Monitoring the crustal temporal variations in Yunnan, China

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Summary

We apply Passive Image Interferometry (PII) to study the temporal variations of seismic velocities with data recorded in Jinggu area, Yunnan Province, China. We process the vertical component data from JIG station in Jinggu area recorded from January 2014 to January 2015, a total of 360 days. We compute the autocorrelation functions to retrieve the Green's functions, and analyze the coda of the autocorrelation functions, which contain information on the scattered wavefield and the complex structures of the Earth medium. Moving Window Cross Spectral (MWCS) technique is applied to compute the temporal variations. We find that the local earthquakes change the stress field and cause seismic velocity variations in the crustal rocks. There is a clear relationship between earthquake occurrence and short term velocity variations. We believe that this approach can be applied to monitor the crustal velocity and stress variations, and help evaluate the earthquake hazard.

Introduction

Noise-based seismic monitoring shows great potential to study the Earth's interior at different scales in space and time. It breaks through the limitation imposed by the dependence on earthquake occurrence. The key point is that we can apply seismic interferometry to retrieve the Green's functions from the cross-correlation of the records of a random seismic wavefield in the study area (Lobkis and Weaver, 2001; Campillo and Paul, 2003; Shapiro et al., 2005; Draganov et al., 2009). The applications of seismic interferometry to seismic ambient noise have been used to retrieve surface waves, estimate their group velocity distribution, and calculate the reflection responses. Surface waves of the Green's function can be extracted from the noise correlation, in addition, it has also been demonstrated that the coda of the Green's function (scattered waves) can be reconstructed from the cross-correlation function (Sens-Schönfelder and Wegler, 2006). The retrieval of scattered waves is applied to detect small changes in the propagating velocities (Sens-Schönfelder and Wegler, 2006). This technique is called Passive Image Interferometry (PII).

Instead of retrieving seismic responses from the cross-correlation between two stations, we calculate the autocorrelation of a single station, which is interpreted as the zero-offset seismic response. Sens-Schönfelder and Wegler (2007) have used the scattered waves retrieved from the autocorrelation functions to monitor the temporal velocity changes.

The main idea for monitoring the evolution of the seismic velocities over time is to compare a 'current' autocorrelation function that represents the situation at a given time period to the 'reference' autocorrelation function that represents an average background state of the studied media. In the first order approximation, the seismic velocity variation (dv/v) can be estimated from the relative traveltime shift (dt/t) between the 'current' and the 'reference' autocorrelation functions. In our study, the Moving Window Cross Spectral (MWCS, Poupinet et al., 1984; Clarke et al., 2011) technique is applied to measure the velocity variations.

Jinggu, in Yunnan Province of China, is located in a seismically active region. A large number of small earthquakes (M<1.0) occurred frequently after a major earthquake (Mw 6.2, 19 km deep) on October 7th, 2014 (Figure 1). In 2014, there are 10,927 small earthquakes occurred in this area following this major earthquake. We apply PII to monitor velocity changes in this region and find that the large velocity changes may seem to relate to the earthquake occurrence, suggesting that this approach can be applied to monitor the crustal velocity and stress variations, and help evaluate the earthquake hazard.

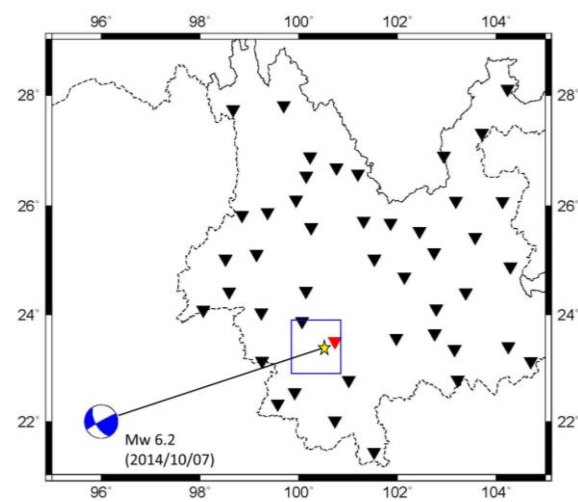

Figure 1: Survey area map. The blue box shows the research area. The black triangles are the stations in Yunnan Province. We apply the continuous record from JIG station (red triangle) to monitor the velocity variations. Location (yellow star) and focal mechanism are shown for the major earthquake (Mw 6.2, October 7th, 2014) in Jinggu area.

