IMPLEMENTATION OF MATRIX FACTORIZATION BASED ON MINIMIZING QUASI-ABSOLUTE DISTANCE FOR ELECTROMAGNETIC GLOBAL SIGNAL ELIMINATION

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ABSTRACT

Anomalous environmental electromagnetic (EM) radiation waves have been reported as the portents of earthquakes. We have been measuring the Extremely Low Frequency (ELF) range all over Japan. Our goal is to predict earthquakes using EM radiation waves.

The recorded data often contain signals unrelated to earthquakes. These signals, as noise, confound earthquake prediction efforts. It is necessary to eliminate noises from observed signals in a preprocessing step. In previous researches, we used ISRA, an algorithm of the Non-negative Matrix Factorization (NMF), to estimate source signal. However, ISRA is not robust for outliers because ISRA's cost function is based on square distance. In order to improve robustness, we should use lower order cost function.

In this paper, we propose matrix factorization method based on quasi-absolute distance for global signal elimination.

1. INTRODUCTION

Japan has suffered extensive damage from huge earthquakes many times. This gives residents reason to worry about the occurrence of giant earthquakes in the near future. The Earthquake Research Committee of Japan reported in 2001 that the probability of giant earthquakes of the Nankai and Tohnankai (Richter magnitude over 8) within 30 years is now between 40% and 50% [1]. Accurate earthquake prediction is urgently needed to minimize earthquake damage.

Anomalous radiations of environmental electromagnetic (EM) waves have been reported as a precursor phenomenon of earthquakes [2, 3]. The radiation is thought to originate in an electrochemical process associated with tectonic movements, and in electrochemical reactions such as the oxidization of reactive materials in the earth's crust, which are ascending from deep under the ground together with magma, although the details of the mechanism are not yet understood. In past researches, we found the strength of ELF magnetic field keeps high level for a few hours to a few weeks before earthquake occurrence. In order to observe precursor EM radiation of earthquakes, we have been measuring Extremely Low Frequency (ELF) magnetic fields of 223 Hz all over Japan (Figure 1) since 1985 with the goal of predicting earthquakes using these signals. This frequency band is slightly influenced by solar activity and the global environment (Figure 2). Observation systems have three axial loop antennas with east-west, north-south, and vertical orientations. Observation devices transform 223 Hz EM waves to 18 Hz by intermediate-frequency transformation, and sample strength of EM field at 50 Hz. The devices record the average of its absolute values over 6-second periods.

Accurate earthquake prediction needs to observe some consistent precursor phenomena of earthquakes. However, the properties of the precursor EM signals are unknown. Additionally, the ELF measurements contain undesired signals associated with thunderclouds, human activity, and other things. These undesired signals distort ELF measurements strongly and often prevent prediction of earthquakes. It is important to remove undesired signals (which are not related to earthquake phenomena) from recorded data before predicting earthquakes. The largest undesired signal, so called global signal, especially affects recorded signals. The global signal is radiated from heat thunderclouds at lower latitudes, and it coincides with the most of the observed signals. The signal which is eliminated its global signal is called local signal. The local signals are emitted by regional EM radiation sources, for example, crustal movement, nearby thunderclouds, or other interference. In order to accurate earthquake prediction, we should extract crustal movement signals. However, we cannot identify this signal because its properties are unknown. Therefore, we enhance local signals as the first step of earthquake prediction.

2. GLOBAL SIGNAL ELIMINATION USING BLIND SOURCE SEPARATION

2.1 Formulation of global signal elimination

We assume that one large source signal $g(t)$ is observed globally. Focusing on a global signal $g(t)$, the observed

