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EXTRACTION OF MICROEARTHQUAKE SIGNALS RECORDED BY THE SEISMIC NETWORK ON MT. EREBUS, ROSS ISLAND, ANTARCTICA

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Abstract: In this paper, we introduce a methodology for the extraction of information from observed microearthquake waves. We show a model for decomposition of time series into several components. In the model each component is expressed by an autoregressive model. The extraction of microearthquake signals from noisy data and the decomposition of *P* and *S* wave signals have been shown as an example of the power of the proposed procedure. Noisy seismic data which was recorded by the seismic network installed on the summit of Mt. Erebus, Ross Island, Antarctica is used to show the power of the procedure.

1. Introduction

Earthquakes occurring within a few hundred kilometers from a seismic network are called local events. Local earthquakes are often characterized by high frequency waves. On the other hand, a transient signal of instrumental or artificial origin often has the same predominant period throughout its duration. Therefore, for a microearthquake of small amplitudes it is difficult to determine the onset times of *P* wave and/or *S* waves.

Since a microearthquake network is required to determine earthquake hypocenters precisely and rapidly, it is crucial to develop an automated system that can determine the first *P* arrival times accurately and efficiently. The waveforms of microearthquakes recorded at neighboring stations are, in general, remarkably dissimilar. This has led to computer algorithms that process each incoming digital seismogram as an independent time series.

In this paper, a methodology for the extraction of arrival time information from the observed seismograms is introduced. Computer programs are developed for the analysis of seismic data both for a temporary seismographic station on the summit of Mt. Erebus, Ross Island, Antarctica during the summer field season in 1980-1981, and for seismic data recorded by the microearthquake network of Hokkaido University.

2. Decomposition of Earthquake Signals into Several Components by the Autoregressive Process

2.1. *Earthquake model*

Since the seismogram is a time series, we can use a statistical method, autoregressive (*AR*) modeling, which has been developed mainly in the field of signal processing. This paper addresses to the problem of decomposition of an observed time series into several components. A specific problem we are considering first is the extraction of microearthquake signals from noisy data. An earthquake is recorded by measuring the ground motion. The ground is always disturbed by various natural phenomena like ocean wave, wind and tide and by various human activities. Without any earthquakes, the ground fluctuates with characteristic frequencies. The motion is called the stationary background noise. Therefore, if the amplitude of the earthquake signal is very small, it is quite difficult to distinguish the earthquake signal from the background noise. We will consider the problem of extracting small earthquake signals from such noisy data.

In a series of papers (AKAIKE, 1973; KITAGAWA, 1981; KITAGAWA and GERSCH, 1984), models for nonstationary time series with drifting mean value function are developed and are applied to the seasonal adjustment of economic time series. In the papers (KITAGAWA and TAKANAMI, 1985; TAKANAMI and KITAGAWA, 1988, 1991; TAKANAMI, 1991), a model for nonstationary time series with changing covariance structure is developed and is applied to the estimation of changing spectrum for earthquake signal. AKAIKE (1979) showed that the trade-off parameter can be considered as the hyper-parameter of a Bayesian model and that it can be determined by maximizing the likelihood of the Bayesian model. The smooth change of the autoregressive coefficients is modeled by a stochastically perturbed linear difference equation. The time series we are considering in this paper also has a second type of non-stationarity. Here a signal with a different stochastic character is superimposed on a stationary time series. A proper model for the seismic data will be

$$\begin{aligned}(\text{observation}) = (\text{background noise}) &+ (\text{earthquake signal})\\ &+ (\text{observational noise}).\end{aligned}$$

We also show the procedure for the decomposition of earthquake signal into *P* and *S* waves and background noise components.

For the decomposition of a time series, we will consider first the model

$$y(n) = r(n) + s(n) + w(n), \tag{1}$$

where $w(n)$ is a white noise sequence such that $w(n) \sim N(0, \sigma^2)$ and $r(n)$ and $s(n)$ are both autoregressive processes,

$$r(n) = \sum_{i=1}^{m} a(i) r(n-i) + u_r(n) \quad \text{and} \quad s(n) = \sum_{i=1}^{j} b(i) s(n-i) + u_s(n). \tag{2}$$

Here $u_r(n)$ and $u_s(n)$ are white noise sequences such that $u_r(n) \sim N(0, \tau_1^2)$ and $u_s(n) \sim N(0, \tau_2^2)$, and τ_1^2 and τ_2^2 are variances for these noise sequences.

