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Signal Processing and Sonification of Seismic Electromagnetic Radiation in the ELF Band

Seiji ADACHI†a), *Nonmember*, **Hiroshi YASUKAWA**†, **Ichi TAKUMI**††, *and* **Masayasu HATA**†, *Regular Members*

SUMMARY We have developed a signal processing method that is appropriate for detecting electromagnetic radiation due to earthquake activities. The radiation is usually accompanied by a background noise that is mainly caused by atmospheric discharges in the tropical regions. Data representing the seismic radiation is presented as sound via the concept of sonification. This is useful for immediately finding out anomalous seismic radiations, which are often followed by a disastrous earthquake, from the massive data collected from over forty observation stations. It is illustrated that the auditory display is valuable for future earthquake prediction systems.

key words: *electromagnetic radiation, earthquake, ELF band*

1. Introduction

According to a theoretical estimation [1], electromagnetic waves due to seismic activities can be radiated as an indication of an impending earthquake. The radiation is thought to originate in an electromechanical 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.

By detecting the radiations, there is a possibility of predicting earthquakes and avoiding disastrous situations. We have already developed over forty observation stations measuring atmospheric electromagnetic radiation at 223 Hz in the extremely low frequency (ELF) band [2], [3]. In the frequency region below several tens of Hz, radiations due to the large-scale movement of the magnetosphere surrounding the earth perturbed by the solar wind dominate. In the region higher than approximately 1000 Hz, the background noise caused by atmospheric discharges in the tropical regions increases. The 223 Hz was also chosen because it is not a multiple of the frequency of the power supply, that is, 50 or 60 Hz.

In spite of this deliberate selection of the observed frequency, the seismic radiation is still accompanied by a background noise caused by atmospheric discharges in the tropical regions. The magnitude of the noise varies *daily*, with a period of twenty-four hours. This is because the altitude of the ionosphere rises at night, and descends during the daytime. The larger the distance between the ionosphere and the surface of the earth, the smaller the attenuation of the noise propagating through them.

The magnitude of the seismic radiation varies much quickly than the daily change of the background noise due to the tropical discharges. This paper describes a signal processing method that is able to discriminate the seismic radiation from the background noise. It also presents a method for transforming the processed signal of the radiation into sound via sonification [4], which is now often applied to the clinical signal processing [5]. The auditory display facilitates immediate searches for anomalous seismic radiations, which may enable us to predict earthquakes.

2. Signal Processing

2.1 Method

Atmospheric discharges in the tropical regions are the main cause of the background noise. The observed signal is, therefore, composed of the radiation due to seismic activities and the background noise due to the tropical discharges. The level of the background noise fluctuates with a period of twenty-four hours. On the other hand, the level of the seismic radiation is usually much smaller than that of the background noise, when the earth's crust is inactive. However, it becomes larger and reaches a detectable level when the earth's crust is seismically active. Because the scale of the fault lines whose dislocations result in earthquakes is much smaller than the scale of the ionosphere, which causes the daily change in the background noise, the seismic radiation fluctuates with much shorter periods than the background noise. This is the distinctive aspect of seismic radiation that should be considered.

As outlined in the previous paragraph, the level of the background noise has a large frequency component of one cycle/day. One method for removing the noise is, therefore, to filter out this frequency component with a low-pass filter. This method, however, has the possibil-

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†The authors are with the Faculty of Information Science and Technology, Aichi Prefectural University, Aichi-ken, 480-1198 Japan.
††The author is with the Faculty of Engineering, Nagoya Institute of Technology, Nagoya-shi, 466-8555 Japan.
a) E-mail: adachi@ist.aichi-pu.ac.jp

ity of filtering out the high-frequency component that originates in the seismic radiation [6].

We, therefore, take another method, in which the high-frequency component is extracted first, the amplitude of the component, that is, the absolute value, is calculated, and then it is filtered by a low-pass filter to see the daily change. This method can be summarized as follows:

- Each observation station is equipped with three loop-coiled antennas directed towards the x, y and z axes with respect to the ground. Each station therefore provides three signals, S_x, S_y and S_z, representing the magnetic field along the the x, y and z axes.
- Take the square root of the sum of the square of the three signals obtained in one station. This is denoted by S.
- The processed signal in the previous step is then high-passed by a filter. The cut-off frequency is f_{HC}.
- Take the amplitude, or the absolute value, of the high-passed signal.
- The amplitude is then low-passed by another filter to get the envelope pattern of the high-passed signal. The cut-off frequency is f_{LC}.

The process of this method is illustrated in Fig. 1.

In the following two sub-sections, we introduce two cases of signal processing, where anomalous radiation is actually observed.

