Automatic S-Phase Arrival Determination of Seismic Signals Using Nonlinear Filtering and Higher-Order Statistics

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ABSTRACT

Automatic seismic P- and S-phases arrival identification has been a challenging scientific goal for the last two decades for seismologists, as it provides them with important seismological information. Based on recent bibliography, various approaches result in efficient P-phase identification, while S- phase identification is still an open problem, since there is an overlap of the S- phase arrival and the P- phase coda. They usually employ simple energy ratio criteria, the linear seismic wave polarity assumption, neural networks or heuristic methods based on seismologists' experience, but they seem to have moderate performance, especially for noisy cases. The proposed method uses a Wavelet Transform-based filtering technique that separates the STationary from the NonSTationary parts of a mixed signal, namely the WTST-NST filter, combined with Higher-Order Statistics (HOS). Initially, the WTST-NST filter is used to remove the undesired P-phase coda (given the P-phase arrival) and the background noise from the seismic data. Then, the HOS are applied on the de-noised signal to detect the S-phase arrival at the location of the maximum value of HOS. The method has been applied on real seismic data recorded in Greece, characterized by human experts as highly noisy cases. Experimental results indicate that the proposed method identifies the S-phase arrival efficiently, since evaluation analysis proves high identification accuracy, when compared to the analysts' findings and due to its low computational complexity, real-time implementation is feasible.

INTRODUCTION

Seismic-phase (or seismic wave) arrival identification and determination are vital tasks for seismologists, as they provide them with important geophysical and seismological information, such as the structure of the Earth's substrata, geotectonic settings, hypocentric and epicentric coordinates of an earthquake, the seismicity of an area and seismic hazard assessment. Seismic-phase arrival identification is the identification of the various seismic waves (compressional or P- waves, transversal or S- waves, Rayleigh, Loeve waves etc.) that arrive at the seismological stations at distinct instants due to the propagation with different mechanisms and through an inhomogeneous media such as the Earth. On the other hand, seismic-phase arrival determination refers to the accurate temporal determination of the arrival of each phase identified. Traditionally, human experts, the analysts, have been carrying out this task. The progress of the science of Seismology though, the vast volume of seismic data to be assessed and undesired effects, such as analysts boredom and tiredness, led to the need for automatization (without human intervention) of the above mentioned procedures, mainly the P- and S- phase identification.

The growth of computational power the last two decades made the implementation of such automatic algorithms feasible. Although several efficient algorithms have been proposed for the P- phase arrival identification and determination, only few ones [1], [2], there have been developed for automatic S- phase arrival identification and determination; this is still considered as an open problem. The main difficulty for the S- phase determination, either manually or automatically, lies in the fact that as S- waves travel with a lower velocity than P- waves, they emerge, although the P- phase coda is not sufficiently dumped. The proposed approach uses Higher-Order Statistics (HOS) and a nonlinear filtering technique based on the Wavelet Transform (WT) [3], and it has been applied on real seismic data recorded in Greece. Evaluation analysis proves that the proposed algorithm results in high identification accuracy, with increased robustness and low computational complexity that leads to its real-time implementation.

SEISMIC WAVE PROPAGATION AND CHARACTERISTICS

Earthquakes are studied using records (seismic traces) of mechanical vibrations of the Earth. These records register the effect on the surface of the Earth of the propagation of different types of waves originating from a certain point or surface in the interior of the Earth. The physical quantity that used to measure this effect is the particle displacement vector and the equipment used to record this quantity is usually a three-component seismogram (3-CS), which records the ground motion in the vertical and two horizontal (usually east-west and south-north) directions. The different types of waves (phases) are due to the different mechanisms of propagation through an elastic medium, such as the interior of the Earth and its inhomogeneity. The types of phases that this work refers to are the P-phases and the S-phases. The P-phases or primary waves are compressional elastic waves i.e. the particle displacement is parallel to the direction of wave

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This work was supported by the Regional Operational Program of the Region of Central Macedonia, Greece, SAE/2 046/2, 1998-2000 C. D. Saragiotis is supported by the Scholarships State Institute (I.K.Y.) of Greece, under Grant 1999-2000.

propagation. The S-phases are transverse waves, i.e., the particle displacement is perpendicular to the wave propagation

Two very significant features of the seismic traces are the arrival times of the compressional elastic waves and the transversal (shear) waves, or P and S arrivals.

