Global Noise Elimination from ELF Band Electromagnetic Signals by Independent Component Analysis

Motoaki Mouri[1], Arao Funase[1,2], Andrzej Cichocki[2], Ichi Takumi[1], Hiroshi Yasukawa[3], and Masayasu Hata[4]

[1] Nagoya Institute of Technology, Graduate School of Engineering, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan
[2] RIKEN BSI, Laboratory for Advanced Brain Signal Processing 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[3] Aichi Prefectural University, Department of Applied Information Technology, Nagakute-cho, Aichi-gun, Aichi, 480-1198, Japan
[4] Chubu University, Matsumoto-cho, Kasugai-city, Aichi, 487-8501, Japan

Abstract. Anomalous radiations of environmental electromagnetic (EM) waves are reported as the portents of earthquakes. We have been measuring the Extremely Low Frequency (ELF) range all over Japan in order to predict earthquakes. The observed signals contain global noise which has stronger power than local signals. Therefore, global noise distorts the results of earthquake-prediction. In order to overcome this distortion, it is necessary to eliminate global noises from the observed signals. In this paper, we propose a method of global noise elimination by Independent Component Analysis (ICA) and evaluate the effectiveness of this method.

1 Introduction

Japan is a country where earthquakes occur frequently, and has received extensive damage from huge earthquakes. The occurrence of giant earthquakes will be worried about in the near future, too. The Earthquake Research Committee of Japan reported in 2001 that the occurrence possibility of very giant earthquakes of Nankai and Tohnankai earthquakes (magnitude over 8) within 30 years reached between 40% and 50% [1].

It is urgent task to achieve an accurate earthquake prediction to help minimize the damages caused by earthquakes. Anomalous radiations of environmental electromagnetic (EM) waves have been reported as the portent to be the earth's crustal motion including earthquakes [2],[3]. We have been measuring Extremely Low Frequency (ELF) magnetic fields all over Japan since 1989, in order to try to predict earthquakes.

However, the EM radiation data contains signals other than the earth's crustal motion. The recorded data are distorted by noise. It is important to remove noise as a preprocessing step for earthquake prediction.

J. Rosca et al. (Eds.): ICA 2006, LNCS 3889, pp. 384–391, 2006.

In the present paper, we propose the method for noise elimination by Independent Component Analysis (ICA) to extract the anomalous EM radiation data more accurately, and evaluate effectiveness of this method.

2 Outline of ELF Band Observation of EM Radiation Data

We have been observing power of 223Hz in EM radiation in about 40 places around the country (Fig.1). This frequency band has been a little influenced by solar activity and the global environment (Fig.2). Observation systems have three axial loop antennas with east-west, north-south, and vertical ranges. Observation devices sample EM levels and average the signals over 6-second periods. These data are transported to our institute on the Public Telephone Network.

The observed signals are composed of the local signals and the global noise. The local signals are caused by regional EM radiation; for example, the earth's