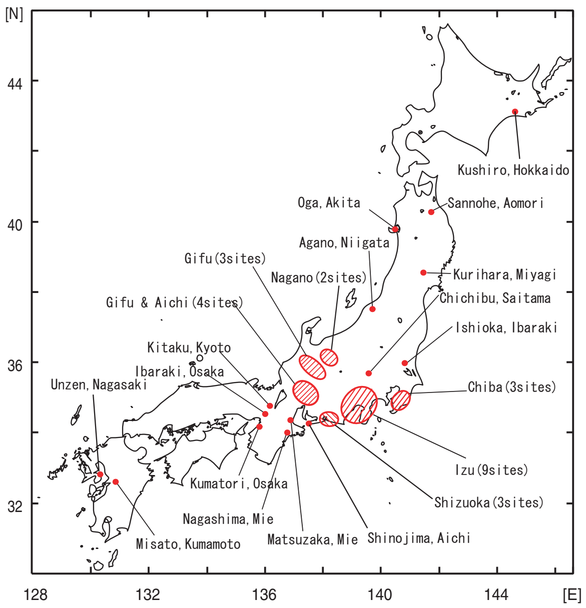


Figure 1: Arrangement of observation sites

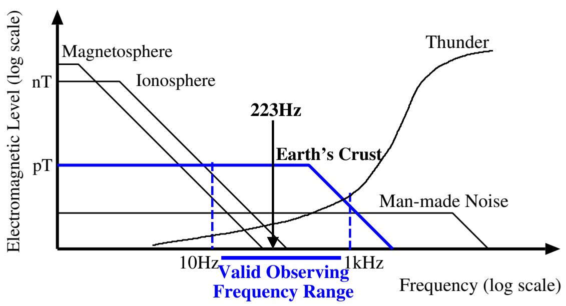


Figure 2: EM radiation levels of each source

signals $\boldsymbol{x}(t)$ are given by

$$\boldsymbol{x}(t) = \boldsymbol{b}g(t) + \boldsymbol{l}(t) \tag{1}$$

where $\boldsymbol{b}$ is sensitivity vector for $g(t)$ corresponding to each observation site. $\boldsymbol{l}(t)$ indicates regional signals (local signals) including the earthquake precursor signal. In this model, the global signal elimination (GSE) is to subtract global signal from observed signals as follows:

$$\boldsymbol{l}(t) = \boldsymbol{x}(t) - \boldsymbol{b}g(t). \tag{2}$$

Therefore, GSE problem is how do we estimate $\boldsymbol{b}g(t)$. In order to solve this problem, we generalize observed signal's model to follows:

$$\boldsymbol{x}(t) = \boldsymbol{A}\boldsymbol{s}(t) \tag{3}$$

where $\boldsymbol{s}(t)$ indicates several source EM signals and $\boldsymbol{A}$ is linear-mixture matrix. In this model, GSE become a problem of BSS and signal identification.

The procedures of GSE using BSS are as follows.

1. Estimating source signals from observed signals by using BSS.
2. Identifying a global signal component from the estimated source signals.
3. Subtracting the global signal from each observed signal as follows:

$$\hat{\boldsymbol{l}}(\boldsymbol{t}) = \boldsymbol{x}(t) - \boldsymbol{A}_g s_g(t), \tag{4}$$

where s_g is global signal in estimated signal and $\boldsymbol{A}_g$ is sensitivity vector corresponding to $s_g(t)$.

2.2 Effectiveness of global signal elimination

In many cases, we compare the SNR of data in order to evaluate effectiveness of method. However, it is impossible to calculate SNR directly from our signals because the true earthquake precursor signal is necessary to calculate SNR. We alternatively use mutual informations as an effectiveness criterion. Mutual information among the observed signals is large value because all observed signals contain the global signal. On the other hand, mutual information among the local signals is relatively small because few electromagnetic radiations spread far. Therefore, the smaller the mutual information, the smaller the global signals are included.

In order to calculate mutual information, we need probability density functions (PDFs) of $P_X(X), P_Y(Y)$ and joint PDF of $P(X,Y)$. We use the quantized histograms about signals instead of PDFs. Therefore, approximate mutual information is calculated by

$$\hat{I}(X;Y) = \sum_{n_X, n_Y} P[n_X, n_Y] \log\left(\frac{P[n_X, n_Y]}{P_X[n_X]P_Y[n_Y]}\right), \tag{5}$$

where $P[\cdot]$ denotes a discrete histogram obtained from real observed data. We usually set quantization width to 0.2 times standard deviation of observed data. The effectiveness criterion of global signal elimination is given by

$$GIC = \sum_{i,j} \frac{\hat{I}(L_i; L_j)}{N(N-1)} \quad (i \neq j), \tag{6}$$

where L_i, L_j $(i, j = 1, ..., N)$ are random variables of local signals l_i, l_j. The smaller GIC is, the more accurately the global signal is removed from the observed data[4].