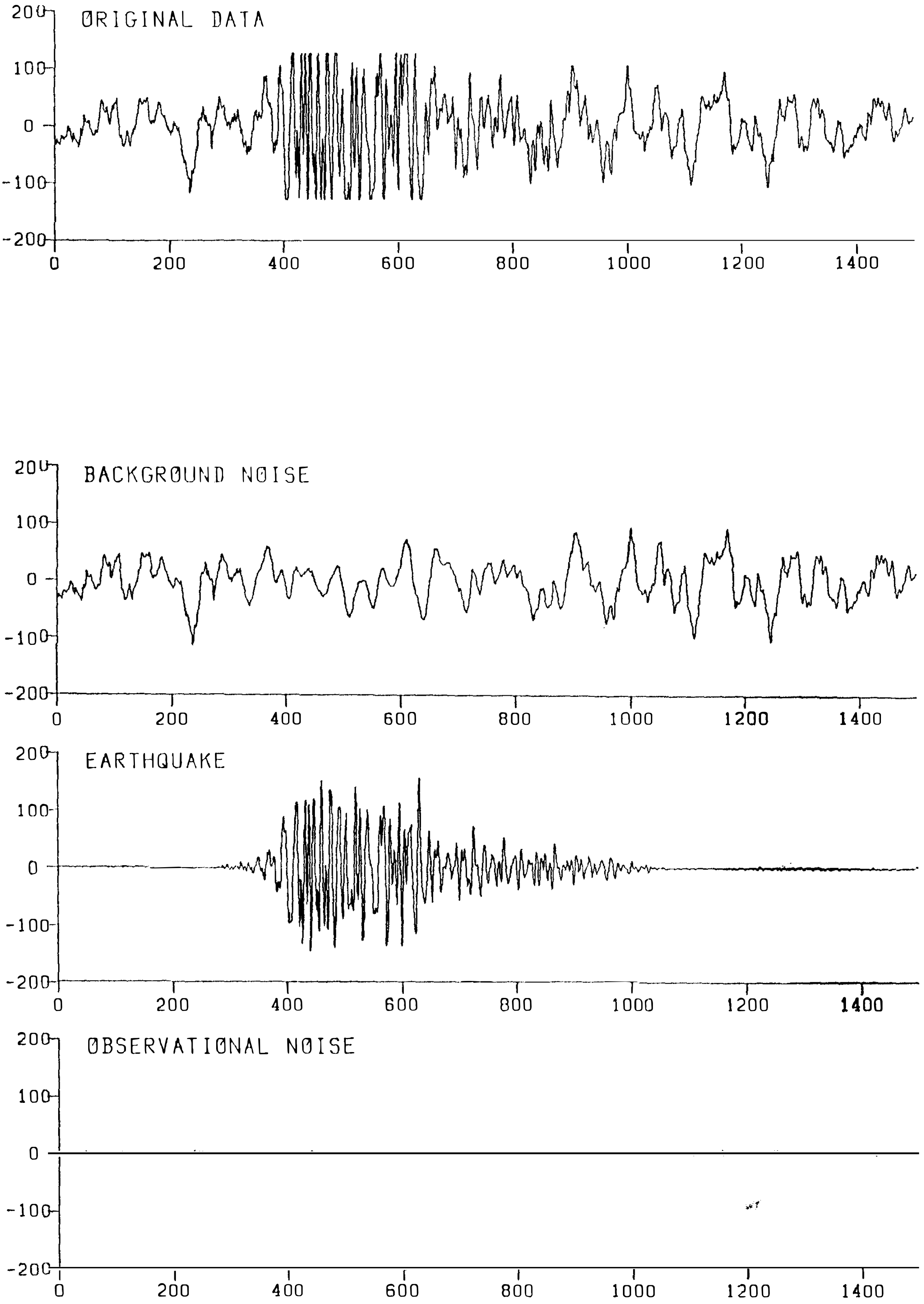

Fig. 1. Decomposition of the seismic data obtained at the summit of Mt. Erebus, Ross Island, Antarctica. Note clear onset of the decomposed seismogram.