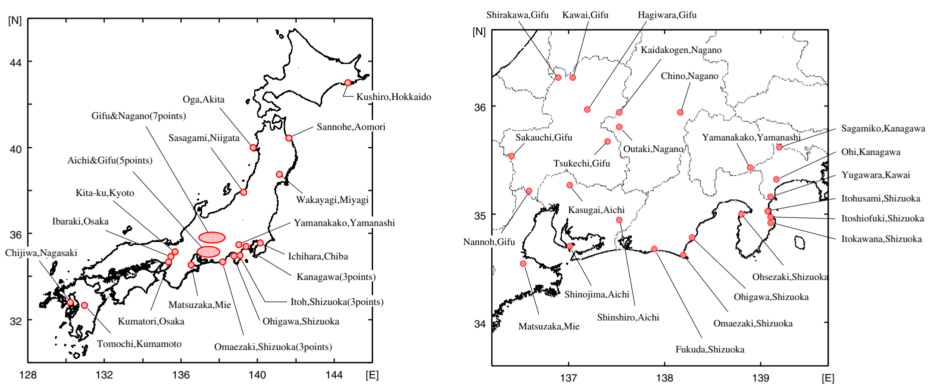

Fig. 1. Arrangement of observation points

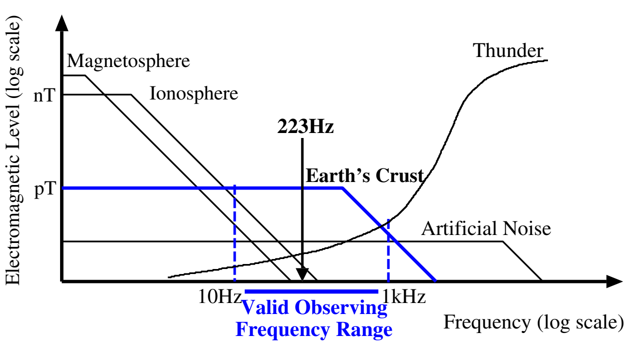

Fig. 2. EM radiation levels of each source

crustal motion, thunderclouds, or other interferences. The local signals in each observation point have different values. The global noise is caused by global EM radiation; for example, heat thunderclouds in lower latitudes, the solar activity, and many others. The radiation from southern heat thunderclouds is influenced by the ionosphere in the spread process. The global noise has a circadian rhythm because the ionosphere changes in a day by the effect of the sun. The global noises in each observation point have almost same values because the global noise is recorded all over the observation point.

The influence of the global noise is especially stronger than many other noises. Eliminating global noise (or extracting local signals) is important as preprocessing of earthquake prediction. The sources of each EM radiations are mutually independent. We estimate the global noise by separating observed signals using ICA next to remove it from the observed data.

3 Method of Global Noise Elimination Using ICA

To estimate the global noise and the local signals accurately, we must analyze the data from all the observation points. However, it is unrealistic that all the observed signals are processed because the number of all source signals is over the number of separable signals. It is necessary to decrease the number of source signals contained in the observed signals. Therefore, we approximately estimate the components from the good signals recorded several observation points. In that case, note that it is difficult to directly separate the global noise and the local signals from all observed signals. We solve this problem by the idea of subtracting global noise from the observed signals.

Procedures of global noise elimination by NG-FICA are as follow.

1. Selecting several good observation points from all observation points.
2. Estimating independent components by ICA from the observed signals recorded in the selected observation points.
3. Selecting a global noise component from among the estimated signals.
4. Calculating the amplitudes of the global noises corresponding to each observed signals.
5. Estimating the enhanced local signals by subtracting each global noises from the observed signals.

3.1 Selecting Observation Points

Since the global noise is large, we must select signals similar to global noise. Global noise has a strong correlation with all the observed signals because global noise is the main component of the observed signals. Therefore, we establish the observed signals priority list in the descending order of following expression.

$$|r_{xx_j}| = \left| \sum_i \frac{E\left[(x_i - \overline{x_i})(x_j - \overline{x_j})\right]}{\sqrt{E\left[(x_i - \overline{x_i})^2\right]}\sqrt{E\left[(x_j - \overline{x_j})^2\right]}} \right| \tag{1}$$

where $|r_{xx_j}|$ is the absolute of sum correlation coefficient between x_j of all the observed signals. We select observation points by hand based on this priority. Experience shows that selecting around 6 observed signals give the best results.

3.2 Source Separation

In ICA, various algorithms are proposed with a focus on assumption independence. The algorithm adopted by this paper is NG-FICA (Natural Gradient - Flexible ICA) [4]. NG-FICA uses kurtosis as independency criterion and uses natural gradient for the learning algorithm. This algorithm is implemented as a part of the package, "ICALAB for signal processing" [5].

In NG-FICA, input data of vector $\boldsymbol{x}$ is applied sphering (prewhitening) as a linear transformation.

$$\boldsymbol{z} = \boldsymbol{Q} \cdot (\boldsymbol{x} - \overline{\boldsymbol{x}}), \quad \boldsymbol{Q} = \left\{ E\left[(\boldsymbol{x} - \overline{\boldsymbol{x}})(\boldsymbol{x} - \overline{\boldsymbol{x}})^T \right] \right\}^{-1/2} \tag{2}$$

where vector $\overline{\boldsymbol{x}}$ is the mean of $\boldsymbol{x}$. $\boldsymbol{Q}$ is calculated by Principal Component Analysis (PCA). The presumption method uses vector $\boldsymbol{z}$ as the input data.