3. MATRIX FACTORIZATION USING ABSOLUTE DISTANCE

We assume the matrix factorization like following:

$$\boldsymbol{X} \approx \boldsymbol{A}\boldsymbol{S} + \boldsymbol{C}, \quad (C_{ik} = c_i) \tag{7}$$

where, $\boldsymbol{X}$ is $n \times T$ matrix, $\boldsymbol{A}$ is $n \times r$ matrix, and $\boldsymbol{S}$ is $r \times T$ matrix. $\boldsymbol{C}$ is $n \times T$ matrix made of c_i that correspond to a continuous current of sensor i.

In order to estimate $\boldsymbol{A}$, $\boldsymbol{S}$, we used ISRA[5], an algorithm of the Non-negative Matrix Factorization (NMF)[6] in previous research[7]. However, ISRA is not robust for outliers because ISRA's cost function is based on square distance. In order to improve robustness, we should use lower order cost function.

The absolute distance is not generally used for cost function because differential calculus is impossible. If

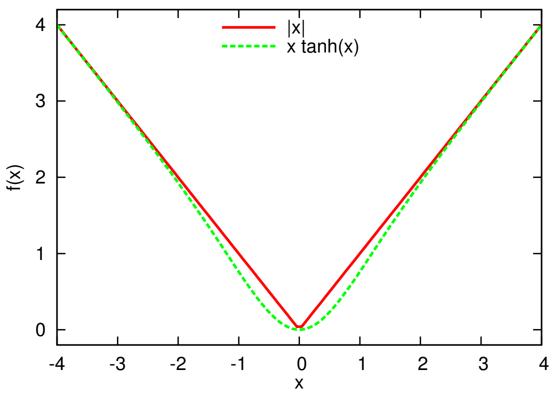


Figure 3: Quasi-absolute distance

we use the absolute function, we need to approximate the function with something differentiable function, or we must define the differential function of quasi-absolute function.

We describe distance function D using $x\tanh(x)$ (Figure.3) that is like absolute function as:

$$D(\boldsymbol{X}||\boldsymbol{AS}+\boldsymbol{C}) \equiv \sum_{i,k} E_{it}\tanh(E_{ik}) \quad (8)$$

where $\boldsymbol{E} = \boldsymbol{X} - \boldsymbol{AS} - \boldsymbol{C}$. The steepest descent update functions of $\boldsymbol{A}$ based on the cost function Eq. (8) are

$$A_{ij} \leftarrow A_{ij} + \eta_A \frac{d}{d\boldsymbol{A}} D, \quad (9)$$

where η_A is step-size coefficient. Because of

$$\frac{d}{dx} x\tanh(x) = \tanh(x) + \frac{x}{\cosh^2(x)}, \quad (10)$$

Eq.(9) is rewritten as

$$A_{ij} \leftarrow A_{ij} + \eta_A \sum_k S_{jk}\left\{\tanh(E_{ik}) + \frac{E_{ik}}{\cosh^2(E_{ik})}\right\} \quad (11)$$

In the same way,

$$S_{jk} \leftarrow S_{jk} + \eta_S \sum_i A_{ij}\left\{\tanh(E_{ik}) + \frac{E_{ik}}{\cosh^2(E_{ik})}\right\}$$

$$c_i \leftarrow c_i + \eta_C \sum_k \left\{\tanh(E_{ik}) + \frac{E_{ik}}{\cosh^2(E_{ik})}\right\} \quad (12)$$

where η_S, η_C are step-size coefficients. Our proposed method updates $\boldsymbol{A}$, $\boldsymbol{S}$ and $\boldsymbol{C}$ enough times concurrently. Nonetheless, it is difficult for proposed method to estimate multi source signals concurrently so far, we estimate source signals one by one.

Eq. (7) can be written column by column as

$$\boldsymbol{x}(t) \approx \boldsymbol{As}(t) + \boldsymbol{c} \quad (t = 1, 2, ..., T) \quad (13)$$

where $\boldsymbol{x}(t)$ and $\boldsymbol{s}(t)$ are the corresponding columns of $\boldsymbol{X}$ and $\boldsymbol{S}$. Therefore, matrix factorization method can estimate component estimation of time-course multivariate data (Figure 4).

