A STATE-SPACE APPROACH TO EXPLORE THE STRAIN BEHAVIOR BEFORE AND AFTER THE 2003 TOKACHI-OKI EARTHQUAKE (M8)

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ABSTRACT

The earth's surface is under continuous influence of a variety of natural forces and human induced sources. A strain data is a good example for such disturbed signals. To determine the geodetic strain behavior before and after the 2003 Tokachi-oki earthquake (M8.0), we decomposed the disturbed strain data into several components of trend, air pressure, earth tide, and precipitations responses. The decomposition of the disturbed strain data and the interpolation of the missing observations are performed very effectively by using the state-space modeling and the Kalman filter/smoother. The data processing validity is confirmed by the fact that the model derived to fit the strain data matches the GPS data extremely well.

Keywords: Signal extraction method, State-space model, Kalman smoother/filtering, Strain, Sacks-Evertson strain meter, 2003 Tokachi-oki earthquake, Slow-slip event.

1 INTRODUCTION

On 26 September 2003 a great interplate earthquake (M8.0) struck the Hokkaido corner in the southernmost Kuril trench. The Hokkaido corner is the site of large earthquakes due to the subduction of the Pacific Plate beneath the Hokkaido, Japan at rate of 8.3 cm/yr. The previous great earthquake was the 1952 Tokachi-oki earthquake (M8.2). A Sacks-Evertson borehole strainmeter (Sacks et al. 1971) was installed in November of 1982 to observe the changes before and after such a huge earthquake (Takanami et al., 1998). The observatory is at the located 105 km from the epicenter of the 2003 Tokachi-oki earthquake. Observational data of near surface crustal strain necessarily include changes produced by non-tectonic sources including atmospheric pressure changes, earth tides and precipitation. The continuity of recorded data is also interrupted at times due to power failure and need for instrument maintenance. Thus there is a need to apply processing techniques to remove changes not of interest in seismological studies. We used here the state-space modeling methods for the smoothing and component decomposition tasks developed by Kitagawa and Matsumoto(1996) and Matsumoto and Kitagawa (2003). In principle, it is possible to treat these two tasks simultaneously using state-space modeling and to fit decomposition into components model for the detection of seismic effects to the data with missing and outlying observations. But because of data volume and the need for very high-order models, we adopted a two-stage analysis strategy composing of smoothing by using a simple Gaussian state-space trend model and decomposition into components by assuming the smoothed observation of strain to be characterized by a nonstationary trend and to be influenced by covariate air pressure, tidal, and precipitation effects. In this paper, we show a specific example of time series modeling for signal extraction problem related to geodetic strain change at the 2003 Tokachi-oki earthquake.

2 APPLICATION OF STATE-SPACE MODEL

The strain has been measured in the borehole at station KMU of Hokkaido University since November 1982. The time series of observations of strain (Figure 1) includes the irregular offsets (due to instrument reset). Missing data, in both the strain (upper trace) and air pressure records (middle trace), are due to power failures because, at that time, no on site battery powered recording was operational. Such power failures caused by strong torrential rainfalls, shaking effects of large earthquakes, as well as the problems with local power supplies. Two anomalous torrential rainfalls drenched the area around KMU on 10, July (157 mm/day) and on 9,

