GLOBAL SIGNAL ELIMINATION FROM ELF BAND ELECTROMAGNETIC SIGNALS BY INDEPENDENT COMPONENT ANALYSIS

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ABSTRACT

Anomalous radiations of environmental electromagnetic (EM) waves have been reported as the portents of earthquakes. Our study's goal is predicting earthquakes using EM signals. We have been measuring the Extremely Low Frequency (ELF) range all over Japan. However, the recorded data contain signals or noises unrelated to earthquakes. These signals and noises work to fail in earthquake-prediction. It is necessary to eliminate noises from observed signals in a preprocessing step. In this paper, we propose a method of global signal elimination by Independent Component Analysis (ICA) and evaluate the effectiveness of this method.

1. INTRODUCTION

Japan is one of the countries where earthquake occurs most frequently, and it 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 in order to minimize the earthquake-damages. Anomalous radiations of environmental electromagnetic (EM) waves have been reported as a precursory phenomenon of earthquake [2, 3, 4]. In order to predict earthquakes, we have been measuring Extremely Low Frequency (ELF) magnetic fields all over Japan since 1989. Our final goal is to predict earthquake using ELF magnetic field signals.

However, the recorded signals include big unwanted signals (noises), and big noises distort results of earthquake-prediction. Therefore, it is important to remove useless signals from recorded data in the preprocessing step.

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

2. INDEPENDENT COMPONENT ANALYSIS

Independent Component Analysis (ICA) is a kind of Blind Source Separation (BSS) or Blind Signal Separation. BSS is the approach taken to estimate original source signals using only the information of the observed signals. ICA is focusing attention on independency of the source signals.
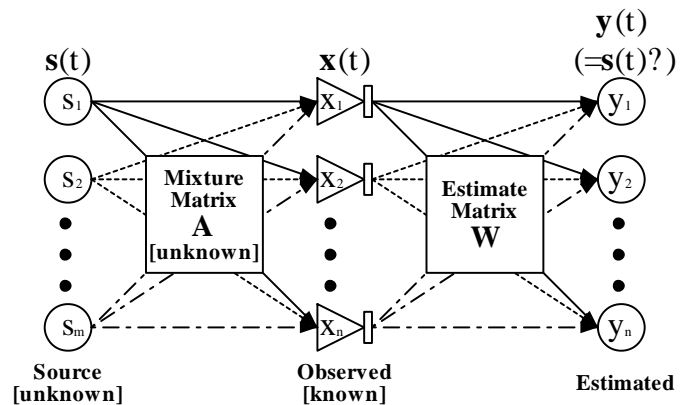

Figure 1: the signal processing model of ICA

Generally, ICA assumes a finite number of components (source signals) $\boldsymbol{s}(t) = [s_1(t), ..., s_m(t)]^T$, and each components are mutually independent. Here t is a discrete time index, m is the number of components and $[...]^T$ means transpose of row vector. These components are linear mixed through unknown $m \times n$ matrix $\boldsymbol{A}$, and n sensors observe and record the mixed signals $\boldsymbol{x}(t) = \boldsymbol{A}\boldsymbol{s}(t)$. ICA algorithm finds a separating $n \times n$ matrix $\boldsymbol{W}$ that extracts independent components from observed signals : $\boldsymbol{y}(t) = \boldsymbol{W}\boldsymbol{x}(t)$. It would be ideal if $\boldsymbol{y}(t)$ equals $\boldsymbol{s}(t)$. However, the estimated signals come out in a random fashion, and their amplitudes are not the same, because we have no or few information of sources.

The algorithm adopted by this paper is NG-FICA (Natural Gradient - Flexible ICA) [5]. 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" [7].

