the problem has been later checked by geophysical evidence which are coming from previous researches on the topic in order to clarify the pros and cons of the method. Illustrating the efficiency of a pure geodetic solution to the problems mentioned above can be seen interesting to those who might be interested to look at the problem from a geodetic point of view. Section two of this paper provides the theoretical background of this method. The third section of the paper discusses the obtained numerical results.

2. LEAST SQUARES HARMONIC ESTIMATION

The least squares harmonic estimation (LS-HE) is a method which was first introduced and applied to GPS position time series by Amiri-Simkooei (see *Amiri-Simkooei, 2007* and *Amiri-Simkooei et al., 2007*). The method is based on the application of harmonic functions for modeling the periodic constituents of a phenomenon. As a generalization of the Fourier spectral analysis, the method is neither limited to evenly spaced data nor to integer frequencies (*Amiri-Simkooei and Asgari, 2012*). The method is actually based on the Least Squares Spectral Analysis (LSSA) developed by *Vaníček (1996)* even when an initial design matrix is present in the model and the covariance matrix, in general, is not a scaled identity matrix. *Amiri-Simkooei and Tiberius (2007)* and *Amiri-Simkooei and Asgari (2012)* provide some examples for the application of this method. The efficiency of this method for the detection of the existing frequencies in a simulated time series as well as the main tidal constituents have been investigated by *Mousavian and Hossainali (2012)*. Results from simulated time series suggest that the LS-HE method is sensitive to the amplitudes of the existing frequencies. Nevertheless, increasing the length of a time series increases the reliability of the results. This is seen through the detection of new constituents in both simulated coordinates and tidal time series by increasing the length of the corresponding records.

2.1. Multivariate harmonic estimation

The functional model of the periodic time series $\boldsymbol{y}^{\mathrm{T}} = [y_1, y_2, \ldots, y_m]$, which is defined on R^m, is in general given by:

$$\boldsymbol{y} = \mathbf{A}\boldsymbol{x} + \sum_{k=1}^{q} \mathbf{A}_k \boldsymbol{x}_k \,, \qquad \mathbf{D}(\boldsymbol{y}) = \mathbf{Q}_y \,, \tag{1}$$

where,

$$\mathbf{A}_k = \begin{bmatrix} \cos\omega_k t_1 & \sin\omega_k t_1 \\ \cos\omega_k t_2 & \sin\omega_k t_2 \\ \vdots & \vdots \\ \cos\omega_k t_m & \sin\omega_k t_m \end{bmatrix}, \qquad \boldsymbol{x} = \begin{bmatrix} y_0 \\ r \end{bmatrix}, \qquad \boldsymbol{x}_k = \begin{bmatrix} a_k \\ b_k \end{bmatrix}.$$

In these equations, y_0 is the zero frequency component of the time series, r is linear rate, a_k and b_k are amplitudes of sine and cosine components corresponding to the frequency ω_k and t_i for $i = 1, 2, \ldots, m$ are observation epochs. $\mathbf{D}(\boldsymbol{y}) = \mathbf{Q}_y$ is the dispersion matrix for the observation vector $\boldsymbol{y}$.

Least Squares Harmonic Estimation has been proposed for finding the unknown parameters in Eq. (1) when the unknown parameters are both ω_k and the coefficients a_k and b_k. In practice the contribution of every frequency in reconstructing the time series is recursively analyzed through the hypothesis test below:

$$\begin{cases} H_0: \quad \boldsymbol{y} = \mathbf{A}\boldsymbol{x} + \sum_{k=1}^{i-1} \mathbf{A}_k \boldsymbol{x}_k \ , \\ H_a: \quad \boldsymbol{y} = \mathbf{A}\boldsymbol{x} + \sum_{k=1}^{i} \mathbf{A}_k \boldsymbol{x}_k \ . \end{cases} \tag{2}$$

A multivariate linear model is a linear model with r time series whose observation vectors have an identical design matrix $\mathbf{A}$ and covariance matrix $\mathbf{D}\left(\mathrm{vec}\left(\mathbf{Y}\right)\right)$ (*Amiri-Simkooei, 2007, 2009*). Therefore, the multivariate form of Eq. (1) can be written as follows (*Amiri-Simkooei and Asgari, 2012*):

$$\mathbf{E}\left(\mathrm{vec}\left(\mathbf{Y}\right)\right) = \left(\mathbf{I}_r \otimes \mathbf{A}\right)\mathrm{vec}\left(\mathbf{X}\right) + \left(\mathbf{I}_r \otimes \mathbf{A}_k\right)\mathrm{vec}\left(\mathbf{X}_k\right), \quad \mathbf{D}\left(\mathrm{vec}\left(\mathbf{Y}\right)\right) = \mathbf{\Sigma} \otimes \mathbf{Q} \ . \tag{3}$$

Multivariate variance component estimation can be used for estimating the $r \times r$ matrix Σ and $m \times m$ matrix **Q** (*Amiri-Simkooei, 2009*).