2.2 Case 1

The signal S detected by an observation station near Yamanashi Yamanakako in September and October '96 is shown by the blue lines in Figs. 2(a) and (b). The vertical axis of the upper part of the figures represents the strength of the magnetic field in pT normalized by the square root of the frequency. The horizontal axis represents the time in the unit of day. An earthquake happened in the eastern part of Yamanashi Prefecture on the 25th of October '96. It was typical of earthquakes in the region. The magnitude was 4.9. The observation station is only ten kilometers away from the estimated epicenter.

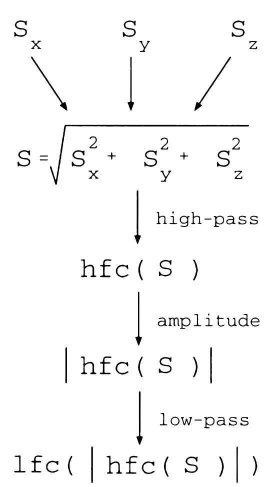


Fig. 1 Flow chart of the signal processing described in Sect. 2.1. `hfc` and `lfc` stand for the high and low frequency components, respectively.

To extract the seismic radiation, the low frequency (LF) component with a frequency smaller than 8 cycles/day is filtered out of the signal. The LF component is mainly composed of the noise slowly varying (with a frequency larger than 1 cycle/day). The amplitude of the residual fast-oscillating component is then calculated. The long-term change of the seismic activity can be regarded as the LF component of the amplitude. The cutoff frequency for the low-pass filtering is set to 0.5 cycle/day.

In the upper part of Figs. 2(a) and (b), the long-term change of the seismic activity is depicted in red lines. The dashed green lines represent the LF component of the signal, S. The lower part of the figure represents the spectrogram of the signal.

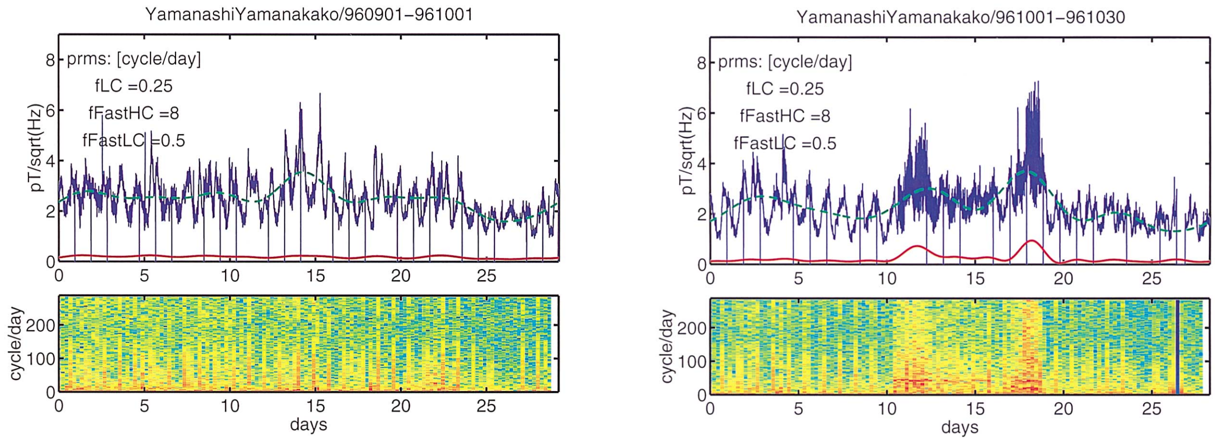
We observe two maxima in the activity on the 13th and 19th of October. The original signal shows that the high-frequency component dominates in the period between the two. This is also illustrated in the spectrogram. The LF component increases in the same period, but the magnitude is the same level as that observed in the first half of September.

2.3 Case 2

The same method of signal processing was applied to an earthquake that happened in the northern part of Wakayama Prefecture, Japan at 5:33 am on the 21st of August. The magnitude was 5.5. The signal S detected by an observation station in Ibaraki, Osaka, in July and in August '99 is shown by blue lines in Figs. 3(a) and (b). The observation station is about a hundred kilometers away.