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

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

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.

$$\Delta \boldsymbol{W} = \eta \left(\boldsymbol{I} - E\left[\boldsymbol{yy^T} - (\boldsymbol{\varphi y^T} + \boldsymbol{y\varphi^T}) \right] \right) \boldsymbol{W} \qquad (2)$$

$$\varphi_i = |y_i|^{\alpha_i - 1} \mathrm{sgn}(y_i) \quad (i = 1, 2, \cdots, n) \qquad (3)$$

where η is the appropriate learning rate (constant number), $\boldsymbol{y}$ is the temporary estimated signal $(= \boldsymbol{Wz})$, and $\mathrm{sgn}(y_i)$ is the signum function of y_i. Gaussian exponent α_i is decided based on the kurtosis $\kappa_i \left(= \frac{E[y_i^4]}{\{E[y_i^2]\}^2} - 3 \right)$ 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:

$$\boldsymbol{y} = \boldsymbol{WQx}. \qquad (4)$$

3. 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.2). This frequency band has been a little influenced by solar activity and the global environment (Fig.3). 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 signal. The local signals are caused by regional EM radiation; for example, crustal movement, adjacent thunderclouds, or other interferences. The local signals in each observation point have different values. The global signal is caused by global EM radiation; for example, heat thunderclouds in lower latitudes, the solar activity, and many others. In the spread process, the radiations from southern heat thunderclouds are influenced by the ionosphere. The global signal has a circadian rhythm because the ionosphere changes in a day by the effect of the sun. The global signals in each observation point have almost the same values because the global signal is recorded all over the observation point.

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

4. METHOD OF GLOBAL SIGNAL ELIMINATION USING ICA

To estimate the global signal 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 EM components from good (containing few sources) signals recorded several observation points. In that case, note that it is difficult to directly separate the global signal and the local signal about all observed signals. We solve this problem by the idea of subtracting global signals from the observed signals.

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

1. Selecting several good observed data from all observation points.
2. Estimating independent components by ICA from the observed signals recorded in the selected observation points.
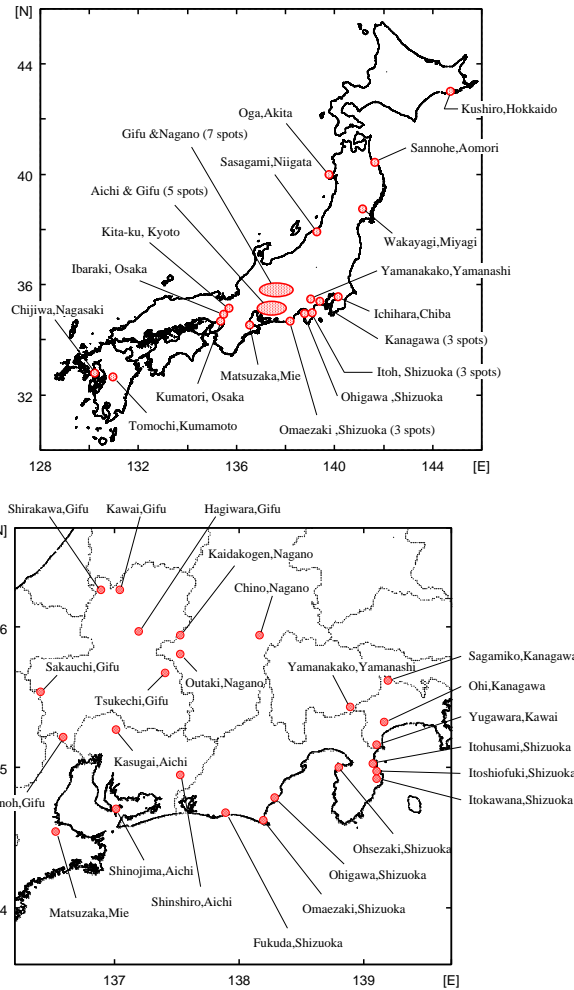