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Method

We can retrieve the seismic Green's functions from the cross-correlation of the ambient noise records of two stations (Equation 1).

$$\partial_\tau C_{AB}(\tau) \propto G^+(A,B,\tau) - G^-(A,B,-\tau) \quad (1)$$

Here, C_{AB} is the cross-correlation function between the two stations. G^+ and G^- are causal and anti-causal Green's functions respectively. In our study, we calculate the autocorrelation function of a single station to retrieve zero-offset response and the coda of the Green's function. The method assumes that the noise is mutually uncorrelated for different source positions. We process the data in the following workflow: 1) deconvolving the instrument response; 2) removing the mean and trend; 3) applying a bandpass filter and keeping data within 0.08 Hz to 1 Hz; 4) applying 'one-bit' amplitude normalization and spectral normalization. Note: "One-bit" amplitude normalization is to replace all positive amplitude with 1 and all negative amplitude with -1. Then, 5) calculating the autocorrelation function for records of each day and stacking the 5-day autocorrelation functions to represent one day (the current) autocorrelation function for reliable results. We also stack the three month autocorrelation functions to generate the reference autocorrelation function.

There are certain advantages to retrieve the scattered waves using autocorrelation functions. When we calculate the autocorrelation functions to reconstruct the Green's functions, we only need continuous records from a single station, which is low-cost and convenient. We also avoid the clock error, which could be corrected in the cross-correlation functions between two station records. The coda of the autocorrelation functions is more sensitive to the velocity changes around the station, thus, we can obtain the stress field changes. Figure 2 shows the Green's functions and their coda retrieved from the autocorrelation functions of the vertical component of JIG Station.

When we apply Moving Window Cross Spectral analysis to compute the variations, the first step is the calculation of delay time between two autocorrelation functions. We calculate that in the frequency domain. Each autocorrelation function is divided into *N* windows, each for a delay-time measurement. The cross spectrum between the current and reference autocorrelation functions is $X(f)$, as shown in equation 2.

$$X(f) = F_{ref}(f) \cdot F_{cur}^*(f) \quad (2)$$

$F_{ref}(f)$ and $F_{cur}(f)$ are Fourier transformed representation, *f* is frequency, the asterisk denotes the complex conjugation. The $X(f)$ can be represented by its amplitude and phase in equation 3.

$$X(f) = |X(f)| e^{i\Phi(f)} \quad (3)$$

We can obtain the delay time between the two cross-correlations from the phase $\Phi(f)$. The delay time is linearly proportional to frequency (Equation 4). For each window, we can obtain dt_i, a time shift between the two signals (subscript *i* for the *i*th window) is estimated from the slope of a linear regression of the samples in the research frequency band *j*, as shown in equation 4 and 5.

$$\Phi_j = m \cdot f_j \quad (4)$$

$$m = 2\pi dt_i \quad (5)$$

Then, to a first order approximation, we assume that the stress field is homogeneous over the region. We will obtain the relationship between velocity perturbation and delay times.

$$-\frac{dt}{t} = \frac{dv}{v} \quad (6)$$

Repeating this process for all time windows, we obtain *N* delay times estimated between two cross-correlation functions. We apply a linear regression to the *N* delay-time measurements, we then obtain the relative time variation dt/t.

In equation 1, we notice that the Green's function can be represented by the time derivative of the cross-correlation function. Because the derivative procedure will only introduce a phase shift that will not affect the detection of velocity variations in the emerged signals, in our study, we do not process the derivative calculation, the Green's functions are approximated by the autocorrelation functions.

In the time variation calculation, we utilize 50% overlapping windows with a period of lag time for the analysis. We test four frequency bands (0.2-0.5 Hz, 0.5-1 Hz, 1-2 Hz, and 2-8 Hz) and find that the velocity variations correspond to the earthquake occurrence (Figure 3) fairly well as shown in figure 4.

Results

Figure 4 shows an example of the daily temporal variations of dv/v obtained from JIG Station in the four different frequency ranges. We select five time periods to explain.

