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Automatic detection and picking of P-wave arrival in locally stationary noise using cross-correlation

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ABSTRACT

Accurate picking of seismic wave arrivals plays a central role in many seismic studies. Nowadays, automatic-picking schemes are indispensable due to the large amount of digital data recorded by wide seismic networks and the need for rapid analysis. The increase of computer power allows the development of more sophisticated algorithms. Many of these algorithms are based on finding change in power, envelope, or statistical properties of the seismic signal in time or frequency domain. But, they have often ignored kind and characteristics of seismic background noise at each recording site. Such information may improve the detector and picker performance if it is taken into account. The aim of this study is to propose a method for picking the arrival of the P-wave in locally stationary seismic background noise. In fact, through analysis of background noise, we have found that it shows local regularity at seismically quiet sites. Therefore, if the background noise satisfies local stationarity, it is evident that occurrence of a seismic event will violate this stationarity. The transition from stationarity to non-stationarity is exploited to pick the P-arrival. To quantify the degree of signal stationarity, we use the normalized cross-correlation function. This method can detect and pick changes both in frequency and amplitude. Thus, it provides robust detection and picking of P-phase onsets even when the signal-to-noise ratio is low. Experimental results on real seismic data, consisting of local seismic events of different signal-to-noise ratios, and comparison with commonly used methods in practice demonstrate the reliable performance of the proposed method.

1. Introduction

Signal detection processes aim to detect the presence of the desired signal in a combination of other signals which can be considered in this case as noise. It is an operation that involves not only the signal-to-noise ratio (SNR), but also other quantities characterizing the signal. Indeed, the signal depends on various parameters such as amplitude, phase and frequency. Unfortunately, these parameters are rendered random because the signal is more or less distorted by the action of heterogeneous environments. This makes its characteristics unpredictable. For instance, the pattern of seismic waves is strongly dependent upon the geology at the source and source mechanism as well as the medium through which they propagate. Therefore, the recorded signal is altered and varied greatly from region to region. This has the unfortunate consequence on the signal detection to be a difficult task. In practice, several different methods have been considered, which are generally based on finding sharp changes in some characteristic properties (e.g. energy, variance, envelop and higher order statistics) of the seismic trace in the time domain, frequency domain or time–frequency representations [1–20]. Generally, seismic phase detection process is followed by phase picking analysis in which more precise measurement of the phase arrival time is performed [21].

In this paper, we are particularly interested in detecting and picking the P-wave for local events. The P-wave or primary wave is the fastest type of the seismic waves, and, consequently, the first to arrive at seismic stations. Seismic phase arrival time identification is a fundamental task in seismology, as it enables scientists to derive important geological and seismological information, such as seismic event location and internal structure of the earth. Traditionally, phase arrival time picking has been carried out manually by analysts. However, the introduction of digital seismic monitoring systems and the increasing volume of data collected by large seismic networks, as well as the need for providing fast earthquake location led to the necessity of developing automatic tasks.

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The automatic seismic detector widely used in practice is based upon signal-to-noise ratio, which deems a detection to occur when the ratio exceeds a predetermined threshold [1–3]. The most common form of this seismic detector was defined as the ratio of the short term average (STA) to long term average (LTA) [1]. Due to the recent advanced technologies and importance of reliable detection and accurate picking tasks, a large effort has been put into finding efficient and sophisticated algorithms that can detect and precisely pick arrivals of seismic waves. Various different approaches to the problem have been proposed in the literature. These include algorithms that examine wave polarization [4,5], methods that use artificial neural [6–8], wavelet-based methods [9–12], spectrogram-based methods [13,14], autoregressive techniques [15], local-maxima distribution [16], higher-order statistics [17,18], and manifold-based approach [22].

