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Analysis of ionospheric precursor of earthquake using GIM-TEC, kriging and neural network (Article) (Open Access)

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Abstract

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Analysis of ionospheric precursor is not easy because the ionosphere is very dynamic as well as the earthquake phenomena. If the analysis method is the same dynamics with the earthquake phenomena, the estimation of earthquake parameters is possible to be realized. Neural network is an adaptive system that changes its structure to solve the problem during a learning phase. Therefore, the neural network is potentially to estimate the parameter of earthquake based on ionospheric precursor. A preliminary attempt was made to construct the neural network that can estimate the epicenter area. The GIM-TEC star method is useful to determine ionospheric anomalies associated with large earthquakes as ionospheric precursor data. The Kriging method is good to interpolate GIM-TEC star data as input of neural networks to estimate the epicenter area. The conclusion of five models of the ionosphere anomalies due to seismic activity show that the epicenter is at the edge of the less developed anomalies, whereas, for the growing anomalies, the epicenter is always located near the boundary of high and low density of TEC anomalies. The boundary is projection of the boundary of the unstressed and stressed rock area below the earth's surface. © 2015 Academic Journals Inc.

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Analysis of Ionospheric Precursor of Earthquake using GIM-TEC, Kriging and Neural Network

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ABSTRACT

Analysis of ionospheric precursor is not easy because the ionosphere is very dynamic as well as the earthquake phenomena. If the analysis method is the same dynamics with the earthquake phenomena, the estimation of earthquake parameters is possible to be realized. Neural network is an adaptive system that changes its structure to solve the problem during a learning phase. Therefore, the neural network is potentially to estimate the parameter of earthquake based on ionospheric precursor. A preliminary attempt was made to construct the neural network that can estimate the epicenter area. The GIM-TEC star method is useful to determine ionospheric anomalies associated with large earthquakes as ionospheric precursor data. The Kriging method is good to interpolate GIM-TEC star data as input of neural networks to estimate the epicenter area. The conclusion of five models of the ionosphere anomalies due to seismic activity show that the epicenter is at the edge of the less developed anomalies, whereas, for the growing anomalies, the epicenter is always located near the boundary of high and low density of TEC anomalies. The boundary is projection of the boundary of the unstressed and stressed rock area below the earth's surface.

Key words: Ionospheric precursor, earthquake, GIM TEC, Kriging, neural network

INTRODUCTION

Before earthquakes, the tectonic forces begin to act on a large block of strong, rigid rocks in the thrust direction. As stresses build up from the left, they cause plastic deformation propagating toward the right. Granite is known as a good insulator, which contains minerals peroxy bonds. The minerals act like a time bomb. When these rocks are subjected to stress, the peroxy bonds break and suddenly mobile electronic charge carriers appear. The volume of rocks undergoing deformation becomes the source of p-holes and electrons. The p-holes are able to flow through unstressed granite, while electrons are blocked from entering the unstressed portion of the rock because granite is not a good conductor. The p-holes flow out of the stressed rock volume into the adjacent unstressed rock. This condition causes accumulated p-holes in the unstressed rock area. The p-holes will shift the p-holes that are in the unstressed rock, up to the surface of the lithosphere up to the ionosphere. The process cause electromagnetic anomalies that can be used

as precursors of earthquakes (Freund *et al*., 2006). These anomalies that appear in the ionosphere before the main seismic shock can be considered as ionospheric precursors (Pulinets and Boyarchuk, 2004; Le *et al*., 2011). The main phenomenological features of ionospheric variations appearing before strong earthquakes are well established and are described by Legen'ka *et al*. (2003), where the GPS TEC is useful to register pre-earthquake ionospheric anomalies (Liu *et al*., 2004).

Modeling of the ionosphere is not easy, because it changes rapidly in terms of time and space. The GPS ionospheric models can be divided into the real-time models and the post-time models. The real-time models are used in positioning and navigation such as Klobuchar model and Wide Area Argumentation System (WAAS). The post-time models can be used for various scientific purposes that are represented by Global Ionosphere Maps (GIM) (Hofmann-Wellenhof *et al*., 2008).

The GPS ionosphere models are also divided into the global models and the local models. The global models employ the measurements from 100 international GPS reference stations of 420 International GNSS Service (IGS) stations that are internationally authenticated. The local models use the observation information from the local GPS reference stations, where the local models have high temporal and spatial resolution (Mannucci *et al*., 1998).

Most of the international ionosphere analysis centers like JPL and CODE use the spherical harmonic expansion method to develop global ionosphere models, while University of Polytechnical Catalunya (UPC) uses the Kriging method based on interpolation (Hernandez-Pajares *et al*., 1999). The spherical harmonic expansion method is generally used for the processing of large capacity data as the global TEC. The large capacity data can be approximated by a few numbers of coefficients, where the information that varies drastically in a very short period of time is eliminated. The Kriging method is an interpolating method where the weight is applied depending on the distance. The Kriging method is too sensitive to the measurements but it can be conveniently applied to the detection of momentous change in a short period of time. The Kriging method is more appropriate to local models (Choi *et al*., 2010).

The focus area of this research is Japan and not the entire global earth. If we use the local models with local station data, we will have problem to distinguish the anomalies by seismic activity or other activities. Otherwise, if we use the global model, the area of the epicenter will be too large that it is less useful for the early warning system. Therefore, we need a combination of local and global modeling techniques by utilizing a global model data. In this research, the global TEC derived from GIM-TEC is obtained through the spherical harmonics expansion and the linear interpolation. To filter the TEC anomalies, we used GIM-TEC star method. To localize the global model of GIM-TEC star, we used Kriging method. After that, the outputs of Kriging method are used as inputs of neural network to estimate the epicenter area.