In Eq. (3) vec and $\otimes$ are the vector and the Kronecker product operators respectively. Moreover, $\mathbf{Y} = \left[y_1, y_2, \ldots, y_r\right]$ is a $m \times r$ matrix which contains the observations of the r time series. Also, $\mathbf{X} = \left[x_1, x_2, \ldots, x_r\right]$ and $\mathbf{X}_k = \left[x_{1k}, x_{2k}, \ldots, x_{rk}\right]$ are the matrices of unknowns with $n \times r$ dimensions. The structure of $\mathbf{I}_r \otimes \mathbf{A}$ indicates that there is a common periodic signal in all of the series but, the amplitude and phase of the common sinusoidal signal can change from one series to another. Nevertheless, it is expected that the signal can be detected using a harmonic estimation technique.

To obtain the power spectrum of the multivariate model, one needs to substitute the terms in Eq. (1) from the multivariate model,

$$\mathbf{I} \otimes \mathbf{A} \rightarrow \mathbf{A}, \quad \mathbf{I} \otimes \mathbf{A}_j \rightarrow \mathbf{A}_j \ . \tag{4}$$

The frequency content of a common signal can then be estimated using the equation below:

$$\omega_k = \arg \max_{\omega_j} P\left(\omega_j\right), \tag{5}$$

$P\left(\omega_j\right)$ is the multivariate power spectrum which is constructed using all of time series simultaneously. It optimally takes into account the cross-correlation of the time series through matrix Σ and their time correlation through matrix **Q** in least-squares sense

$$P\left(\omega_j\right) = \mathrm{tr}\left(\hat{\mathbf{E}}^{\mathrm{T}} Q^{-1} \mathbf{A}_j \left(\mathbf{A}_j^{\mathrm{T}} \mathbf{Q}^{-1} \mathbf{P}_A^{\perp} \mathbf{A}_j\right)^{-1} \mathbf{A}_j^{\mathrm{T}} \mathbf{Q}^{-1} \hat{\mathbf{E}} \boldsymbol{\Sigma}^{-1}\right), \tag{6a}$$

$$\mathbf{P}_A^{\perp} = \mathbf{I} - \mathbf{A}\left(\mathbf{A}^{\mathrm{T}} \mathbf{Q}^{-1} \mathbf{A}\right)^{-1} \mathbf{A}^{\mathrm{T}} \mathbf{Q}^{-1}, \tag{6b}$$

$$\Sigma \cong \hat{\Sigma} = \frac{\hat{\mathbf{E}}^{\mathrm{T}} \mathbf{Q}^{-1} \hat{\mathbf{E}}}{m - n}. \tag{6c}$$

Least-squares residuals $\hat{\mathbf{E}}$ consist of r groups and are computed by (*Amiri-Simkooei, 2009*):

$$\hat{\mathbf{E}} = \mathbf{P}_A^{\perp} \mathbf{Y}. \tag{7}$$

Matrix $\mathbf{A}_j$ has the same structure as $\mathbf{A}_k$, but it is constructed using the frequency of interest. For testing the significance of a desired signal, the following statistics is used:

$$T = \mathrm{tr}\left(\hat{\mathbf{E}}^{\mathrm{T}} \mathbf{Q}^{-1} \mathbf{A}_k \left(\mathbf{A}_k^{\mathrm{T}} \mathbf{Q}^{-1} \mathbf{P}_A^{\perp} \mathbf{A}_k\right)^{-1} \mathbf{A}_k^{\mathrm{T}} \mathbf{Q}^{-1} \hat{\mathbf{E}} \boldsymbol{\Sigma}^{-1}\right). \tag{8}$$

The above equation has a central chi-square distribution with $2r$ degrees of freedom under the null hypothesis given in Eq. (2):

$$T \sim \chi^2\left(2r, 0\right). \tag{9}$$

3. RESULTS AND DISCUSSION

In this study, the GPS time series of 43 permanent stations in the Pacific Northwest Geodetic Array (PANGA) located in the Cascadia subduction zone have been used for detecting the episodic tremors and slips as well as geodetic evidence on the segmentation of this area based on the recurrence intervals of these events.