The autoregressive model for the earthquake signal can be obtained by fitting the AR model to a part of data where the earthquake signal apparently exists. Here if we assume the stationarity of the background noise and observational noise, it follows that the parameters m, $a(1)$, $\cdots$, $a(m)$, τ_1^2 and σ^2 are known and only l, $b(l)$, $\cdots$, $b(l)$ and τ_2^2 are the unknown quantities. They can be estimated by the minimum AIC procedure (AKAIKE, 1973).

2.2. *Application of autoregressive models to the Mt. Erebus and Hokkaido events*

As an example, we applied this procedure to the volcanic earthquakes that occurred at and near Mt. Erebus which is an active volcano in Ross Island, Antarctica (TAKANAMI *et al.*, 1982, 1983a, b). Figure 1 shows the result of this application. The event was observed at the summit station of the seismic network which had been kept for temporary observation from December 25, 1980 to January 5, 1981. The location of the hypocenter is unknown, but it must be located near the summit judging from the original seismogram shown in the top of Fig. 1. The three decomposed components are shown in the lower parts of Fig. 1. It is noticeable that the weak first part of earthquake signal is extracted clearly. Even for such a weak microseismic signal, our proposed method is proved to be valid. Further we have applied the model for de-

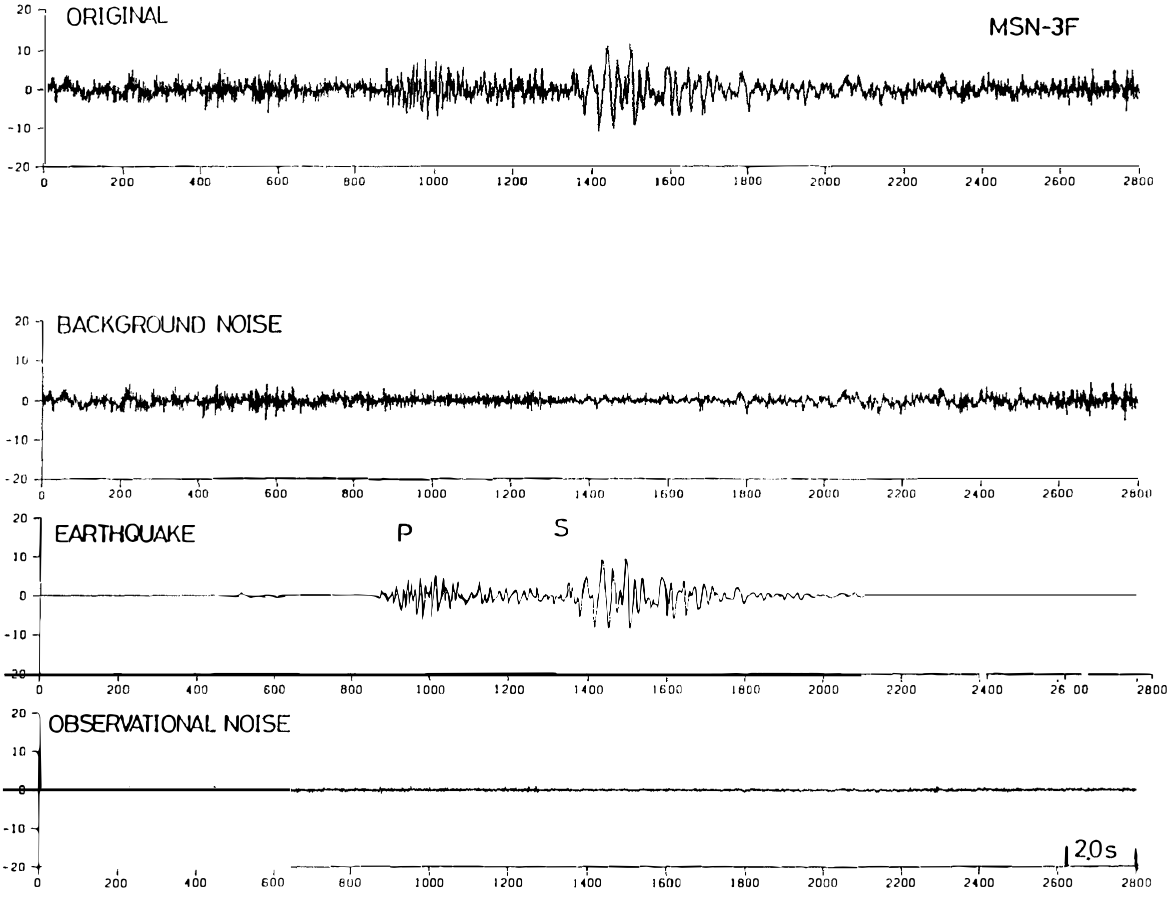

Fig. 2. Decomposition of the heavy noisy seismic data recorded at station Misono (MNS). From the top: original, background noise, earthquake signal, and observational noise.

composition of time series to a noisy seismogram. This is a record of north-south component of microearthquake signal observed at Misono (one of seismic stations of Hokkaido University), at 0849, March 21, 1982. The magnitude is $M=2.1$. The epicenter is about 30 km to the south of this station. In Fig. 2, the model for the decomposition of time series into background noise, seismic signal, and observational noise is shown. The isolation of the noisy seismic signal is also shown to exemplify the proposed procedure.