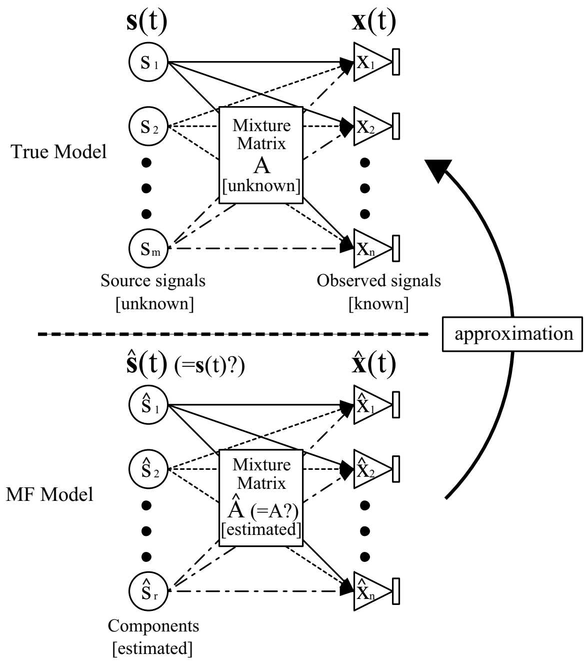


Figure 4: Signal model of matrix factorization at BSS

S_{jt} of one row vector in matrix $\boldsymbol{S}$ corresponds to global signal $g(t)$ because global signal is one of the source signal. A_{ij} of one column vector in matrix $\boldsymbol{A}$ corresponds sensitivity vector $\boldsymbol{b}$ for global signal.

4. EXAMPLES OF GLOBAL SIGNAL ELIMINATION

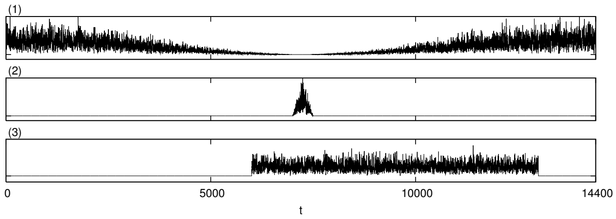
4.1 Applying to generated signals

First, we generate 3 source signals shown in figure 5(a). In the figure, horizontal axis indicates sampling index, and vertical axes indicate amplitudes. 5(a)(1) is global signal, (2) and (3) are common signals among several observation sites assumed EM waves from thundercloud and artifacts.

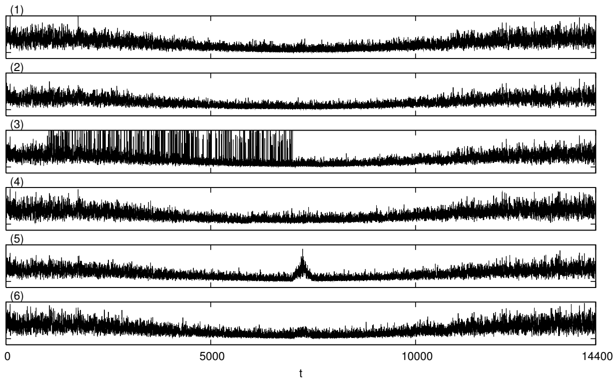
Second, we make 12 observed signals from sources by mixing linearly and individually adding absolute Gaussian-noise. Third, we set the weight of global source signal to almost even values, and larger than average of the other sources' weights. Finally, we added many large impulses to observed signal (3) while $1001 \leq t \leq 7000$ because this experiment is checking robustness of proposed method for outliers. Figure 5(b) shows 6 of the observed signals. Identically, the local signals should become as Figure 5(c).

We apply the global signal elimination to these generated observed signals. We use $r = 3$ at proposed method because the number of signals for estimation r is the number of assumed sources usually.