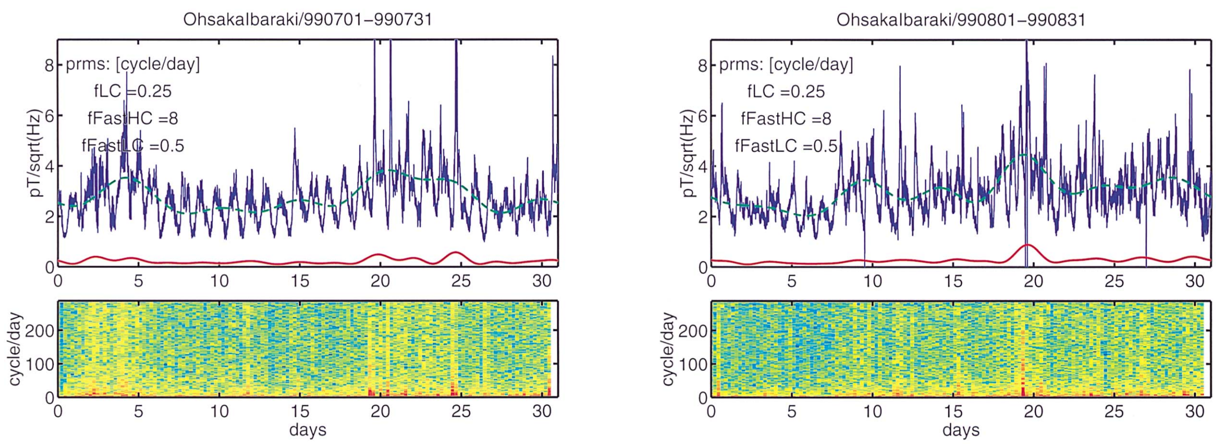
The same parameters are used: 8 cycles/day as the cutoff for the high-pass filtering and 0.5 cycle/day as the cutoff for the low-pass filtering. The red lines in the upper part of Figs. 3(a) and (b) represent the long-term change in seismic activity. For comparison, the LF components (with a frequency smaller than 0.25 cycle/day) of the signal S are also shown by the dashed green lines.

The largest amplitude of the seismic activity is observed on August 20, which was one day before the earthquake occurred. The peak is outstanding as compared with other local maxima observed over the two months. The spectrogram in the lower part of the figure shows that the level of the high-frequency component was extremely high on that day. The LF component of the original signal also has a peak on August 20. The



(a) (b)

Fig. 2 The signal detected at an observation station in Yamanakako, Yamanashi (blue line), the low-frequency component of the signal (dashed green line), and that of the amplitude of the fast-oscillating component of the original signal (red line). The cutoff frequency for the low-pass filter is shown in the figures as `fLC=0.25` cycle/day. Those for obtaining the seismic activity (red line) are shown as `fFastHC = 8` and `fFastLC=0.5` cycle/day. Observations were made on the (a) 1st to 30th of September '96 and (b) 1st to 30th of October '96.



(a) (b)

Fig. 3 The signal detected at an observation station in Ibaraki, Osaka (blue line), the low-frequency component of the signal (dashed green line), and that of the amplitude of the fast-oscillating component of the original signal (red line). Observations were made on the (a) 1st to 31st of July '99 and (b) 1st to 31st of August '99.

magnitude is, however, comparable with other peaks, such as that observed in July 5. The seismic activity extracted through the above process is more promising for earthquake prediction than the LF component of the original signal.

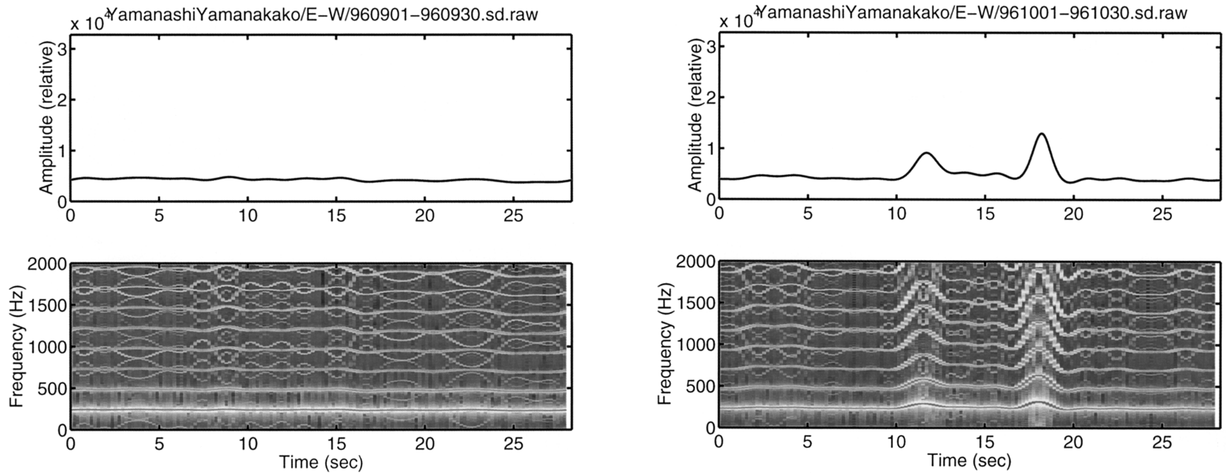
3. Sonification

3.1 Method

We have attempted to generate sounds modulated by the long-term change of seismic activity. Both the amplitude and the frequency of a steady sound with a sawtooth wave were modulated. A sound of n seconds is generated for the observed data of n days. The sonification method can be described as follows:

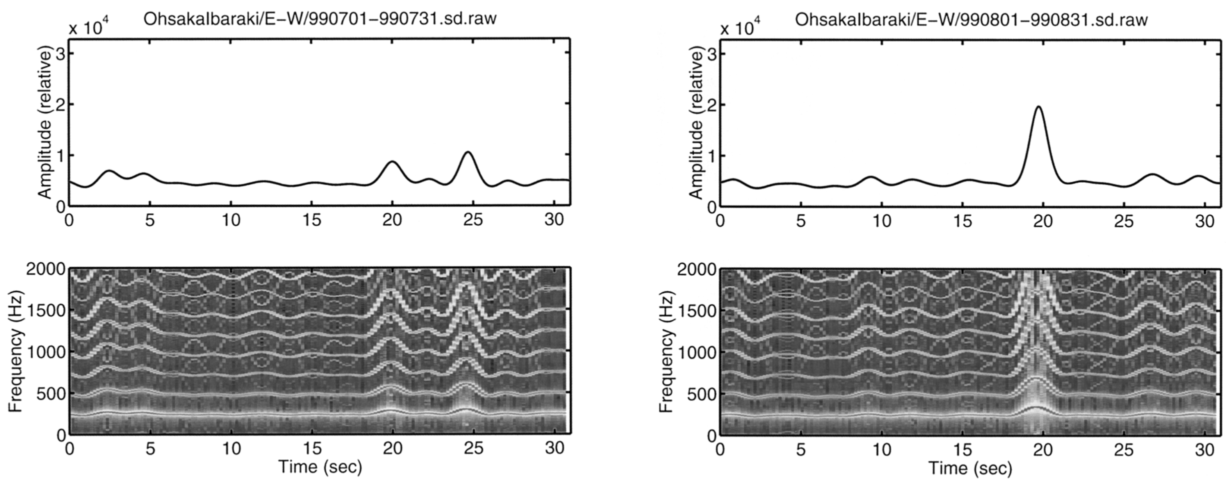
- Take the seismic activity that is extracted by the signal processing method described in the previous section, as a modulation source.
- Generate a steady sawtooth wave as a career.
- Modulate both the amplitude and the frequency of the career.
- Adjust the sampling frequency to generate a sound of n seconds from the modulation source of n days.

The career frequency of the sawtooth wave is set to



(a) (b)

Fig. 4 Amplitude (upper) and spectrogram (lower) of the sound generated by the method described in Sect. 3. Signals modulating the sound are of Yamanakako Yamanashi on the (a) 1st to 30th of September '96 and (b) 1st to 30th of October '96.



(a) (b)

Fig. 5 Amplitude (upper) and spectrogram (lower) of the sound generated by the method described in Sect. 3. Signals modulating the sound are of Ibaraki Osaka on the (a) 1st to 31st of July '99 and (b) 1st to 31st of August '99.

200 Hz. The instantaneous frequency is linearly proportional to the level of the modulation signal. On the other hand, the amplitude is logarithmically proportional to the level of the modulation signal (The decibel of the amplitude is linearly proportional).

3.2 Discussion

The amplitude and the spectrogram of the sounds for the data shown in Case 1 are depicted in Figs. 4(a) and (b). The changes in the sound corresponding to the maxima of the activity on the 13th and the 19th of October are striking. The auditory display is also applied to Case 2. The amplitude and the spectrogram of the sounds are depicted in Figs. 5(a) and (b). Note that just before the earthquake occurred on the 21st of August, both the amplitude and frequency of the sound suddenly rose. This change appears to warn of the earthquake that occurred shortly after.

To examine the effect of the sonification, a preliminary experiment of the subjective estimation was carried out. In the experiment, one subject was employed to listen to the generated sound. We call this the auditory presentation. He was also instructed, at the same time, to view figures similar to those shown in Figs. 2 and 3, where the original signal S, the seismic activity and the LF component of S were plotted. We call this the visual presentation.