2.3. Decomposition of earthquake signals into P, S waves, and background noise

It may be possible to use this procedure for the decomposition of earthquake signal into several components, *e.g.* P and S waves and other components. We developed the procedure for the decomposition of earthquake signal into P, S waves and background noise components. As an extension of the model, we will consider here the model

$$\text{(observation)}=\text{(background noise)}+(P\text{-wave signal})+(S\text{-wave signal}) \\ +\text{(observational noise)},$$

namely,

$$y(n)=r(n)+P(n)+S(n)+w(n), \qquad (3)$$

where $w(n)$ is a white noise sequence such that $w(n)\sim N(0, \sigma^2)$ and $r(n)$, $P(n)$ and $S(n)$ are autoregressive processes:

$$r(n)=\sum_{i=1}^{m} a(i)r(n-i)+u_r(n), \quad P(n)=\sum_{i=1}^{j} b(i)P(n-i)+u_p(n), \\ \text{and} \quad S(n)=\sum_{i=1}^{k} c(i)S(n-i)+u_s(n). \qquad (4)$$

Here, $u_r(n)$, $u_p(n)$ and $u_s(n)$ are white noise sequences such that $u_r(n)\sim N(0, \tau_1^2)$, $u_p(n)\sim N(0, \tau_2^2)$ and $u_s(n)\sim N(0, \tau_3^2)$, and τ_1^2, τ_2^2 and τ_3^2 are the variances for these noise sequences.

Figure 3 shows the record of east-west component of microearthquake signal observed at Hiroo (one of the seismic stations of Hokkaido University), Japan, at 0745, March 25, 1982. The magnitude is $M=1.9$. The epicenter is about 40 km to the west of this station MYR. The original record is sampled at each 0.01084 second with minimum resolution of 1.0.

Figure 3 also exhibits the decomposition by the piece-wise modeling of changing variances for model P and S-waves, together with theoretical spectra of the corresponding stochastic processes. Incidentally, a small wave train apparently exists prior to the main S-wave as found in the middle of Fig. 3. This small train, however, has gone unnoticed before. According to the above decomposition, it is a part of the S-wave model, from which important information about the source and the ray-path may be extracted.