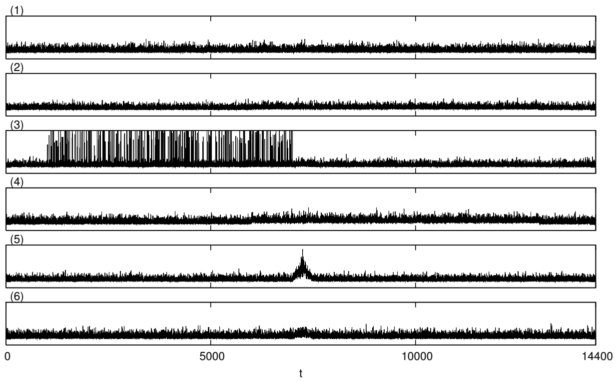
Figure 6 shows observed signal (3) and its estimated local signals using each method. Figure 6(a) of observed signal have a large wave at 1 cycle that is global signal. Figure 6(b) of estimated local signal using ISRA also have a small 1 cycle wave. On the other hand, Figure 6(c) of proposed method does not have. The results



(a) Source signals

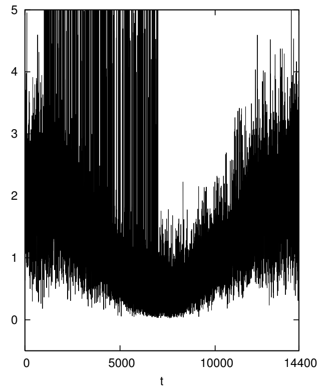


(b) Observed signals (6 of 12)

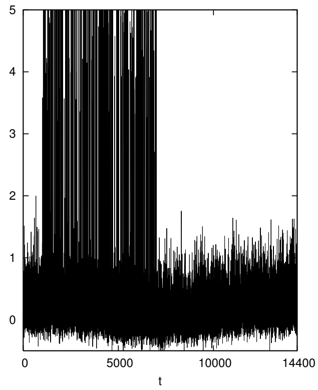


(c) Ideal local signals (6 of 12)

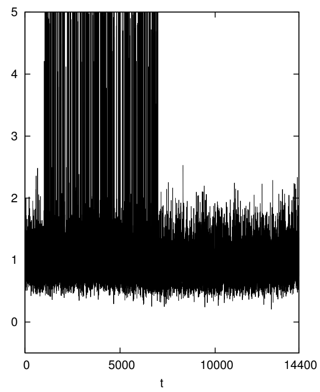
Figure 5: Generated signals



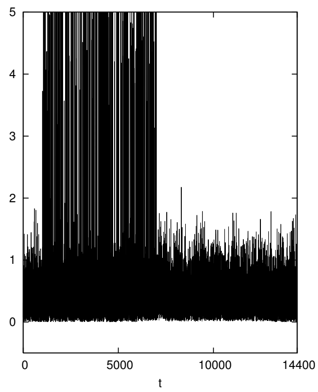
(a) Raw (observed signal)



(b) ISRA



(c) Proposal ($x \tanh(x)$)



(d) Ideal local signal

Figure 6: Estimated local signals at observed signal (3) that was added many large impulses

Table 1: *GIC* and SNR

Method (r)	*GIC*	SNR
Raw	0.5349	-3.4224
Previous method (ISRA)	0.0460	12.4081
Proposal	0.0436	14.6746
Ideal	0.0295	—

of evaluating numerical effectiveness about global signal elimination are shown in table 1. In the case of using proposed method, both of *GIC* and SNR are better than using ISRA's. These facts mean proposed method works better than ISRA about global signal elimination.

4.2 Applying to ELF electromagnetic signals

We applied our proposed method to observed signals containing earthquake precursor electromagnetic radiation. An anomalous signal was observed for several hours on March 17, 2005, at Unzen in Nagasaki Prefecture (hereafter called Unzen) before West Off Fukuoka Prefecture Earthquake (M 7.0, on March 20). We attempted to estimate local signals on this day because we consider this anomalous signal relate to the earthquake.

Figure 7(a) shows our ELF observed signals (3 of 27 sites) on March 17, 2005. The vertical axes indicate the electromagnetic levels [pT/$\sqrt{\text{Hz}}$] and the horizontal axes indicate the time courses [hours]. Observed signals have daily variations in common which are related to the global signal. Daily variations like these account most of usual observed signals. Observed signal (2) at Unzen, the nearest site from the epicenter, have many impulses.