The update nonlinear functions are based on the following expressions.

$$\Delta \boldsymbol{W} = \eta \left(\boldsymbol{I} - E\left[\boldsymbol{y}\boldsymbol{y}^{\boldsymbol{T}} - (\boldsymbol{\varphi}\boldsymbol{y}^{\boldsymbol{T}} + \boldsymbol{y}\boldsymbol{\varphi}^{\boldsymbol{T}}) \right] \right) \boldsymbol{W} \tag{3}$$

$$\varphi_i = |y_i|^{\alpha_i - 1} \mathrm{sgn}(y_i) \quad (i = 1, 2, \cdots, n) \tag{4}$$

where η is the appropriate learning rate (constant number), $\boldsymbol{y}$ is the temporary estimated signal ($= \boldsymbol{W}\boldsymbol{z}$), and $\mathrm{sgn}(y_i)$ is the signum function of y_i. Gaussian exponent α_i is decided based on the kurtosis κ_i $\left(= \frac{E[{y_i}^4]}{\{E[{y_i}^2]\}^2} - 3 \right)$ of y_i; α_i is decided near 0 if κ_i is big, but α_i is decided 4 if κ_i is small. Finally, the independent components $\boldsymbol{y}$ are estimated as:

$$\boldsymbol{y} = \boldsymbol{W}\boldsymbol{Q}\boldsymbol{x}. \tag{5}$$

3.3 Selection of Global Noise Component

By the ICA, a global noise is extracted as one of the estimated signals. However, the estimated signals come out in a random fashion due the permutation ambiguity. Therefore, it is necessary to identify the global noise component from the estimated signals. We select one component y_g which has a maximal value by the following expression.

$$|r_{xy_g}| = \left| \sum_i \frac{E\left[(x_i - \overline{x_i})(y_g - \overline{y_g}) \right]}{\sqrt{E\left[(x_i - \overline{x_i})^2 \right]} \sqrt{E\left[(y_g - \overline{y_g})^2 \right]}} \right| \tag{6}$$

3.4 Calculation of Local Signals

The amplitudes of the estimated global noise component and the actual global noise are not the same, because the estimated components may have arbitrary scale factors. Therefore, it is necessary to adjust the amplitude of the global noise component for each observed signals. When the amplitude of global noise component was appropriately weighted, the mean square error (MSE) between the observed signal and global noise component would be minimized. The MSE between the observed signal x_j and the weighted global noise component $b_j y_g$ is calculated as $E[((x_j - \overline{x_j}) - b_j(y_g - \overline{y_g}))^2]$. The appropriately weight b_j which gives the least MSE, is obtained by the following expression:

$$b_j = \frac{E\left[(x_j - \overline{x_j})(y_g - \overline{y_g})\right]}{E\left[(y_g - \overline{y_g})^2\right]} \tag{7}$$

Using vector $\boldsymbol{b}$ constructed from b_j, local signals are calculated as:

$$\boldsymbol{x_L} = \boldsymbol{x} - \boldsymbol{b} y_g. \tag{8}$$

4 Sample Case of Global Noise Elimination

4.1 Processing Data

An anomalous signal was observed for two days starting from January 4, 2001, at the observation point in Nannoh, Gifu Prefecture (call Nannoh after this). We tried to obtain local signals about this day by eliminating the global noise by the proposed method. The recorded signals from Nannoh might have anomalous signals related to the earthquake, because an earthquake (magnitude 4.8) occurred in Tohnoh, Gifu Prefecture on January 6.

4.2 Results

Fig.3 and Fig.4 show the signals that were observed in Kawai, Gifu Prefecture (call Kawai after this) and Nannoh on January 4, 2001. The vertical axes show the EM levels (pT$\sqrt{\text{Hz}}$) and the horizontal axes indicate the time courses (hours). Both of these signals have high amplitudes in nighttime and have low amplitudes in daytime. Changes like these are mostly observed for all observation points throughout the year. In other words, these signals have global noises like a circadian rhythm.

Fig.5 shows one of the separated components from the observed signals by the ICA algorithm [4],[5]. The vertical axis shows the amplitude of estimated signal and the horizon axis indicates the time course. This component has global noise features, because it has a strong correlation to each observed signal (Table1). and this signal has a high amplitude in nighttime and low in daytime. Therefore, this component is selected as global noise.