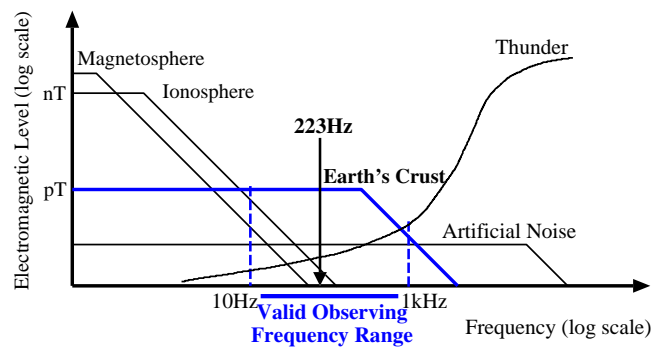Figure 2: Arrangement of observation points

Figure 3: EM radiation levels of each source

3. Selecting a global signal component from among the estimated signals.
4. Calculating the amplitudes of the global signals corresponding to each observed signals.
5. Estimating the enhanced local signals by subtracting each global signal from the observed signals.

4.1 Selecting observed data

In order to obtain a good approximation, we must select signals similar to global signal. Usually, the global signal is much larger than other signals composing the observed signal. Therefore, firstly, we roughly calculate the global signal g by following expression.

$$g = \frac{1}{N} \sum_i \frac{x_i - \overline{x_i}}{\sqrt{E\left[(x_i - \overline{x_i})^2\right]}} \qquad (5)$$

where N is number of observation points, x_i is the recorded signal in observation point i, and $\overline{x_i}$ is mean of x_i. Secondly, we establish the priority against the observed signals of following expression.

$$r_{gx_j} = \frac{E\left[g(x_j - \overline{x_j})\right]}{\sqrt{E\left[g^2\right]}\sqrt{E\left[(x_j - \overline{x_j})^2\right]}} \qquad (6)$$

where r_{gx_j} is the correlation coefficient between g and x_j. We select observation points by hand based on this priority. In this step, we substitutes analysis signals $\boldsymbol{x}$ for $\tilde{\boldsymbol{x}}$ whose dimension is r smaller than the dimension of $\boldsymbol{x}$. Experience shows the case of r is around 6 gives the best results.

4.2 Estimation of global signal component

We apply NG-FICA to $\tilde{\boldsymbol{x}}$, and obtain estimated source signals $\boldsymbol{y}$. Because a global signal is assumed one component, it extracted as one of the estimated signals. However, the number of the estimated signals is r as the same as $\tilde{\boldsymbol{x}}$, and components come out in a random fashion due the permutation ambiguity. Therefore, it is necessary to identify the global signal component from the estimated signals. We select one component y_k which has a maximal value by the following expression.

$$|r_{gy_k}| = \left| \frac{E\left[g(y_k - \overline{y_k})\right]}{\sqrt{E\left[g^2\right]}\sqrt{E\left[(y_k - \overline{y_k})^2\right]}} \right| \qquad (7)$$

4.3 Calculation of enhanced local signals

The amplitudes of the estimated global signal component and the actual global signal are not the same, because the estimated components may have arbitrary scale factors. Therefore, it is necessary to adjust the amplitude of the global signal component for each observed signals. When the amplitude of global signal component was appropriately weighted, the mean square error (MSE) between the observed signal and global signal component would be minimized. The MSE between the observed signal x_j and the weighted global signal 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:

$$b_j = \frac{E\left[(x_j - \overline{x_j})(y_g - \overline{y_g})\right]}{E\left[(y_g - \overline{y_g})^2\right]} \qquad (8)$$

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

$$\boldsymbol{x_L} = \boldsymbol{x} - \boldsymbol{b}y_g. \qquad (9)$$

5. SAMPLE CASE OF GLOBAL SIGNAL ELIMINATION

5.1 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 signal 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.

5.2 Results

Fig.4 and Fig.5 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 electromagnetic 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 a circadian rhythm like global signal.