PANGA is a network of GPS receivers that are distributed continuously throughout the Pacific Northwest of the US and Canada. This network monitors crustal deformation using the daily positions of each station to measure their motion relative to stations on the stable part of the North America plate. In order to analyze the code and phase data of this network, the precise point positioning method (*Zumberge et al., 1997*) is used. For this purpose, using precise orbital information, the position of the measuring station along with the other unknown parameters such as receiver clock error, is calculated by GIPSY/OASIS II (*Miller et al., 2002*; *Szeliga et al., 2008*).

Cascadia is an active subduction zone at which episodic tremors and slips (ETSs) are repeatedly seen. Since the discovery of these events, several studies have been performed for determining characteristics like focal mechanisms and epicenters using seismic records. Moreover, various methods such as cross correlation analysis (*Dragert et al., 2001*), wavelet analysis (*Szeliga et al., 2008*), hyperbolic tangent curve fitting (*Haltkamp and Brudzinski, 2010*) and univariate harmonic estimation *(Mousavian and Hossainali,* *2013*) have been used for estimating characteristics like recurrence intervals and slip magnitudes for these events. Based on the computed recurrence intervals, *Brudzinski and Allen (2007)* suggest that Cascadia can be divided into 3 distinct coherent zones located at the northern, middle and southern parts of this area. This segmentation is given in Fig. 1. As seen in this figure, recurrence periods of ETS events in the northern, middle and southern zones are 14 ± 2, 19 ± 4 and 10 ± 2 months, respectively. This implies that a common signal is expected in each coherent zone.

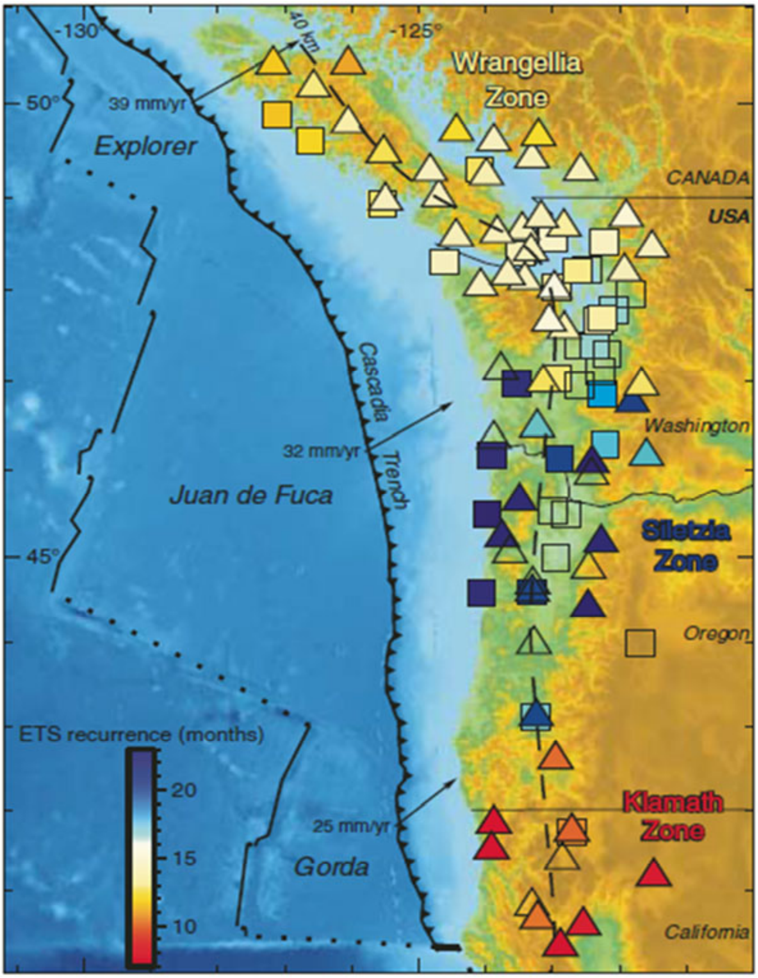

Fig. 1. Segmentation of episodic tremor and slip (ETS) along the Cascadia subduction zone according to their recurrence intervals. Squares and triangles are permanent GPS stations and broadband seismometers respectively. The corresponding color at each station indicates the recurrence interval of the ETSs (*Brudzinski and Allen, 2007*, © 2007 Geological Society of America).