The local signals of Kawai and Nannoh are shown in Fig.6 and Fig.7. Their axes are the same as those in Fig.3. These signals do not have circadian rhythm like the raw observed signals. In addition, the local signal in Nannoh has clearly anomalous signals since about 6 a.m. From these results, it is evident that the proposed method can eliminate global noise from observed signals.

Table 1. Coefficients of observed signals and global noise (from Fig.5)

Kushiro, Hokkaido	—
Sannohe, Aomori	-0.82223442
Oga, Akita	-0.83796101
Wakayagi, Miyagi	-0.94404159
Ichihara, Chiba	0.05078791
Sasagami, Niigata	-0.87207873
Yugawara, Kanagawa	-0.81599893
Sagamiko, Kanagawa	-0.64286322
Yamanakako, Yamanashi	-0.80240557
ItohUsami, Shizuoka	-0.95962168
ItohShiofuki, Shizuoka	-0.75264114
ItohKawana, Shizuoka	-0.81597344
Oosezaki, Shizuoka	-0.80150511
Omaezaki, Shizuoka	-0.64272118
Ohtaki, Nagano	-0.94814968
KaidaKougen, Nagano	-0.89521541
Kawai, Gifu	-0.79121470
Shirakawa, Gifu	-0.84631972
Hagiwara, Gifu	-0.88124143
Tsukechi, Gifu	-0.80214358
Sakauchi, Gifu	-0.94820738
Nannoh, Gifu	-0.62218944
Kasugai, Aichi	—
Shinojima, Aichi	—
Matsuzaka, Mie	-0.53462919
Kitaku, Kyoto	-0.92216432
Kumatori, Osaka	-0.71976842
Ibaraki, Osaka	-0.90787270
Chijiwa, Nagasaki	-0.88037934
Tomochi, Kumamoto	-0.81322911
Average	-0.784147501

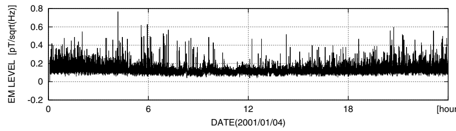

Fig. 3. Observed signal (January 4, 2001 at Kawai, Gifu)

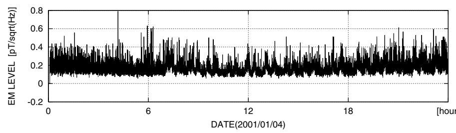

Fig. 4. Observed signal (January 4, 2001 at Nannoh, Gifu)

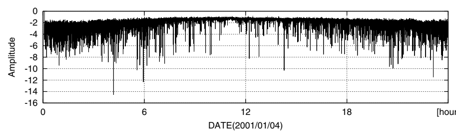

Fig. 5. Global noise component

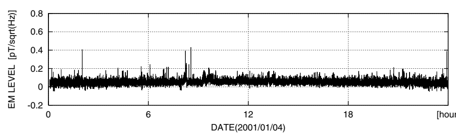

Fig. 6. Local signal (January 4, 2001 at Kawai, Gifu)

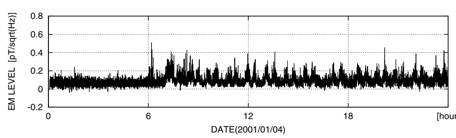

Fig. 7. Local signal (January 4, 2001 at Nannoh, Gifu)

5 Effectiveness of ICA in Global Noise Elimination

In above results, we confirmed that the proposed method can remove the global noise from observed signals. In this section, we confirm how well this method can remove the global noise compared with an observed signal and a signal processed by the conventional method. In order to compare results, we focus on frequency of processed signals because the period of global noises is 1 day. The conventional method is similar to the proposed method, but uses PCA instead of ICA.

5.1 Procedure and Processing Data

1. k = 1.
2. Extracting observed signals from k day to (k+3) day.
3. Computing local signals from the extracted observed signals by the proposed and conventional methods.
4. Normalizing the observed and local signals.
5. Applying the Blackman window to each signal.
6. Processing the DFT of each signal.
7. k = k+1, and go to step 2.

The processing data are observed from Kawai, Gifu for January 2001. These data did not have any anomalous signals.