The estimation of earthquake based on ionospheric precursor cannot be done exactly and quickly because of the ionosphere is very dynamic as well as the earthquake phenomena. If the precursor analysis method to estimate the earthquake parameter is the same dynamic as earthquakes phenomena, it is possible to be realized. Neural network is an adaptive system that changes its structure to solve the problem during a learning phase. Neural network has ability to establish a relationship between an input and output space, the past data and possibility of the future, using fast calculation. Therefore, the neural network is potentially to estimate the parameter of earthquakes based on ionospheric precursor. Neural network has ability to establish the correlation of interseismic, pre-seismic and co-seismic anomalies. Neural network, which has been trained with the past seismic anomalies data will be able to analyze the new seismic anomalies data to give the possibility of the next earthquake.

A preliminary attempt was made to construct a neural network that can estimate the epicenter area of an earthquake based on ionospheric precursor. In this study, the epicenter area can be obtained by analysis of neural networks to the spread of the density anomaly curve. The outer points of the Co-Seismic anomalies, which position are closest to the plate boundaries or fault are the epicenter area. The results of this study can be used as an early warning system to minimize the victims of earthquakes.

MATERIALS AND METHODS

The layout of this study is schematically shown in Fig. 1.

The first step of this study used GIM-TEC method to calculate TEC global. The next step, we used GIM-TEC star method to filter the TEC anomalies. To localize the global model of GIM-TEC star, we used Kriging method. After that, the outputs of Kriging method are used as inputs of neural network to estimate the epicenter area.

GIM-TEC method: The GIM-TEC derived by CODE is selected. The IONEX file was downloaded from Center for Orbit Determination in Europe (CODE; ftp://ftp.unibe.ch/aiub/CODE/) to obtain the observation information, the navigation data and the DCB values of the GPS satellites and GPS reference stations. The second step is time synchronization of the observation information of the GPS reference stations. The next step is calculation of the elevation angle and azimuth angle between the individual reference stations and the satellites. After that the ionosphere pierce point was calculated using the radius of the earth as well as the altitude. The vertical TEC were determined using the mapping function as a function of the satellite altitude after the visual direction TEC was determined based on the observation data. Finally, the spherical harmonic expansion method was applied to calculated the vertical TEC corresponding to the grid of which latitude and longitude are 2.5 and 5°C, respectively (Schaer *et al*., 1998).

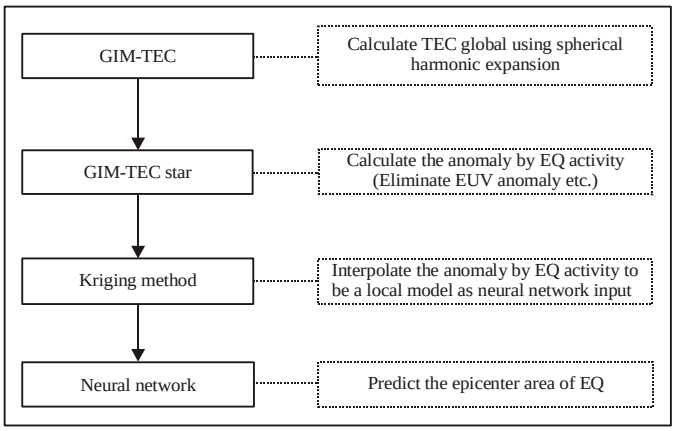

Fig. 1: Research scheme. The first step, the GIM derived by CODE is selected. The vertical TEC derived from GIM-TEC is obtained through the spherical harmonics expansion and the linear interpolation. The next step, we used GIM-TEC star method to filter the TEC anomalies. To localize the global model of GIM-TEC star, we used Kriging method. After that, the outputs of Kriging Method are used as inputs of neural network to estimate the epicenter area

GIM-TEC star method (GIM-TEC*): The TEC ionospheric models by GIM-TEC contain the specified anomalies caused by earthquake activity and the daily variation of TEC anomalies caused by solar activity. In the second step, we used GIM-TEC star method (GIM-TEC*) to filter TEC anomalies. To minimize possible confounding effects of consecutive earthquakes and properly identify the abnormal signals, we computed the mean GIM-TEC values for the previous 15 days and the corresponding standard deviation (σ) as a reference at specific times:

$$\overline{\text{GIM}-\text{TEC}}\,(t) = \frac{\sum_{i=1}^{n} \text{GIM}-\text{TEC}_i\,(t)}{n} \tag{1}$$

$$\sigma\,(t) = \sqrt{\frac{\sum_{i=1}^{n}\left(\text{GIM}-\text{TEC}_i\,(t) - \overline{\text{GIM}-\text{TEC}}\,(t)\right)^2}{n}} \tag{2}$$

Then, we derived the GIM-TEC*(t) values by the following equation (Kon *et al*., 2011):

$$\text{GIM}-\text{TEC}^*(t) = \frac{\text{GIM}-\text{TEC}(t) - \overline{\text{GIM}-\text{TEC}}\,(t)}{\sigma t} \tag{3}$$

In this study, we linearly interpolate yielding a 1-h resolution at a grid point.

Kriging method: The focus area of this research is Japan and not the whole world. Therefore, the global ionospheric TEC model of GIM-TEC star method needs to be minimized with the good interpolation method for local models that is Kriging method. In this step, we localize the global model of GIM-TEC star using Kriging method. The kriging method is the linear unbiased estimator and interpolator that the main purpose of the kriging method is to estimate a certain unknown variable (Z*) as a linear combination of the known values (Z_i) that shown in this equation:

$$Z^* = \Sigma_i\, \omega_i\, Z_i$$

where, ω_i are the weights computed by the kriging equations that are applied to each value $Z(x_i) = Z_i$. The random function Z_i belongs to the stationary random functions family in order to apply the ordinary kriging method that the mean values and the standard deviation of Z_i have to be independent of the location where the unbiased condition over the weights ($\Sigma_i\, \omega_i = 1$) is imposed. The next step, the variance is minimized with the help of the Lagrange multipliers in order to impose the unbiased condition (Orus *et al*., 2005). Previously to use the kriging method it is necessary to determine the semivariogram. This is a function that describes the spatial correlation among the data used in the interpolation, which knowledge is important, since it is used as the main input of the kriging algorithm.