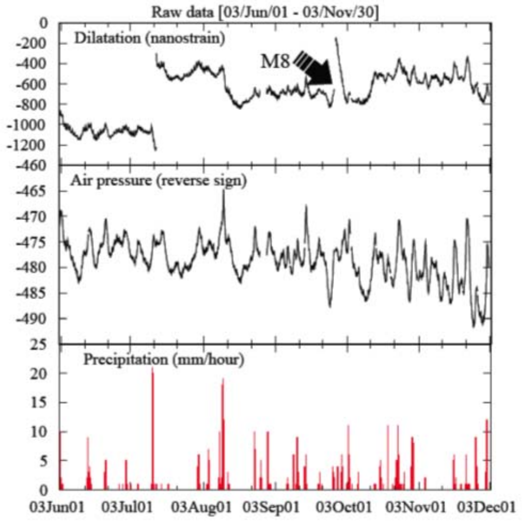

Figure 1. The observations of strain (dilatation), air pressure and precipitation (from top to bottom). The plotted period is from the first of June to the end of November 2003. M8 indicates the occurrence time of the 2003 Tokachi-oki earthquake of magnitude 8. The large jump indicates the reset of observation due to loss of power for 12 hours. Note the jump indicated by M8 is not indicative of the coseismic strain step of the 2003 Tokachi-oki earthquake. The missing data is indicated by a gap in the plotted line.

August (107 mm/day), respectively. In the earlier torrential rainfall, the power supply was also interrupted. Although it is possible to interpolate for the missing data and correct outliers by using a simple non-Gaussian state space model (Kitagawa & Matsumoto, 1996; Matsumoto, 1999), it is almost impossible to restore the missing data at the time of the 2003 Tokachi-oki earthquake. In this paper, we do not deal with such coseismic crustal movement. As to such coseismic behavior, many papers have already been published (e.g. Ozawa et al., 2004; Yagi, 2004; Fukuda et al., 2009; Miwazaki et al., 2008). We address here slow strain changes immediately following the earthquake. Because strain changes induced by non-tectonic changes can mask such slow changes it is necessary to de-convolve those components of the data in order to obtain a reliable estimate of the slow tectonic changes. We used here the state-space modeling method for the smoothing and component decomposition tasks. Successful studies to detect groundwater level have been carried out using the same approach (Kitagawa & Matsumoto, 1996; Matsumoto & Kitagawa, 2003; Matsumoto et al., 2003). As in those papers, the observation data of strain, y_n can be represented by the following model composed of several components

$$y_n = t_n + P_n + E_n + R_n + \varepsilon_n ,$$

$$\varepsilon_n \sim N(0, \sigma^2), \qquad n = 1, \cdots, N \tag{1}$$

where N is the number of observations. t_n, P_n, E_n, R_n and ε_n are trend, air pressure effect, earth tide effect, precipitation effect and observation noise components, respectively. The trend components is expressed by the following first-order trend model (Kitagawa & Gersch, 1984),

$$t_n = t_{n-1} + w_n ,$$

$$w_n \sim N(0, \tau^2) \tag{2}$$

The other components are as given below,

$$P_n = \sum_{i=0}^{m} a_i p_{n-1} \tag{3}$$

$$E_n = \sum_{i=0}^{\ell} b_i et_{n-i} \tag{4}$$

$$R_n = \sum_{i=1}^{k} c_i R_{n-i} + \sum_{i=1}^{k} d_i r_{n-i} \tag{5}$$

where p_n, et_n and r_n are the observed air pressure, the theoretical earth tide and the observed precipitation, respectively. For the precipitation effect, we used the ARMAX type model (Box and Jenkins, 1976) as given the model (5) because precipitation effects may continue for a very long time following the precipitation. The regression coefficients a_i and b_i can be estimated by the Kalman filter. On the other hand, c_i and d_i need to be estimated by numerically maximizing the likelihood function. When the effects of covariates, P_n, E_n and R_n were removed from y_n, the trend was expected to be a geodetic strain before and after the Tokachi-oki earthquake, indicated by the label M8. Next we describe the result of decomposition of 6 months of strain observations at KMU into the trend and the several induced strain components.