Based on the theoretical background mentioned before (see Section 2), multivariate harmonic estimation is able to detect an existing common signal. Therefore, application of multivariate harmonic estimation to the time series of permanent GPS stations in Cascadia provides new evidence on the recurrence intervals of the ETSs and the segmentation of this area suggested above.

Figure 2 illustrates the spatial distribution of the GPS stations employed for this purpose. These stations provide a reasonable coverage for the study area. Moreover, this configuration provides us the possibility of the comparison of the obtained results to those reported by others, for example (*Szeliga et al., 2008*). To analyze the above arguments, GPS stations are divided into three distinct groups located in the northern, middle and southern parts of the study area. The GPS stations of each group as well as the corresponding time spans are given in Fig. 3.

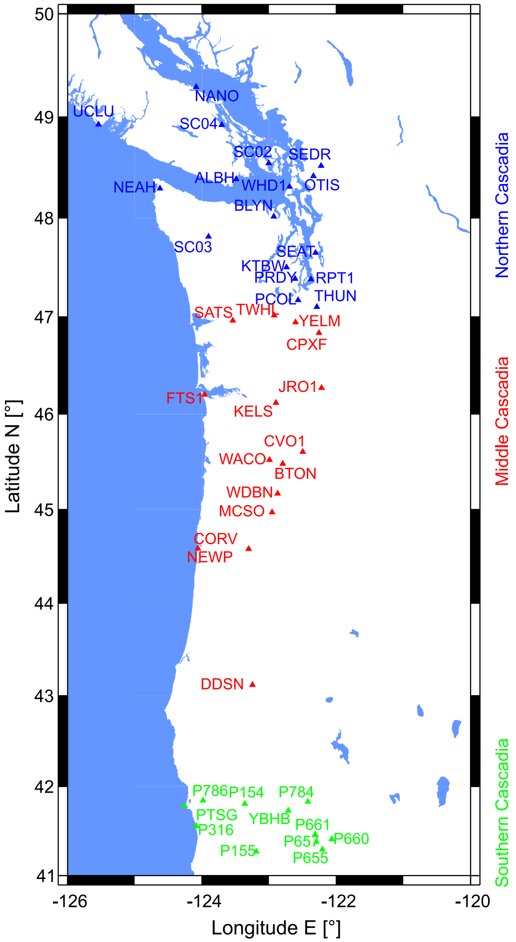

Fig. 2. Geographical location of the selected stations of PANGA.