Neural network method: The next step, we used the output of Kriging Method as input of neural network to estimate the epicenter area. The neural network has been developed as an analysis method of ionospheric precursor to estimate earthquake parameter. The development has included the development and modification of the structure and training algorithm to construct a neural network that can estimate the epicenter area. The layout of this method is schematically shown in Fig. 2.

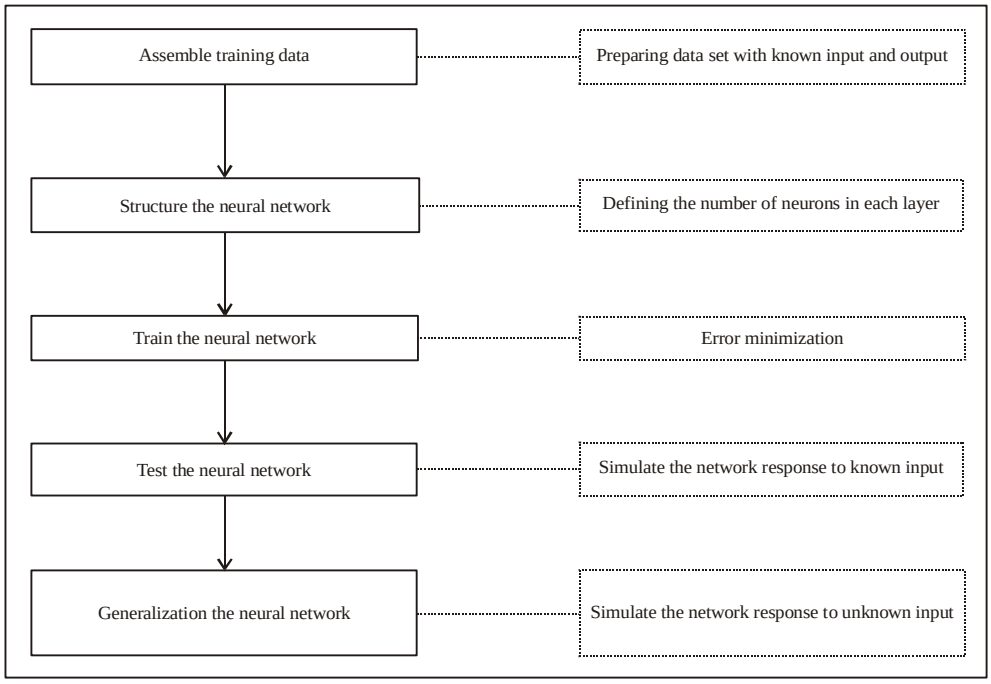

Fig. 2: Research scheme. For the first, the data of the past earthquake ionospheric anomalies in some areas (GIM-TEC star model using Kriging interpolation) were collected to prepare data set with known input and output. The second step the Neural Network was created and then we trained it with the past data. The process of initializing the weights comprises by training in order to minimize the error between the computed output and the desired output for all samples. After that The Neural Network was tested in order to simulate the network response of known input. Afterwards the neural network was tested using parts excluded from the training set. This procedure or, generalization phase calculates the model characteristics corresponding of unknown input

This study is based on application of back propagation with tan-sigmoid computing unit which allows the output data range from -1-1, so the data needs to be simplified in order to run as activation function (Sompotan *et al*., 2011). The neural network contains three layers that are an input layer, a hidden layer and an output layer (Fig. 3). There is no connection between neurons in the same layer. Connections are only between adjacent layers.

A neuron, a simple processing node, is used to calculate the output a according to an input n. The weighted (W) sum of all outputs of neurons in previous layers is the value of input n for neuron i outside of input layer. Neurons in previous layers are indicated by index j:

$$n_i = b+\Sigma_j W_{ij}\alpha_j \quad (4)$$

The value of output is calculated according to a tan-sigmoid function as follows:

$$\alpha_i = \frac{2}{1+e^{-n_i}}-1 \quad (5)$$

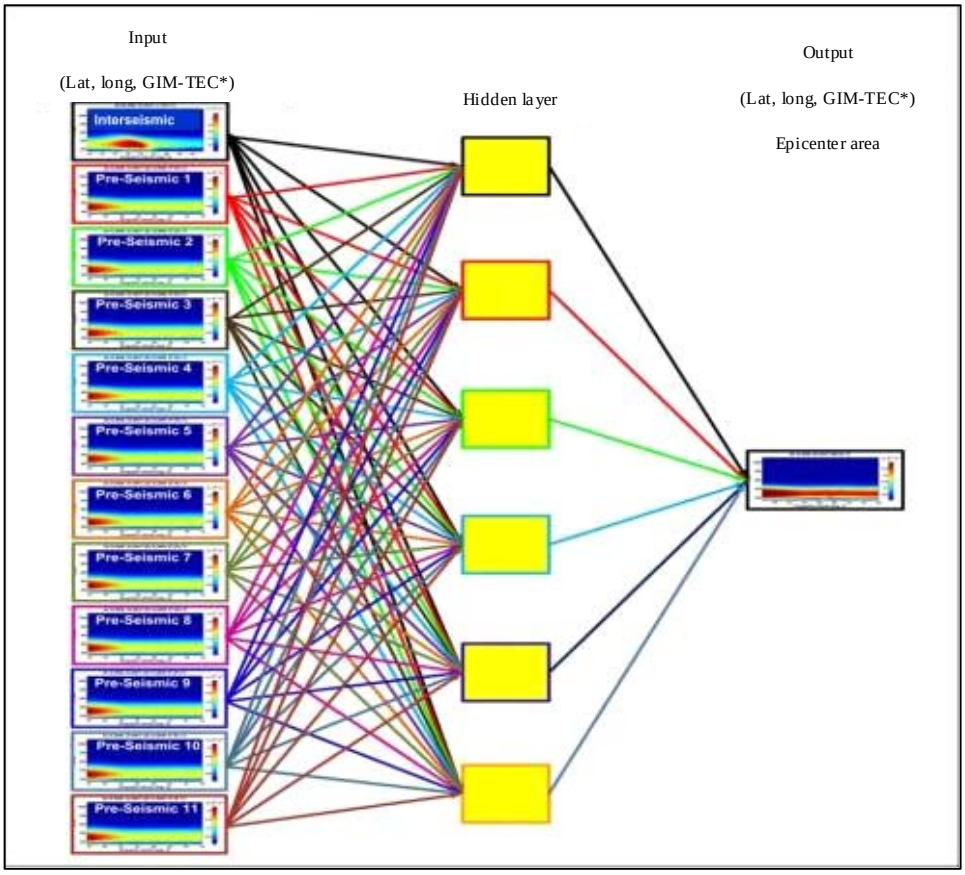

Fig. 3: Neural network structure. The feed-forward back propagation neural network consists of three layers that are input, hidden layer and output. The information flows from input to hidden layer and then through output. The latitude and longitude of interseismic and Pre-seismic (GIM-TEC star model using Kriging interpolation) are used as input to find latitude and longitude of Co-seismic. The outer points of the Co-Seismic anomalies which position are closest to the plate boundaries or fault are the epicenter area

The epicenter area can be obtained by analysis of neural networks (Fig. 3) to the spread of the density anomaly curve. The outer points of the Co-Seismic anomalies, which position are closest to the plate boundaries or fault are the epicenter area.

A training process is initiated in which the structure and output function remain unchanged. The process of initializing the weights W comprises by training in order to minimize the error between the computed output and the desired output for all samples. The corresponding data sets were fed to neural network in order to train the networks. As a rule of thumb, the maximum data needed for training, testing and generalization of neural network are usually considered to be two times the number of connection between neurons. The network was trained with TRAINGDX training function. Afterwards the neural network was tested using parts excluded from the training set. This procedure or, generalization phase calculates the model characteristics corresponding to unknown input travel times. If the network can provide the right decisions on data that has not been used during the learning process, it will indicate that the neural network can estimate the

epicenter area. The performance goal for all neural network applications was set to 1e-005 (Sompotan *et al*., 2011). In other words, the generalization performance is considered accurate for different models, when this goal is achieved.

RESULTS AND DISCUSSION

In this study, The GIM-TEC method was used to model the combined anomalies due to seismic activity and EUV, which was then filtered by the GIM-TEC star method to obtain the specific anomaly due to earthquake activity. The global model of TEC anomaly was then interpolated using the good method for local interpolation that is Kriging method to localize the area of anomaly associated with the position of the epicenter area appropriate to the focus area of this study. The local model of the ionosphere precursor covers the whole territory of Japan (30°-45° LU, 125°-155° BT). The model was then analyzed with the neural network to estimate the epicenter area (≈2,5°×5°).

The results of GIM-TEC star models with Kriging interpolation for M6.1 earthquake that occurred on August 10, 2009 (Fig. 4) show the changes in ionosphere density where the ionospheric precursors anomaly appeared 5 days before the earthquake precisely at 12.00 UT on August 05, 2009. This result confirms the previous studies that the changes in ionosphere density may be due to the inflow of energy from the earth and then propagated upward, which perturb ionosphere (Gwal *et al*., 2011). From the anomaly, the position of the epicenter was visible point on the edge or outer portion of the anomaly. This result confirms the explanation of Freund's laboratory experiments (Freund *et al*., 2006) that the positive ions that recombine in the ionosphere