The common feature in these five time periods, is that the major velocity changes are related to the earthquake occurrences. In the period (a) we find that in 0.2-2 Hz frequency band, there are clearly velocity drops. We believe these earthquakes place impact on the stress field in the depth between 5 km to 10 km and reduce the velocity. There are no large variations in the frequency between 2-8 Hz, which means these earthquakes do not change the surface stress field. In the period (b), the velocity drop appears in the frequency between 0.5-2 Hz. The velocity has an increasing trend in frequency 0.2-0.5 Hz. There are no obvious changes in frequency 2-8 Hz. The earthquakes change the stress field in the depth around 5 km. This is coherent with the depth of the earthquakes in the earthquake catalogue. In the period (c), the velocity changes appear in all the four frequency bands in different levels. In 2-8 Hz, there is a small increase in velocity. In 0.5-2 Hz, a 4% velocity drop occurs during this period. The Magnitude 1.5 earthquake in February 26th, 2014 may lead to the velocity variations. The earthquake is located at 5 km in depth, which relates to the velocity changes in 0.5-2 Hz. In the period (d), a clear velocity drop is in the frequency 2-8 Hz, we think the two shallow earthquakes on May 20th, 2014 change the surface stress field. In 1-2 Hz, the velocity increases, while in 0.5-1 Hz, the velocity reduces. In the period (f), a large earthquake (Mw 6.2) occurred on October 7th, 2014. Since the depth is 19 km, it's quite deep. It should not change the surface stress field. So in 2-8 Hz, there is no large velocity changes. In 0.2-2 Hz, the velocity changes a little, which reflects the stress field changes under 10 km.

Besides the major velocity changes, we also observe the velocity recovery phenomenon after a large velocity decrease and velocity increasing phenomenon before a sudden velocity drop. The velocity recovery phenomenon is quite obvious in 1-2 Hz of period (c). We can see after a large velocity drop, velocity increases in a trend. This trend lasts about 30 days, before another earthquake occurs and changes the stress field again. The velocity increasing phenomenon appears clearly in 0.2-0.5 Hz of period (b) and 0.5-1 Hz of period (c), we observe an increasing velocity trend (stress increase) before a velocity jump (stress release). This may help us to analyze the possibility of an earthquake occurrence.

Conclusions

We have computed the relative velocity variations in Jinggu area through the analysis of the scattered waves from the autocorrelation functions of seismic noise in the frequency band 0.08 Hz to 1 Hz. The stability of the measurement is ensured through 5 day averaging of the autocorrelation functions. The Moving Window Cross Spectral (MWCS) technique is applied to measure the temporal velocity variations. We find that the velocity gaps are coherent with the earthquakes. The earthquakes produce changes in the regional stress field, thus, velocities vary. We also notice that before a large velocity drop, there is always a trend of velocity increasing (stress accumulation) and after a large velocity jump, there is a velocity healing (stress recovery). This may help us to study the occurrence of the earthquake. We believe that applying PII method to monitoring the regional velocity changes is a promising approach.