Fig.6 shows one of the separated components from the observed signals by the ICA algorithm [5],[7]. The vertical axis shows the amplitude of estimated signal and the horizon axis indicates the time course. This component has global signal features, because it has a strong correlation to each observed signal (Table1). and this signal has high amplitude in nighttime and low in daytime. Therefore, this component is selected as global signal.

The local signals of Kawai and Nannoh are shown in Fig.7 and Fig.8. Their axes are the same as those in Fig.4. 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 signal from observed signals.

6. EFFECTIVENESS OF ICA IN GLOBAL SIGNAL ELIMINATION

In above results, we confirmed that the proposed method could remove the global signal from observed signals. In this section, we confirm how well this method can remove the global signal 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 signals is 1 day. The conventional method is similar to the proposed method, but uses PCA instead of ICA.

6.1 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.

6.2 Results

Fig.9 shows the amplitude spectrums of the observed signals from Kawai. The vertical axis shows the amplitude spectrums and the horizon axis indicates the 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 signal.

Fig.10 and 11 show the amplitude spectrums of the local signals calculated by the conventional method (Fig.10) and the proposed method (Fig.11). By the conventional method, a few results have a large value at 1 day. Global signals
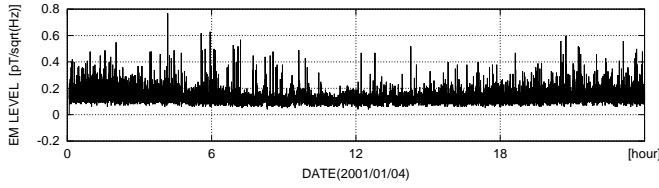
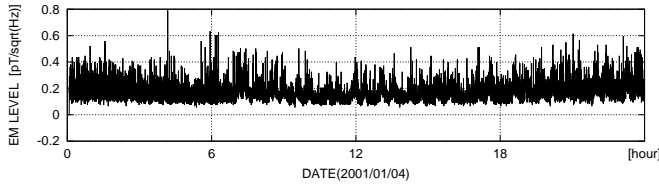Figure 4: Observed signal (January 4, 2001 at Kawai)
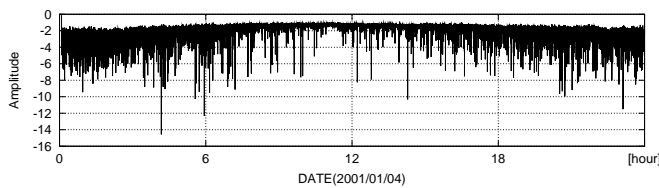

Figure 5: Observed signal (January 4, 2001 at Nannoh)

Figure 6: Global signal component

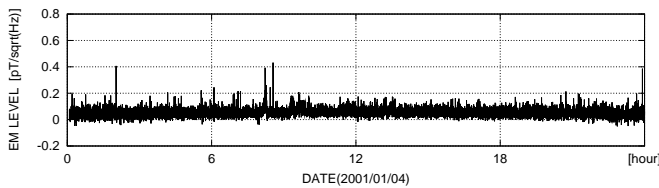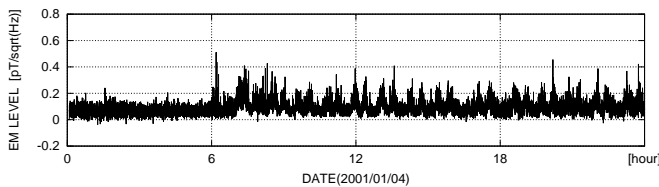

Figure 7: Local signal (January 4, 2001 at Kawai)

Figure 8: Local signal (January 4, 2001 at Nannoh)

Table 1: Coefficients of observed signals and global signal (Figure 6)

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
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

cannot be perfectly eliminated. On the other hand, proposed method succeeds at elimination global signals from all data.