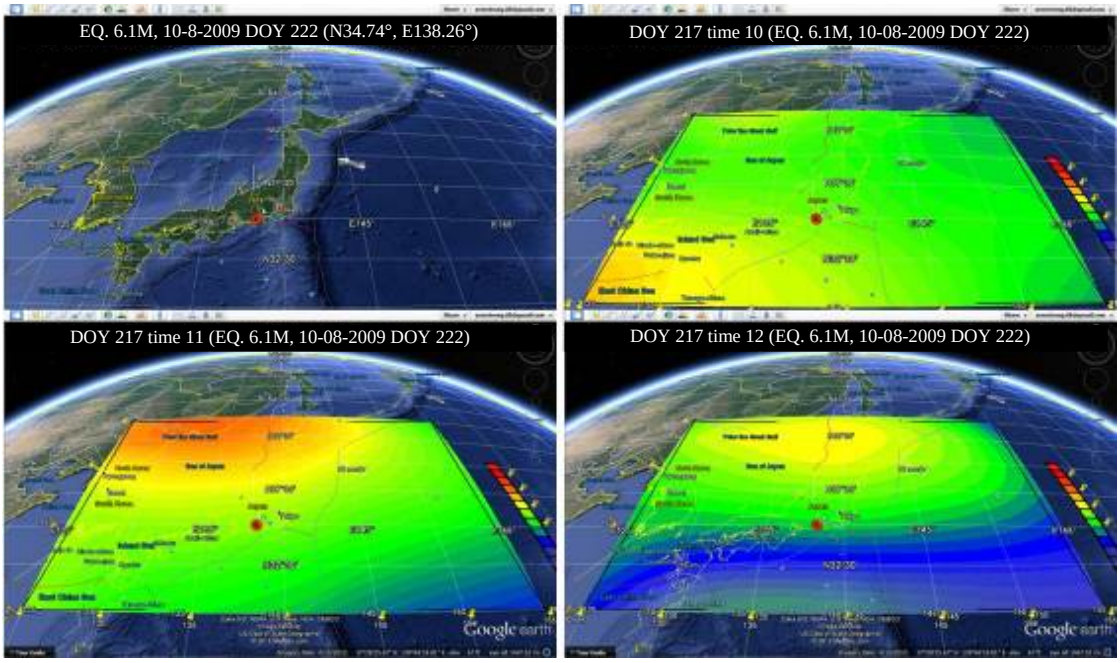

Fig. 4: GIM-TEC star model using Kriging Interpolation for M6.1 earthquake that occurred on August 10, 2009 show that the ionospheric precursors anomaly appeared 5 days before the earthquake precisely at 12.00 UT on August 05, 2009. From the anomaly, the position of the epicenter was visible point on the edge or outer portion of the anomaly

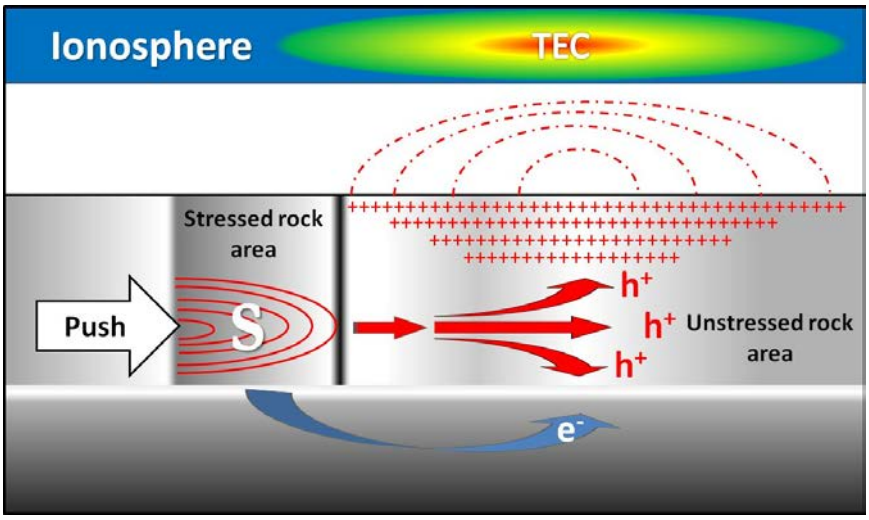

Fig. 5: Positive ions in the area of earthquake activity (stressed rock area) through the boundary into the unstressed rock area. It causes, the positive ions in the unstressed rock area were accumulated, so that the ions up to the surface towards the ionosphere. In the ionosphere, the ions recombine neutral atoms to form many charged particles. It cause, the electron density has been changed that shown in the form of an anomaly. The boundary of the unstressed and stressed rock area below the earth's surface is projected in the ionosphere in the form of the field of high and low density limits of TEC anomaly that its position adjacent to the epicenter

and change the electron density, were up from the surface of the unstressed rock area, so that the appearance of anomalies surrounding the epicenter point were low density. This is due to the ions in the area of earthquake activity (stressed rock area) through the boundary into the unstressed rock area. It causes, the positive ions in the unstressed rock area were accumulated so that the ions up to the surface towards the ionosphere. In the ionosphere, the ions recombine neutral atoms to form many charged particles. It cause, the electron density has been changed that shown in the form of an anomaly. The boundary of the unstressed and stressed rock area below the earth's surface is projected in the ionosphere in the form of the field of high and low density limits of TEC anomaly that its position adjacent to the epicenter (Fig. 5).

The results of GIM-TEC star models with Kriging interpolation for M6.6 earthquake that occurred on July 16, 2007 (Fig. 6) shows that the ionospheric precursors anomaly appeared 5 days before the earthquake precisely at 12.00 UT on July 11, 2007. This result confirms the previous studies suggestions, that the observations of daytime and nighttime TEC variations can be used as precursors (Kuo *et al*., 2011). From the anomaly, the position of the epicenter was located between areas of high and low density anomaly. It also confirms the previous explanation that the boundary of the unstressed and stressed rock area below the earth's surface is projected in the ionosphere in the form of the boundary of high and low density of TEC anomaly that its position adjacent to the epicenter.

The results of GIM-TEC star models with Kriging interpolation for M6.3 earthquake that occurred on December 20, 2008 (Fig. 7) shows that the ionospheric precursors anomaly appeared