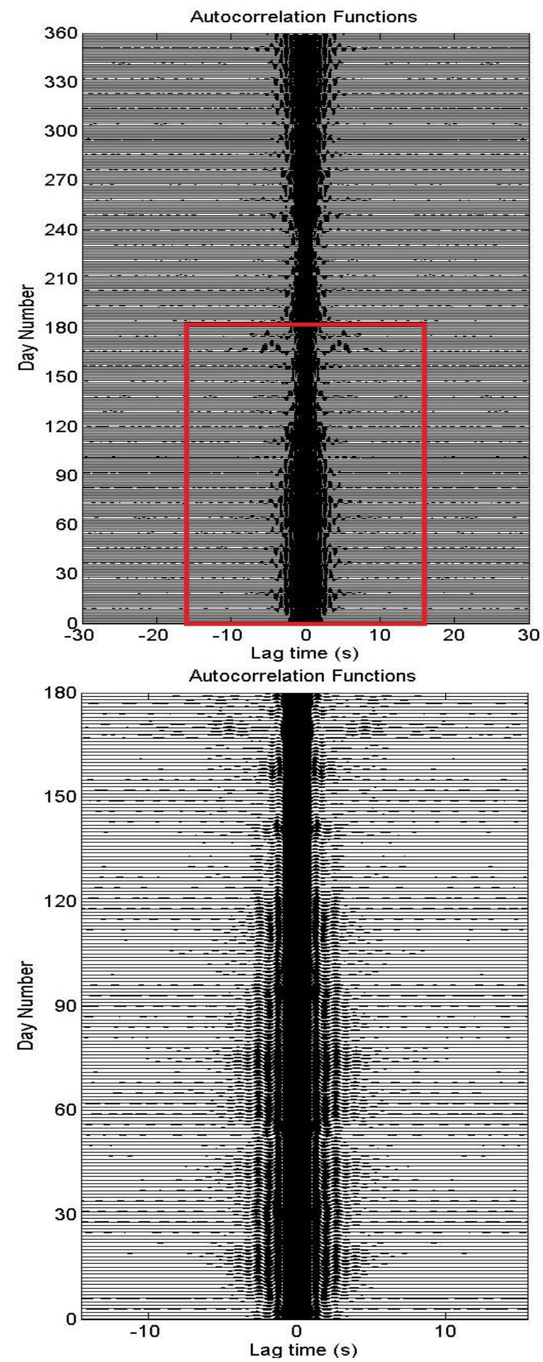

Figure 2: The autocorrelation functions. The top panel shows the 360 day autocorrelation functions, the bottom panel zooms in the red boxed area of the top panel. We can see the coda of the autocorrelations clearly, they are coherent over many days.

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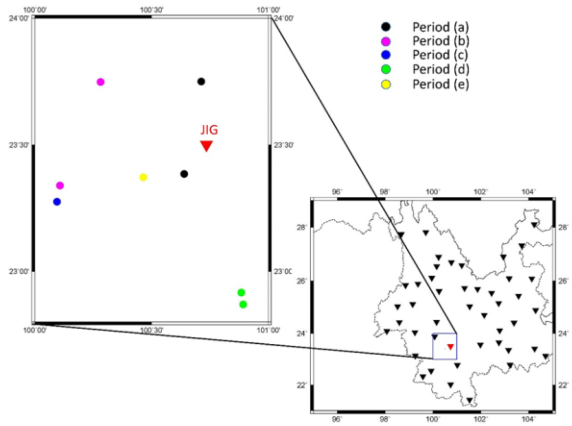

	Date	Time	Latitude	Longitude	Depth	Magnitude
a	01/03	04:50:15.9	23.751	100.713	5 km	2.4
	01/08	10:00:14.1	23.386	100.640	9 km	2.1
b	01/17	04:12:49.8	23.340	100.108	6 km	2.2
	01/26	19:46:40.7	23.749	100.282	8 km	2.5
c	02/26	07:42:27.8	23.276	100.095	5 km	1.5
d	05/20	07:39:55.3	22.869	100.892	5 km	1.4
	05/20	13:32:32.7	22.916	100.884	5 km	1.6
e	10/07	21:49:39.7	23.374	100.465	19 km	6.2

Figure 3: The dominant earthquakes. The top panel shows the locations of the dominant earthquakes in each period on the map. The bottom panel shows the information of the dominant earthquake events in each period.

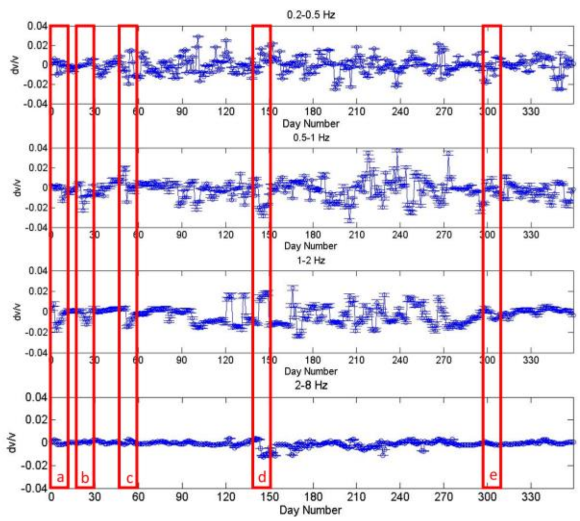

Figure 4: The temporal velocity changes in four different frequency bands. Five time windows are plot on it, in the each time window there are significant velocity changes.

Acknowledgments

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