THE WTST-NST FILTER

The WTST-NST filter [3], is a non-linear filter based on the WT. Its function is to separate the non-stationary part of a signal from its stationary one. It does so adaptively, based on MultiResoloution-Decomposition (MR-D) and MR–Reconstruction (MRR), combined with hard thresholding. Its flow diagram is shown in Fig. 1.

In this work, the WTST-NST filter is applied on the segment of the seismic signal included in the region between the pre-defined (by an analyst or a P-phase determination method, such as [4]-[10]) P arrival and the estimated location of the maximum value of the seismic trace after the P arrival. In particular, this nonlinear filter is used to separate the P-phase coda from the S-phase that emerges simultaneously.

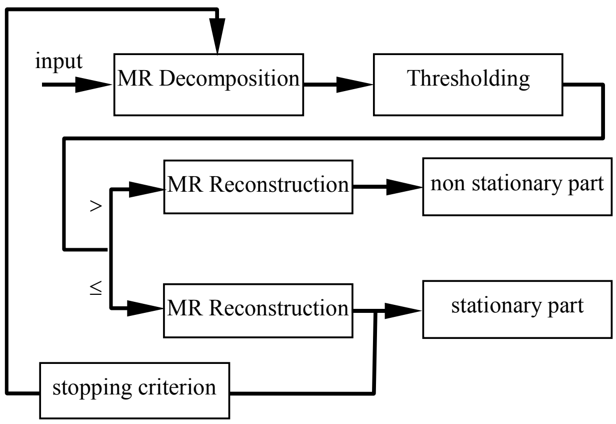

Figure 1: Simplified flow chart of the WTST-NST filter.

HIGHER-ORDER STATISTICS

HOS is a relatively new probabilistic approach of stochastic signals with many applications. A thorough and mathematically detailed treatise on HOS can be found in [11]. In this work, the HOS have been used to determine the emergence of a non-Gaussian signal (seismic signal) from a normally distributed background signal (noise). This is due to a basic property of normally distributed signals to have zero valued HOS, such as the skewness (3rd-order statistic) and the kurtosis (4th-order statistic) and signals with asymmetric or heavy-tailed distributions to have high values of skewness and kurtosis [11].

The estimates of the skewness $\hat{\gamma}_3^x$ and kurtosis $\hat{\gamma}_4^x$ of a M -length time series $x(k)$ are given by

$$\hat{\gamma}_3^x = \frac{\sum_{i=1}^{M}\left(x(i)-\hat{m}^x\right)^3}{(M-1)(\hat{\sigma}^x)^3}, \quad \hat{\gamma}_4^x = \frac{\sum_{i=1}^{M}\left(x(i)-\hat{m}^x\right)^4}{(M-1)(\hat{\sigma}^x)^4}-3, \qquad (1)$$

where $\hat{m}^x$ and $\hat{\sigma}^x$ are the mean value and the standard deviation of $x(k)$, respectively.

IMPLEMENTATION AND EXPERIMENTAL RESULTS

For the S-phase arrival determination the proposed method acts in two steps (see Fig. 2). In the first step, the WTST-NST filter is applied on a windowed seismic signal, as previously explained, located in the area of the S-phase arrival, in order to eliminate the P-phase coda from this area. Then, in step two, the skewness and kurtosis parameters of the de-noised S-phase area are calculated, using a moving time-window of 100 samples in length, in order to reveal the change of the distribution of the signal, which denotes the exact location of the S-phase arrival. It should be noted that the S-phase arrival is selected as the time where the first abrupt change in the values of the HOS parameters occurs and not as the time where the HOS parameters present maximum values. This is due to the fact that the skewness and kurtosis parameters take a maximum value when a sufficient part of the S-phase is included in the moving time-window and not when the S-phase first arrives.