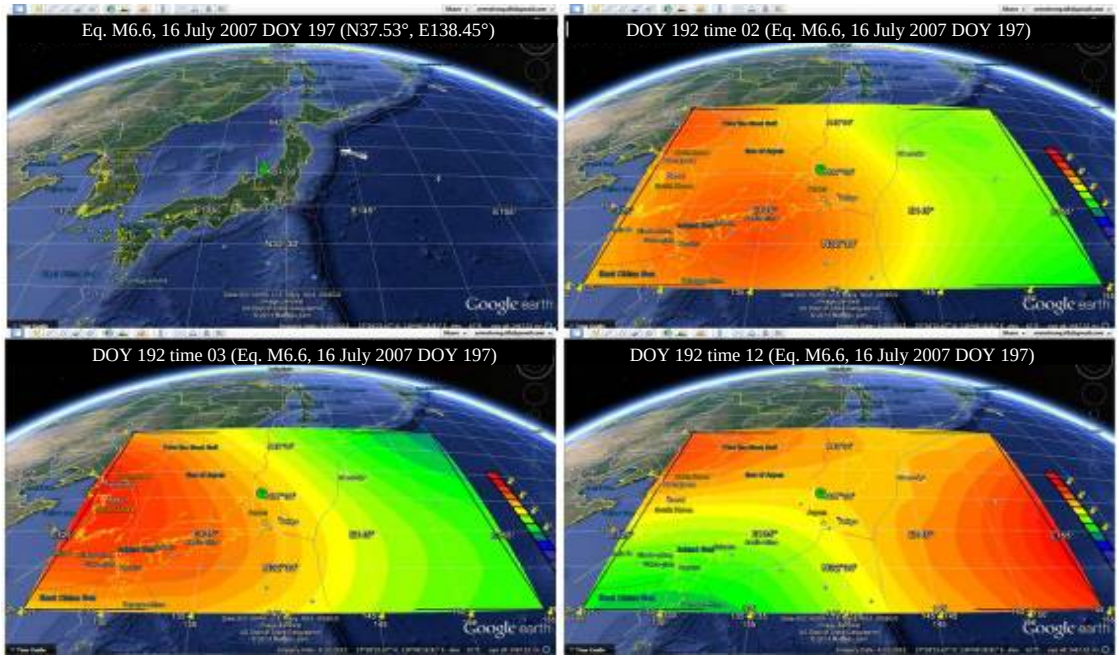

Fig. 6: GIM-TEC star models using Kriging interpolation for M6.6 earthquake that occurred on July 16, 2007 shows that the ionospheric precursors anomaly appeared 5 days before the earthquake precisely at 12.00 UT on July 11, 2007. From the anomaly, the position of the epicenter was located between areas of high and low density anomaly

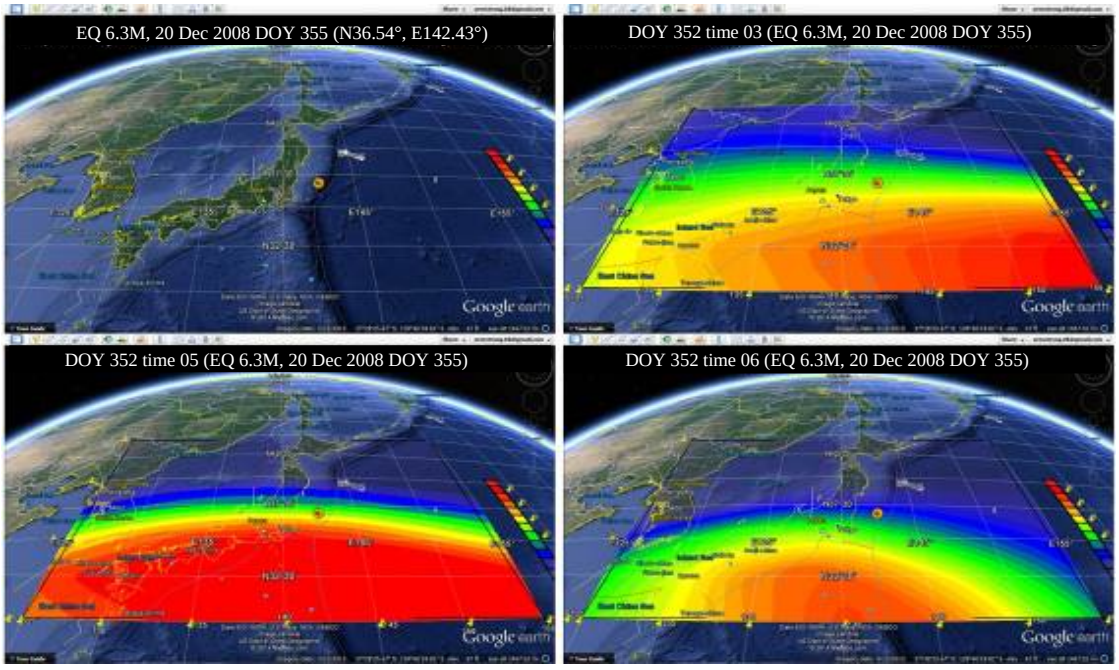

Fig. 7: GIM-TEC star model using Kriging interpolation for M6.3 earthquake that occurred on December 20, 2008 shows that the ionospheric precursors anomaly appeared 3 days before the earthquake precisely at 03.00 UT on December 17, 2008. From the anomaly, the position of the epicenter was visible point on the edge or outer portion of the anomaly