In an effort to detect weak seismic events as well as pick low SNR and emergent arrivals, numerous techniques have been examined. Among the time-domain approaches, we can cite the widely used function for similarity detection and measure, called cross-correlation. The cross-correlation technique is becoming a standard method for identifying seismic signals from repeating sources [23]. Indeed, several studies have investigated this technique for detectability of low-magnitude events which are too weak to be sensed using conventional energy detectors [24–36]. The idea was to continuously quantify the existing similarity between a preselected event signal, considered as a template, and the successive time segments of incoming data. Segments which display similar signal to the template are identified by a remarkable correlation coefficient value (an upward variation of correlation coefficient occurs). The implementation of cross-correlation detector (also called matched filter detector) in practical monitoring systems has some limitations [28]. This is due to the fact that it entirely relays upon signal similarity between events, while the majority of seismic events come from unknown and dissimilar sources, and consequently have unknown and different waveforms, thus difficult to make a template waveform. This method could only be efficient in situations where the two compared events are recorded at the same station and generated from repeating seismic sources, or occurred within very close proximity of each other and were associated with similar source mechanisms [28,31]. However, due to the complicated source mechanisms (therefore highly varying source functions) and strong heterogeneity within the medium as well as frequency dependence upon the distance between recording stations and source (the frequency decreases rapidly as the source-receiver increases), the applicability of correlation detector using the previous recorded events as templates is restricted to exceptional situations such as aftershock sequences and repeating sources [28,30]. The aim of this study is to investigate another approach for using the cross-correlation. The basic idea behind this approach was motivated by the fact that seismic background noise sources can be locally stationary. Indeed, through analysis of seismic background noise, we have found that it satisfies local stationarity at seismically quiet recording sites. Hence, two consecutive segments of background noise recorded by the same instrument will show similarity when they are generated by the same stationary noise sources. In other words, the background noise properties computed over short time intervals do not vary significantly from one interval to the next. On the contrary, occurrence of a seismic event will violate the stationarity of the background noise. This property can be exploited to detect and pick the P-wave arrival.

The main contribution of this study is to extend the applicability of the cross-correlation technique in the field of seismic detection and picking. Such technique provides a high sensitive detector for both frequency and amplitude variations. Therefore, it mainly addresses the problem of automatic detection and picking, especially when the signal-to-noise ratio is low.

As previously assumed by Takanami and Kitagawa [37], the proposed method is based on the assumption that the background noise can be divided into locally stationary segments. Because seismic events and background noise are generated by two different processes, arrival of seismic phase is usually accompanied with changes in signal characteristics. This makes the intervals before and after the P-wave onset different. In order to detect abrupt changes and pick the precise time instant at which properties are suddenly changed, an algorithm has been developed. In this study, we demonstrate the accuracy of the algorithm on many seismic local events detected by STA/LTA energy detector. An online standalone version of the algorithm is still under examination.

The rest of this paper is organized as follows. In Section 2, we firstly address the notion of stationarity in the wide sense, and then, we define the correlation functions and their estimates. Subsequently, we explain how the proposed method can be used for both P-onset detection and picking. Section 3 demonstrates examination results of the method using both synthetic and real seismic signals. Examination on seismic data includes comparison with results derived by analysts and frequently used automatic algorithms. Finally, we draw conclusions in Section 4.

2. Mathematical background and methodology

2.1. Stationarity in wide sense

Stationarity refers to time invariance of some, or all, characteristics of a random process, depending on stationarity in wide or in strict sense [38–41]. In this paper, we use the term "stationary" to mean stationary in wide sense.

Consider a time history $x(t)$, the first statistical quantities of interest are the ensemble mean values at arbitrary fixed values of t. These are defined by [40]:

$$\mu_x(t) = E\big[x(t)\big] \tag{1}$$

where $E[\cdot]$ denotes the expectation operator.

The next statistical quantities of interest are the covariance functions at arbitrary fixed values of t. These are defined by [40]:

$$C_{xx}(t, t+\tau) = E\big[\big(x(t) - \mu_x(t)\big)\big(x(t+\tau) - \mu_x(t+\tau)\big)\big] \tag{2}$$

where τ is the time lag.

In the case where these quantities vary as time t varies, the process is said to be non-stationary [40]. Therefore:

- The mean values are different at different times, and must be calculated separately for every t of interest. That is,

$$\mu_x(t_1) \neq \mu_x(t_2) \quad \text{if } t_1 \neq t_2 \tag{3}$$

- The covariance functions are different for different combinations of t_1 and t_2.

In the case where the mean values $\mu_x(t)$ and the covariance function $C_{xx}(t, t+\tau)$ yield the same results for all fixed values of t (they are independent of time translations), the process is said to be weakly stationary or stationary in wide sense [40]. So, for stationary random processes, the mean values become constant (independent of t) and the covariance functions are dependent only on the time lag τ. That is, for all t,

$$\mu_x(t) = \mu_x \tag{4}$$

and

$$C_{xx}(t, t+\tau) = C_{xx}(\tau) \tag{5}$$