3 RESULTS OF THE IMPLEMENTATION OF STATE-SPACE METHOD

Figure 2 illustrates the decomposition of observations into the trend, the air pressure effect, the precipitation effect, and the earth tide effect. Judging from the smoothed trend excepting the trend just after the 2003 Tokachi-oki earthquake, it is confirmed that the influence of the air pressure, the precipitation and the earth tide were successfully removed by the state-space modeling. Consequently, it turns out that a clear slow change of trend appeared immediately after the 2003 Tokachi-oki earthquake. This indicates that a slow-slip event occurred after the 2003 Tokachi-oki earthquake in the vicinity of KMU. The slow-slip event consists of two stages as shown in Figure 2. The first stage started immediately after the Tokachi-oki earthquake until 30 September with a second stage continuing to 23 October. The strain change after the Tokachi-oki earthquake is characterized by a 4-days contraction followed by a 23-days extension. An interpretational model has been illustrated in Figure 3. According to Linde et al. (1996), we generate a quasi-static time series of deformations as the rupture surface grows with down-dip propagation as shown in Figure 3b. The strain change calculated by the model fits to the observations at KMU extremely well. The GPS data at the various surrounding sites operated by GSI are also suitable to the model well especially considering the simplicity of the model (Takanami et al., 2009). Namely, the model is that a large two-stage slow-slip earthquake (equivalent moment magnitude 7.4) occurred mainly on the ruptured zone of 2003 Tokachi-oki. We might incidentally remark that no pre-seismic strain change was detected by the present work.

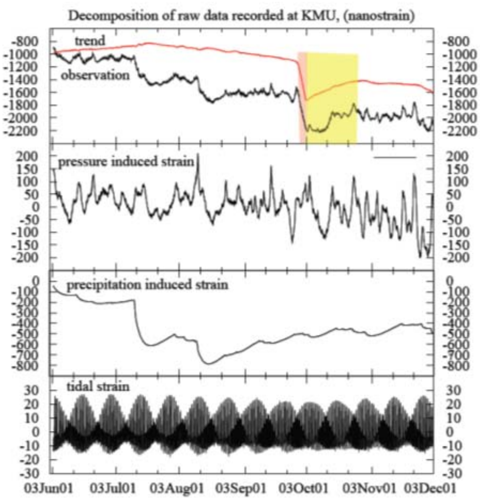

Figure 2. The decomposition of observations recorded by the borehole strainmeter at KMU. From top to bottom, extracted trend (red line), observations of strain, air pressure effect, precipitation effect and earth tide effect are illustrated. A big variation in trend indicates the slow-slip event occurred immediately after the 2003 Tokachi-oki earthquake. It consists of two stages of higher strain rate for about 4days (red patch) and lower strain rate for about 23 days (yellow patch).

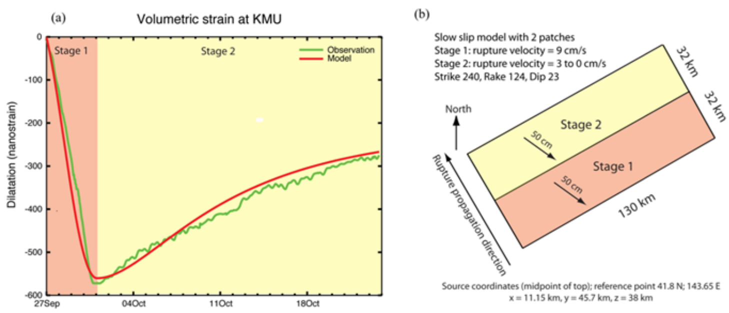

Figure 3. (a) Fitting model curve (red line) inferred from two propagating fault models in Figure 3 (b) to observation data (green line) in stage I (red zone) and II (yellow zone). (b) Schematic propagating fault model for slow slip event consisted of stage I (Red) and II (yellow).

3 CONCLUSION

We confirmed that the state-space approach was very highly effective in isolating a trend of geodetic strain observations. We handled missing and jumping strain observations and deletion of the air pressure, earth tide, and precipitation effects using the state-space modeling method. A slow slip event was clearly detected immediately following the 2003 Tokachi-oki earthquake (M8.0). It consists of two consecutive stages of a 4-day and a 23-day slow slip occurring largely in the ruptured zone of the 2003 earthquake (M8). We can say that the data processing validity is confirmed by the fact that a model derived to fit the strain data making no use of GPS also fits the GPS data extremely well especially considering the simplicity of the model. If the present data processing did not work well then we would not get such consistency. No pre-seismic strain change was detected.

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