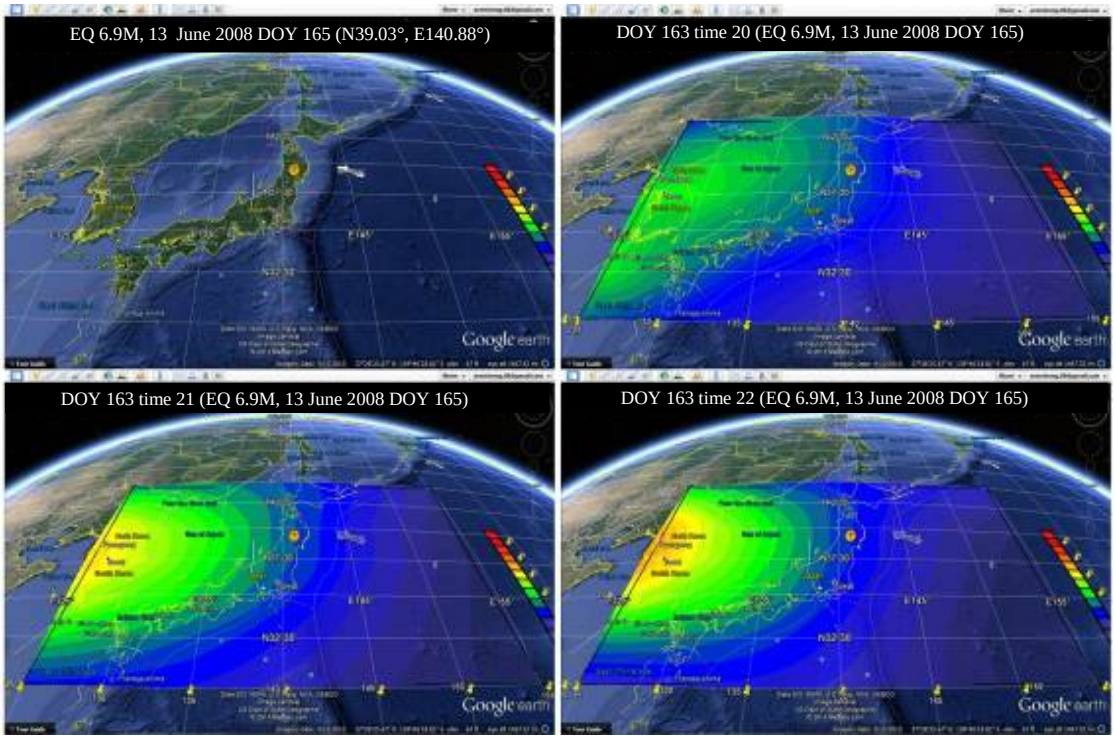

Fig. 8: GIM-TEC star models with Kriging interpolation for M6.9 earthquake that occurred on June 13, 2008 show that the ionospheric precursors anomaly appeared 2 days before the earthquake precisely at 21.00 UT on June 11, 2008. From the anomaly, the position of the epicenter was visible point on the edge or outer portion of the anomaly

3 days before the earthquake precisely at 03.00 UT on December 17, 2008. The results of GIM-TEC star models with Kriging interpolation for M6.9 earthquake that occurred on June 13, 2008 (Fig. 8) shows that the ionospheric precursors anomaly appeared 2 days before the earthquake precisely at 21.00 UT on June 11, 2008. From two models, the position of the epicenter was visible point on the edge or outer portion of the anomaly. This result confirms the previous explanation that the positive ions that recombine in the ionosphere and change the electron density, were up from the surface of the unstressed rock area, so that the appearance of anomalies surrounding the epicenter point were low density. This is because the ions in the area of earthquake activity through the boundary into the unstressed rock area. It causes, the positive ions in the unstressed rock area were accumulated, so that the ions up to the surface towards the ionosphere. In the ionosphere, the ions recombine neutral atoms to form many charged particles. It cause, the electron density has been changed that shown in the form of an anomaly. The boundary of the unstressed and the stressed rock area below the earth's surface is projected in the ionosphere in the form of the boundary of high and low density of TEC anomaly that its position adjacent to the epicenter.

The results of GIM-TEC star models with Kriging interpolation for M6.4 earthquake that occurred on June 05, 2009 (Fig. 9) show that the ionospheric precursors anomaly appeared 3 days

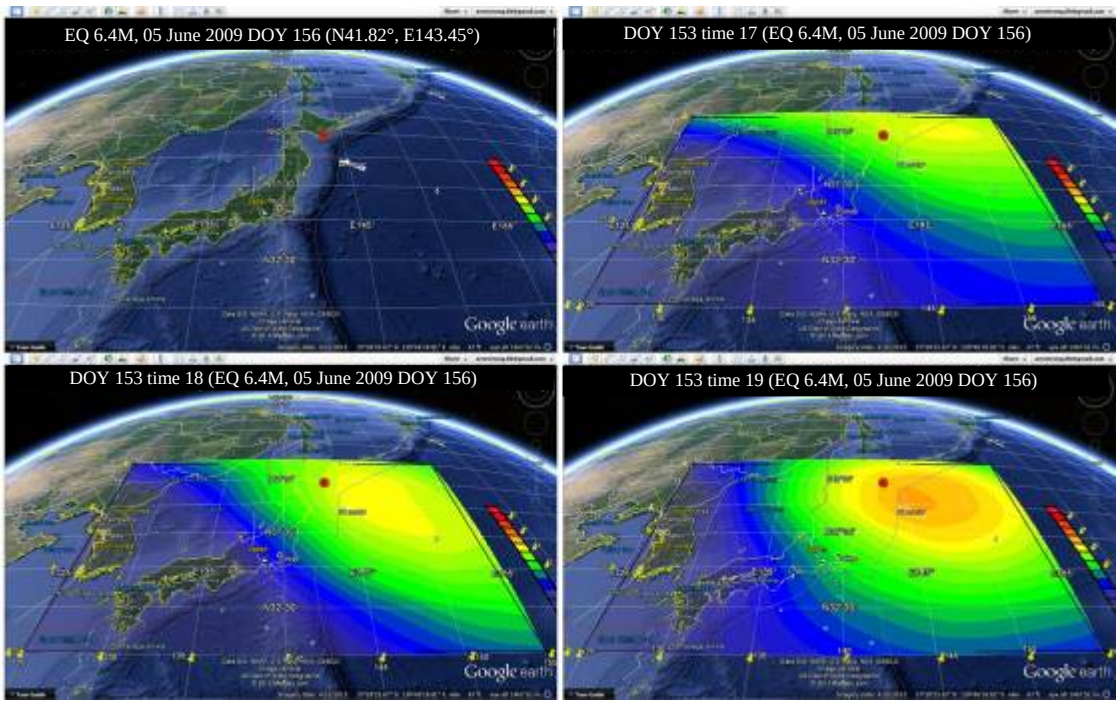

Fig. 9:GIM-TEC star models using Kriging interpolation for M6.4 earthquake that occurred on June 05, 2009 shows that the ionospheric precursors anomaly appeared 3 days before the earthquake precisely at 19.00 UT on June 02, 2009. From the anomaly, the position of the epicenter was located between areas of high and low density anomaly

before the earthquake precisely at 19.00 UT on June 02, 2009. From the anomaly, the position of the epicenter was located between areas of high and low density anomaly. It also confirms the previous explanation that the boundary of the unstressed and stressed rock area below the earth's surface is projected in the ionosphere in the form of the boundary of high and low density of TEC anomaly that its position adjacent to the epicenter.