Fig.12 shows the average amplitude spectrums of each signal shown in Fig.9,10, and 11. The amplitude of the circadian rhythm in the case of the proposed method is lower than in the case of conventional method. Moreover, in period shorter than half a day, both local signals have almost same amplitude. It means that the proposed method does not shrink signals other than circadian rhythm (or global signal) components.

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

7. CONCLUSION

In this paper, we proposed a global signal 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 signal 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 signal. 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.
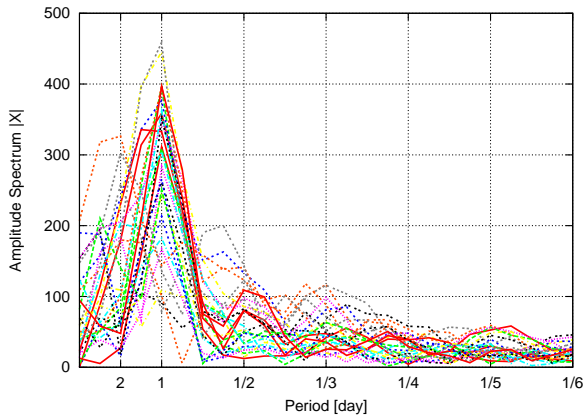
8. ACKNOWLEDGMENT

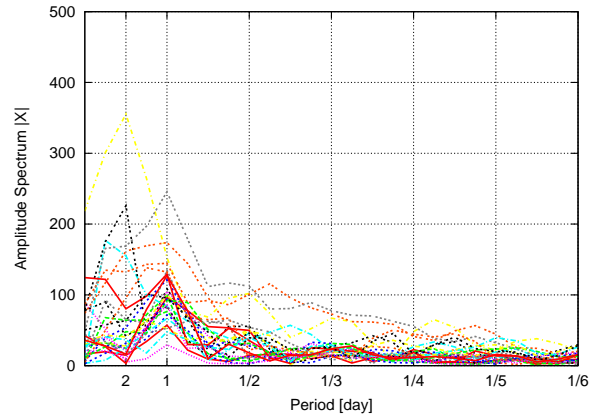Figure 9: Amplitude spectrum of observed signal

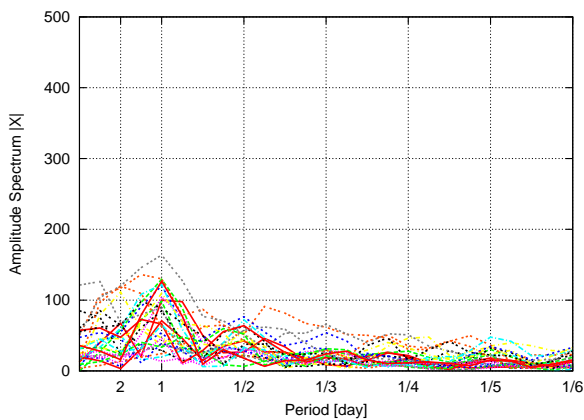Figure 10: Amplitude spectrum of local signal using conventional method

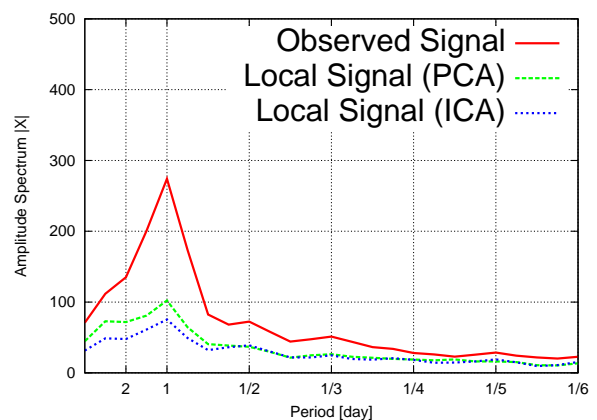Figure 11: Amplitude spectrum of local signal using proposed method

Figure 12: Average amplitude spectrum of each signal

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