5.2 Results

Fig.8 shows the amplitude spectrums of the observed signals from Kawai. The vertical axis shows the amplitude spectrums and the horizon axis indicates the

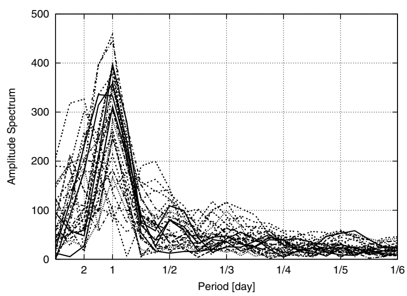

Fig. 8. Amplitude spectrum of observed signal

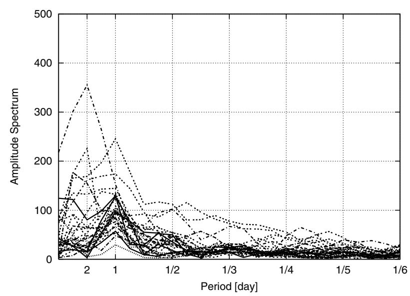

Fig. 9. Amplitude spectrum of local signal using conventional method

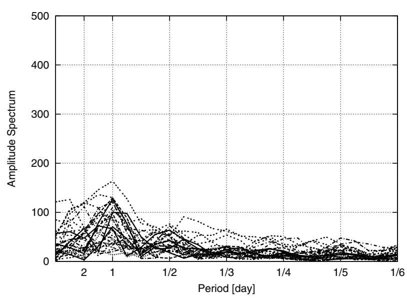

Fig. 10. Amplitude spectrum of local signal using proposed method

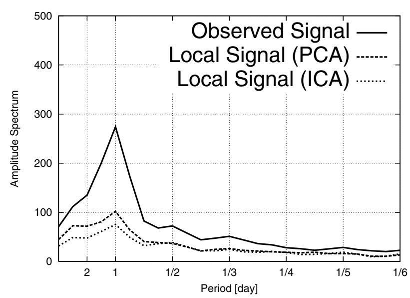

Fig. 11. Average amplitude spectrum of each signal

period. The plotted processing results during one month (28 lines) are overlapping. From this figure, all observed signals have the peak at 1 day. The main factor of these peaks is the circadian rhythm of the global noise.

Fig.9 and 10 show the amplitude spectrums of the local signals calculated by the conventional method (Fig.9) and the proposed method (Fig.10). By the conventional method, a few results have a large value at 1 day. Global noise cannot be perfectly eliminated. On the other hand, proposed method succeeds at elimination global noises from all data.

Fig.11 shows the average amplitude spectrums of each signals shown in Fig.8,9, and 10. The shrinkage of the circadian rhythm in the case of the proposed method is smaller than in the case of conventional method.

Thus, The proposed method is more effective in eliminating global noise than the conventional method.

6 Conclusion

In this paper, we proposed a global noise elimination method by ICA. The proposed method actually calculated local signals in sample case. Compared with the conventional method by PCA, the proposed method can eliminate global noise more effectively.

In future works, we plan to automatically select observation points. The current selection method involves a heavy workload because it needs trial and error. Investigation of applying alternative ICA algorithms is also important, because NG-FICA sometimes does not provide good results for extracting global noise. It is necessary to modify a preprocessing and/or apply more robust ICA algorithms. Moreover, we will verify the effectiveness of the proposed method by anomalous detection and source estimation.

Acknowledgment

This research was supported in part by JSPS for the Grant-in-Aid for Scientific Research (A)17206042.

References

1. The Headquarters for Earthquake Research Promotion Earthquake Research Committee, “Long-term evaluations of Earthquake on Nankai Trough (in Japanese)”, 8th Conference of Subcommittee for Instituting Results in Society (2001).
2. Gokhberg,M.B., V.A.Morgunov, T.Yoshino and I.Tomizawa, “Experimental measurements of EM emissions possibly related to earthquakes in Japan”, J.Geophys.Res., 87, pp.7824-7829, (1982).
3. Edit by M. Hayakawa and Y. Fujisawa “EM phenomena related to earthquake prediction”, Terra Scientific(TERAPUB), Tokyo, (1994).
4. S. Choi, A. Cichocki, and S. Amari, “Flexible independent component analysis”, Journal of VLSI Signal Processing, Vol.26, No.1/2, pp.25-38, (2000).
5. A. Cichocki, S. Amari, K. Siwek, T. Tanaka, et al., ICALAB toolboxes [available online at http://www.bsp.brain.riken.jp/ICALAB/]