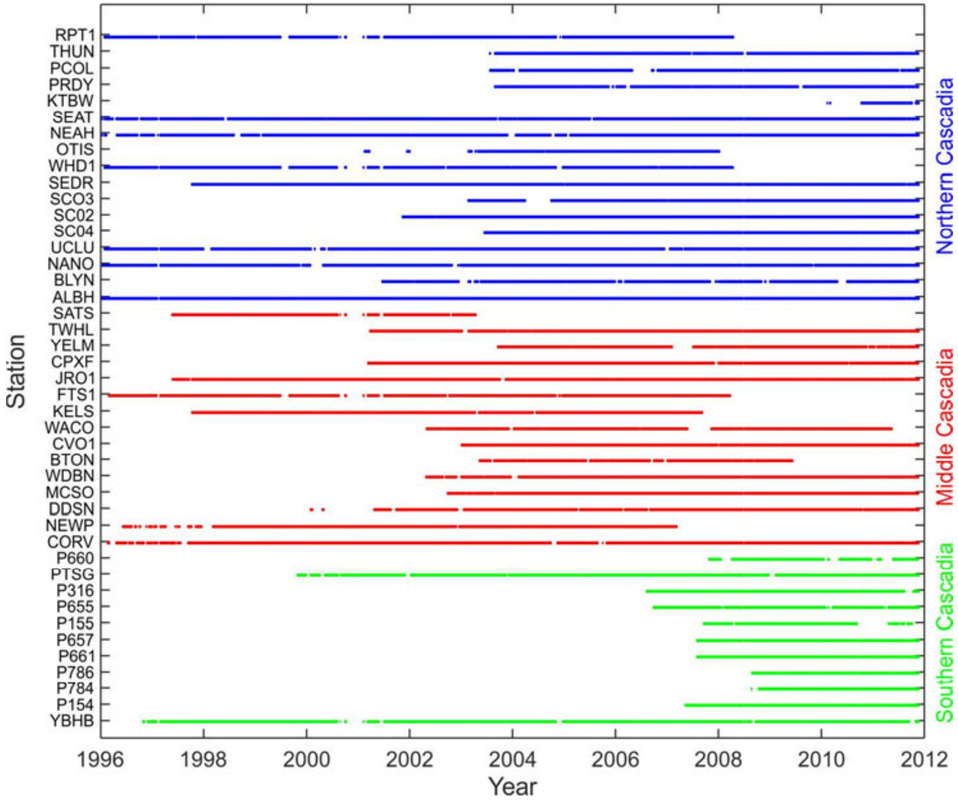

Fig. 3. Data available at GPS stations of this study located in the northern, middle and southern parts of Cascadia.

Since least squares harmonic estimation is sensitive to the time span of the dataset (*Mousavian and Hossainali, 2013*), from above stations, ones with maximum overlap are used in multivariate analysis.

The vertical time series are not used in determining the ETS times especially due to the larger scatter for this component that is common globally (*Holtkamp and Brudzinski, 2010*). For the stations that are close to the plate interface and are located at the vicinity of a tremor, the residual time series exhibits a sawtooth behavior. *Rogers and Dragert (2003)* used this behavior in order to detect the ETS times. Moreover, the sawtooth behavior of the ETS events is more obvious in the time series of the east component as compared to the north component. Therefore, the east component of GPS time series is used for analyzing the ETS events.

To analyze the coordinate time series of each group, semi-annual and annual effects as well as linear trends are firstly removed from the time series of the GPS stations. If an antenna is changed, the resulting offsets are also modeled using Heaviside functions, and removed. The adopted noise model is a combination of flicker and white noise. This has been accepted as the appropriate noise model for the GPS time series (*Mao et al., 1999*). Nevertheless, the w-test statistic (*Amiri-Simkooei, 2007*) is also used to check the efficiency of this model in this research.

The power spectrum of the common signal in each group has been constructed using the frequencies identified in the multivariate least squares harmonic estimation process. The peaks in the power spectrum whose frequencies are statistically significant (as implies by the statistical test of the LS-HE method) correspond to the main periodic components which reconstruct the common signal. The power spectrum of common signal for the stations located in the northern, middle and southern zones are demonstrated in Figs 4−6, respectively. In each figure, the horizontal axis indicates the existing frequencies in the spectrum of the time series (in days) and the vertical axis gives the power spectrum of each frequency.

Marked frequencies in the above figures are the constituents whose periods are within the reported recurrence intervals for the ETSs in each region: In the northern, middle and southern Cascadia, the proposed recurrence intervals for transient slips are 14 ± 2, 19 ± 4 and 10 ± 2 months, respectively. The frequency components with periods 445.4 days

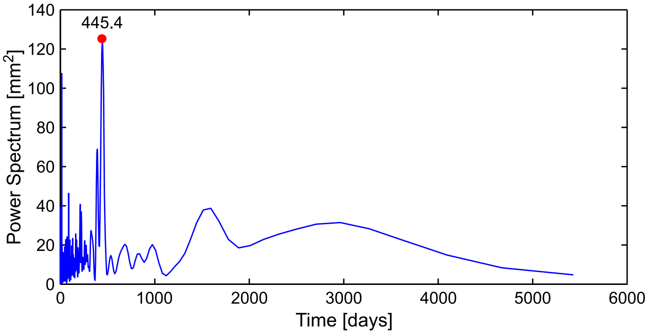

Fig. 4. Power spectrum of the common signal which is constructed with the east component of the GPS time series for stations located in the northern Cascadia. The peak which is indicated by a full circle corresponds to the mean period of ETSs in this region.

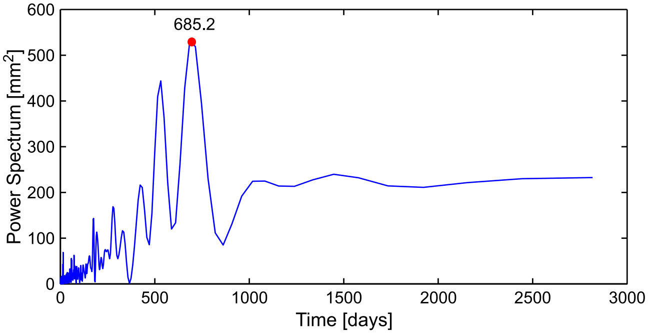

Fig. 5. The same as in Fig. 4, but for stations in the middle part of Cascadia.