The report from the subject indicates that, in Case 1, the correspondence between the auditory and visual presentations is good. Both of them drastically change on the 13th and the 19th of October. This part drew his attention the most, whereas there was no particular attention paid to other periods in both presentations in common. In Case 2, on the other hand, there is a difference. In the visual presentation, there is no strong attention paid to the data during the two months, whereas, in the auditory presentation, a sudden change at the point of the 20th of August drew the subject's isolated attention during these months. The latter case may indicate the merit of the auditory presentation over the visual one.

Before arriving at the modulation method presented here, we tried several different modulation parameters and schemes. Varieties in the frequency of the career signal and the depth of the frequency modulation did not change the degree of the sonification effect very much. The dependency of the amplitude on the modulation signal, however, did change the effect. If it changes to be linear, the loudness change will not be obtained even at the maximum of the modulation signal. It should, thus, be logarithmic. This is a natural consequence of the loudness characteristic in the auditory system.

The sonification we presented here produces an alarm whose sound changes continuously. Using this, it may be difficult to directly predict earthquakes, although it provides a quite concise representation of the amount of anomalous radiation due to seismic activities. We also considered other presentation methods, such as an alarm with sound and flashing light, which assume states of either active or inactive. In a future earthquake prediction system, these are favorable and should be implemented, because they would directly tell of the impeding earthquake with high probability. These would be issued when the estimated earthquake activity increases over a threshold. Determining the threshold is, however, somewhat difficult. Before attempting this, we should collect more cases where earthquakes occurred and the estimated earthquake activity showed good correspondence. We are now examining the relation between anomalous radiations and earthquakes that have happened by applying the sonification method described here to a large set of radiation data collected by ourselves.

4. Conclusions

We have presented a signal processing method to discriminate earthquake activity from background noise in an observed electromagnetic wave in the ELF band. Two actual cases of the analysis show that the method is viable for future earthquake prediction. The auditory display is also shown to be useful for finding anomalous radiations among the massive data collected from observation stations.

We started our investigation with only a few cases for analysis. Before the method is actually used for prediction, it is important to accumulate cases indicating good correspondence between earthquake activity extracted by this signal processing and actual earthquakes. To this end, we are now testing the method by applying it to observed radiation data collected by ourselves.

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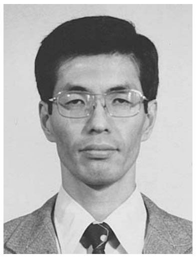
Seiji Adachi was born in Osaka, Japan, on January 10, 1961. He received a B.S. degree in mathematics, and B.S., M.S. and Ph.D. degrees in physics from Osaka University, Osaka, Japan, in 1983, 1986, 1988, and 1991, respectively. He joined the ATR Human Information Processing Research Laboratories in 1992. In 1998, he joined the Faculty of Information Science and Technology, Aichi Prefectural University, as an associate professor. Dr. Adachi is a member of the Acoustical Society of America, the Catgut Acoustical Society, the Acoustical Society of Japan, and the Information Processing Society of Japan.



Hiroshi Yasukawa received B.E., M.E. and Ph.D. degrees in electrical and electronics engineering from Shizuoka University, Hamamatsu, in 1970, 1972, and 1993, respectively. He joined the Nippon Telegraph and Telephone Public Corporation in 1972. He worked on research and development on analog and digital communication systems in the NTT Laboratories. Since April 1998, he has been a professor of Aichi Prefectural University. His research interests include digital signal processing, communication systems, and information networks. Dr. Yasukawa is a member of the IEEE, the Information Processing Society of Japan, the Acoustical Society of Japan, the Information Theory and Its Application Society and the European Association for Speech, Signal and Image Processing (EURASIP).

Ichi Takumi received B.E. and M.S. degrees from Nagoya Institute of Technology, Nagoya, Japan in 1982 and 1984, respectively, both in electronic engineering. After graduation he joined Oki Electric Co. He has a Doctor of Eng. degree from Nagoya Institute of Technology. Since December 1985, he has been with Nagoya Institute of Technology, where he is now an Associate Professor of Department of Artificial Intelligence and Computer Science. His current research interests include digital signal processing and digital communications. He is a member of the Society of Instrument and Control Engineerings of Japan.

Masayasu Hata graduated in 1958 from Department of Electronic Engineering, Faculty of Engineering, Nagoya Institute of Technology, and affiliated with Oki Electric Co. He has a Doctor of Eng. degree from Tokyo Institute of Technology. He was engaged in R&D of digital communication system, application of electronic circuits and millimeter wave communication equipment. Retired from Oki Electric Co. in 1985 and became a Professor in the Department of Artificial Intelligence and Computer Science, Nagoya Institute of Technology. Since 1998 he has been with Aichi Prefectural University as a Professor in the Department of Applied Information Technology. He is engaged in research on digital signal processing and information communication.