The conclusion of five models of the ionosphere anomalies due to seismic activity show that significant TEC anomalies would accompany prior to larger earthquakes around Japan. These results confirm the previous results that show the existence of the positive TEC anomaly 2-5 days prior to the large earthquakes in mid-latitude, especially around Japan (Kon *et al*., 2011; Zakharenkova *et al*., 2007). These results look like different with Liu's reports that show significance of negative TEC anomalies before large earthquakes in Taiwan (Liu *et al*., 2004). The difference may be caused by the geomagnetic latitude dependence. These five models show that the epicenter position is at the edge of the less developed anomalies, whereas for the growing anomalies, the epicenter is always located near the boundary of high and low density of TEC anomalies (Fig. 10).

Five models of neural network showed the epicenter area (≈2,5°×5°), where the epicenter point is always at the edge of the epicenter area. This result shows the accuracy of the neural network to estimate the epicenter area.

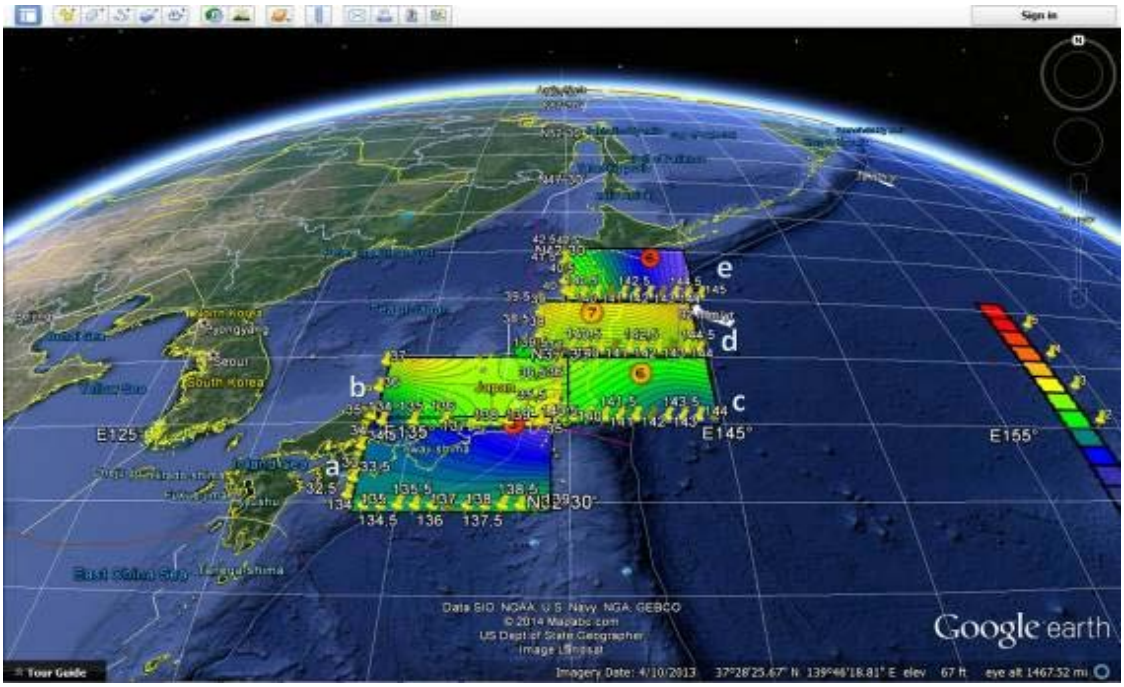

Fig. 10: Neural network model of 5 big earthquake occurred in Japan from 1998-2010, (a) Neural network model of 5 days before M6.1 earthquake occurred on August 10, 2009, (b) Neural network model of 5 days before M6.6 earthquake occurred on July 16, 2007, (c) Neural network model of 3 days before M6.3 earthquake occurred on December 20, 2008, (d) Neural network model of 2 days before M6.9 earthquake occurred on June 13, 2008 and (e) Neural network model of 3 days before M6.6 earthquake occurred on June 05, 2009. Five models of neural network show that the epicenter is always at the edge of the epicenter area

CONCLUSION

The GIM-TEC star method is useful to determine ionospheric anomalies associated with large earthquakes as ionospheric precursor data. The Kriging method is good to interpolate GIM-TEC star data as input data of neural networks to estimate the epicenter area. Five models of the ionospheric precursor in this research show that the epicenter position is at the edge of the less developed anomalies, whereas for the growing anomalies, the epicenter is always located near the boundary of high and low density of TEC anomalies. This result confirms the theory of the relationship between the seismic activities beneath the earth's surface with the changed of electron density in the ionosphere, where the boundary of the unstressed and stressed rock area below the earth's surface is projected in the ionosphere in the form of the boundary of high and low density of TEC anomaly. Neural network models show the epicenter area (≈2,5°×5°), where the epicenter point is always at the edge of the epicenter area. The success of the neural network to estimate the epicenter area is a new stage for development of the earthquake prediction method.

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