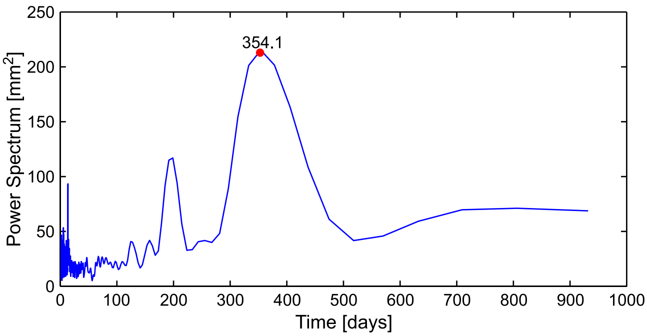

Fig. 6. The same as in Fig. 4, but for stations in the southern part of Cascadia.

(14.8 months), 685.2 days (22.8 months) and 354.1 days (11.8 months) detected in the northern, middle and southern parts in turn, conform to the mean period of the ETSs in these regions.

To provide geodetic evidence on the segmentation of the study area, different combinations of the GPS stations including: stations located in the southern and northern, northern and middle, also southern and middle zones have been analyzed together.

At first, a group of stations including those in northern and middle zones have been analyzed together. The detected period of the common signal is 459.4 days. This period conforms to the reported recurrence interval for ETSs in both northern and southern part of the study area. This is due to the existing overlap between the ETSs periods in these regions (14 ± 2 and 19 ± 4 months, respectively). As a result, the deployed method fails to provide any evidence on the boundary between the northern and middle zones. Therefore, geophysical evidence are the only constraints available on the boundary of these areas.

Next, a group of stations from southern and middle zones have been analyzed together. In this case, the detected periods for the common signal do not conform to the recurrence intervals of these zones. This implies that there is no common frequency between the episodic tremors in these regions.

Finally, stations in the southern and northern zones have been analyzed together. The common frequencies which are detected for these stations are neither in the range of recurrence interval for transient slips in the northern zone nor in the corresponding range in the southern part of the study area. This implies that there is no common frequency between the episodic tremors in these regions. This is supported by the different geophysical characteristics of the ETS events which are reported in previous studies (*Kao et al. 2009*).

4. CONCLUSIONS

To summarize the discussion above, we conclude:

a) Multivariate least squares harmonic estimation of the GPS coordinate time series can provide geodetic evidence on the mean period of ETSs in an specific region if the adopted series are of sufficient length. In this study, the presented evidence are consistent with the recurrence intervals derived from the analysis of seismic records.

b) Multivariate analysis takes the spatio-temporal correlation of the GPS time series into account. For stations that are far away from an ETS epicenter, the amplitude of the ETS signal on the GPS time series might be weak. As the result, univariate analysis of the corresponding GPS time series might fail to detect the ETS signal. This is seen for example at station CORV. The univariate analysis of the GPS time series of this station suggests a constituent whose period is 1627.76 days (*Mousavian and Hossainali, 2013*)**.** This period does not conform to the reported recurrence interval for ETSs in this region. However, application of the LS-HE in multivariate form to the coordinate time series of the GPS stations located in the middle Cascadia (including this station) results in a common frequency that conforms to the reported recurrence interval for ETSs in this region. In addition, according to the previous studies, recurrence interval of ETSs at some stations like SEAT is not as regular as others (e.g. station ALBH) (e.g. *Szeliga et. al., 2008*). In these circumstances, univariate harmonic estimation again fails to confirm the occurrence of ETS events. The spatio-temporal correlation of the GPS time series at the stations which are located in the same geophysical area is partly due to the geophysical characteristics of the area. This correlation increases when the GPS stations are close to each other. By taking this property into account in multivariate approach, it is even possible to detect ETS signals for these stations.

c) Multivariate least squares harmonic analysis also appears to confirm the geophysical segmentation of Cascadia ETSs into the three regions (the northern, middle and southern ones). Namely, when analyzing together the northern and middle, middle and southern, or northern and southern zone stations, either an average common ETSs period (the northern and middle zones) or no common ETSs periods have been found.

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