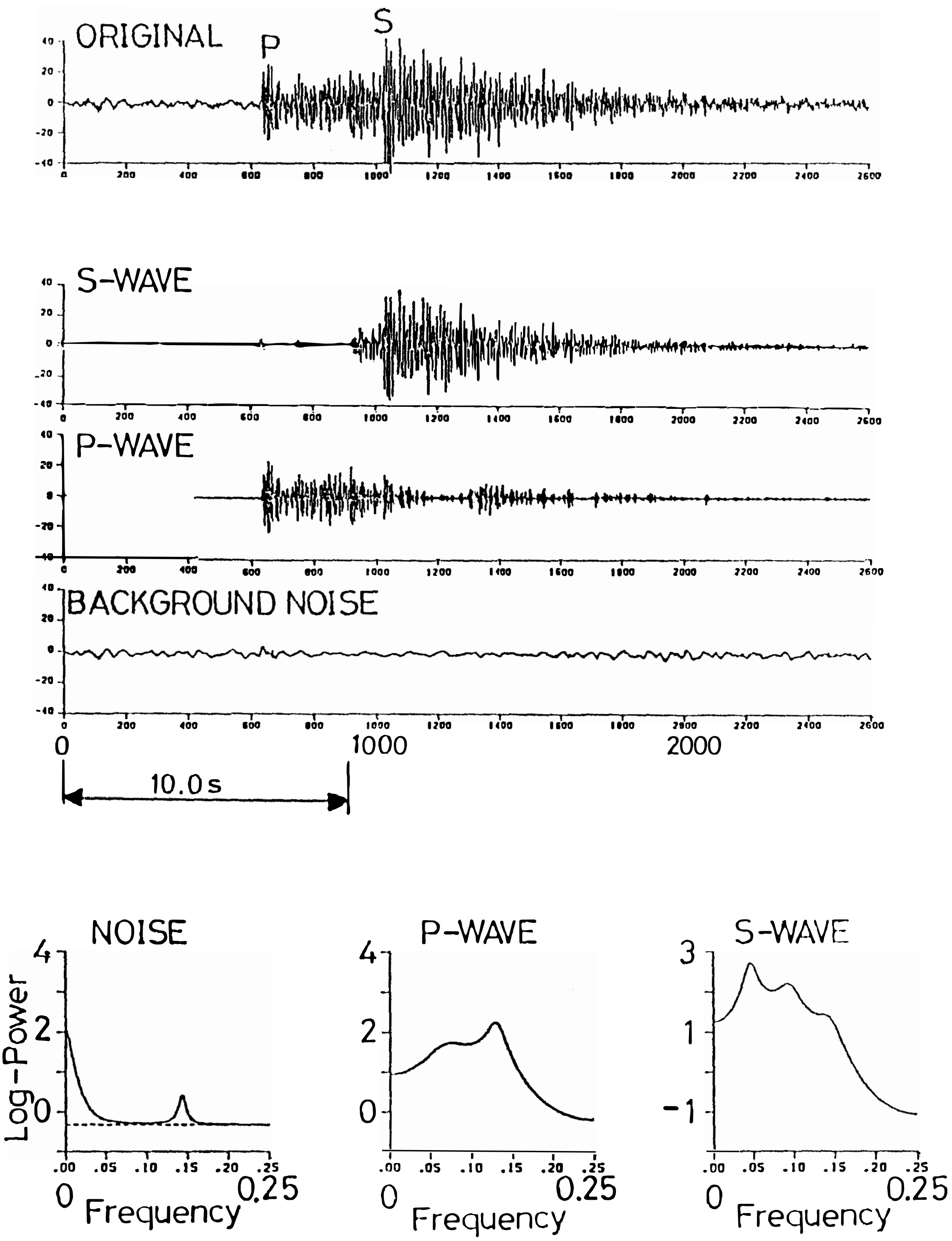

Fig. 3. Decomposition by local likelihood: an east-west component seismogram at station Moyori (MYR). From top to bottom: original data, S-wave, P-wave, background noise, and theoretical spectra of component models (background noise plus observational noise (····), P-wave and S-wave signal model. Frequency normalized by sampling rate).

3. Conclusion

A model for the decomposition of time series into several components has been presented. The estimation of the parameters of the model is crucial and the component *AR* models are determined by the minimum AIC procedure. As examples, two microearthquake signals are isolated from noisy data of a volcanic earthquake that occurred at and near the Mt. Erebus which is an active volcano in Ross Island, Antarctica (TAKANAMI *et al.*, 1982, 1983a, b) and from a local earthquake occurring off Urakawa which is in a higher seismic region in Hokkaido. Next, a model for the decomposition of time series into four components, *P* wave, *S* wave, background noise, and observational noise is shown. *P* and *S*-wave signals are identified in noisy data by using the fitted model. We found another arrival just before the main *S*-wave. This decomposition analysis is especially useful in detailed study of shear waves, which carry an important information about the ray-paths and the sources.

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