Figure 7(b) and (c) show estimated local signals using each ISRA and proposed method. The common daily variations should disappear if the global signal correctly eliminated. However, ISRA fail to eliminate from Unzen's signal. On the other hand, proposed method enough eliminate from Unzen's signal. Table 2 shows *GIC*s of using each method. Proposed method's *GIC* is smaller than ISRA's. These facts mean proposed method works better than ISRA also in the case of applying to ELF electromagnetic signals.

5. CONCLUSION

In this paper, we proposed matrix factorization method based on quasi-absolute distance. We applied proposed method to analyze multivariate data include outliers. In the simulation using generated signals and in the experiment using ELF electromagnetic signals, proposed method worked better than ISRA for global signal elimination. We showed proposed method is robust for the data including many outliers. Especially, it means much that proposed method succeeded to eliminate global signal from the ELF data which ISRA failed.

However, it is difficult for proposed method to estimate multi source signals concurrently. Adaptation to multi source estimation and elevation of stability are important future works. Also we should try other cost functions near L_1 norm. Of course, we will verify the effectiveness of the proposed method by anomalous detection and source estimation in earthquake prediction.

6. ACKNOWLEDGMENT

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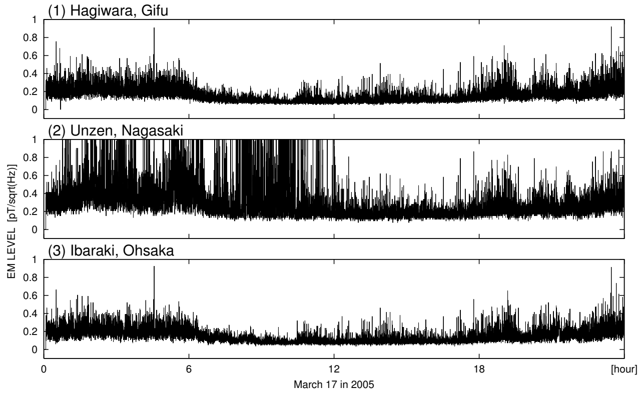
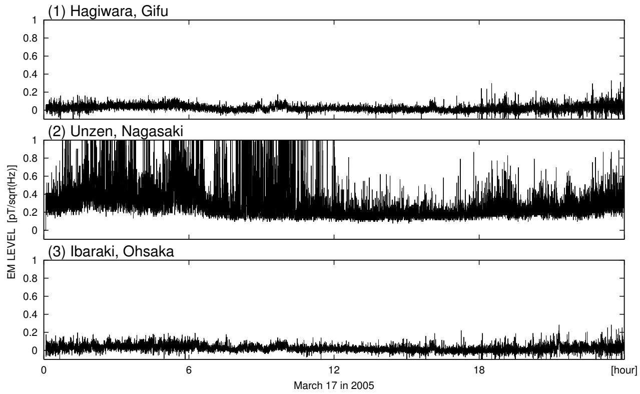
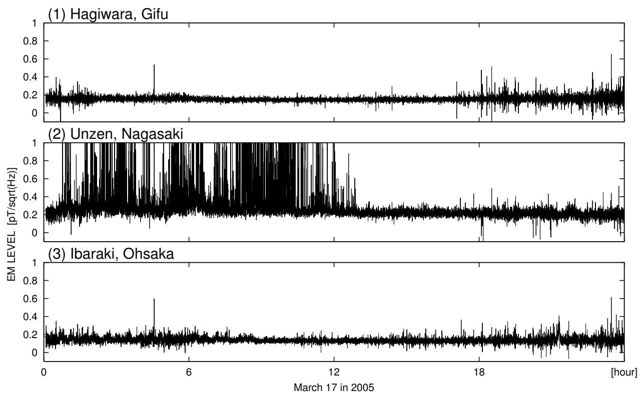


(a) ELF Observed signals



(b) Estimated local signals using ISRA



(c) Estimated local signals using proposed method ($x\tanh(x)$)

Figure 7: Signals on March 17 in 2005

Table 2: *GIC*

Method	*GIC*
Raw	0.2447
Previous method (ISRA)	0.0886
Proposal	0.0740