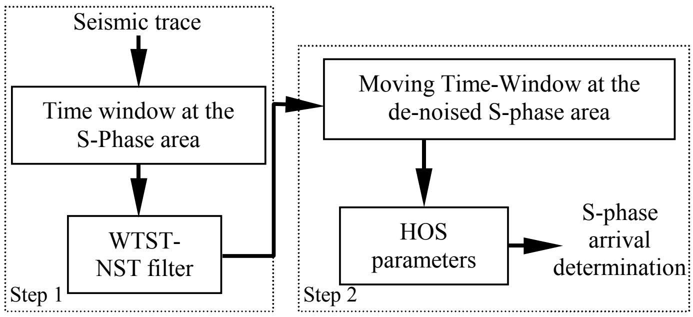

Figure 2: Block diagram of the proposed scheme.

The proposed method was conducted on typical, highly noisy, seismic data (earthquakes in the area of Central Macedonia, Greece) collected by the seismological network of the Department of Geophysics School of Geology of Aristotle University of Thessaloniki, Greece. The seismic data were acquired using a 12-bit A/D converter, after antialiasing filtering, with a sampling frequency of f_s=50 Hz. The lengths of the processed records ranged from 8000 to 12000 samples. Parameters to be considered are the length of the moving time-window on which the HOS parameters are calculated and the hard thresholding parameter F_{adj} used in the WTST-NST filter. Typical results are shown in Figs. 3 and 4.

ALGORITHM EVALUATION AND DISCUSSION

The algorithm has impressive results in a variety of signals even some highly noise-contaminated data. The difference between the algorithm's and the analyst's S-phase picking varied from –10 to +3 samples, indicating a highly accurate performance of the proposed scheme. Regarding the moving time-window length it must be sufficiently long, in order to give reliable values, but also not too long, as this may smooth the HOS parameters and miss the exact S-phase arrival. Best time-window lengths seemed to be 100 samples (or $2 \cdot f_s$

samples) for the data examined. The parameter F_{adj} should belong into the interval [2.0, 3.0] depending on the noise level, or in most cases into the interval [2.0, 2.7]. The time of implementation is negligible relative to the time of the signals examined due to its low computational cost.

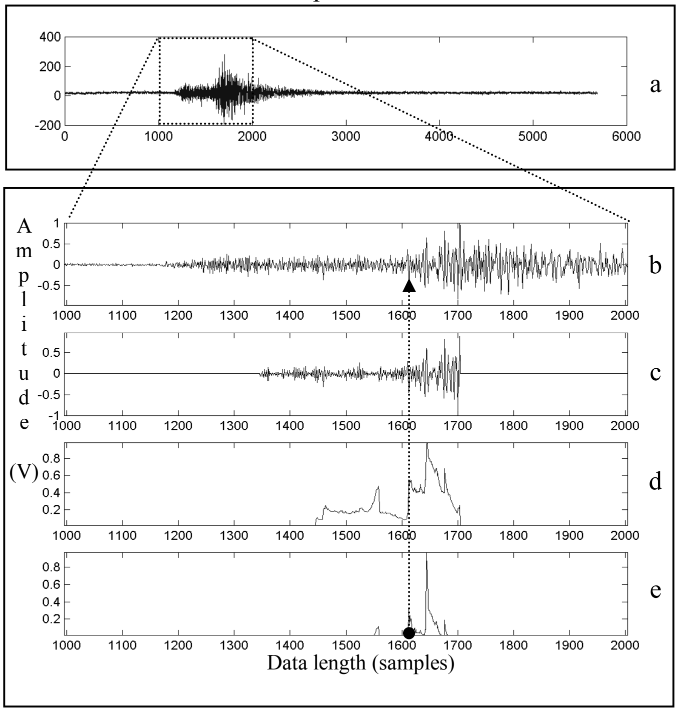

Figure 3: (a) The recorded seismic trace, (b) The output of the time-window located at the S-phase area, (c) The output of the WTST-NST filter, (d) The estimated skewness for a moving time-window of 100 samples in length, (e) the derivative of the skewness. The dashed arrow located at the maximum value of (e) indicates the estimated S-phase arrival. The deviation from the analyst's estimation is –6 samples.

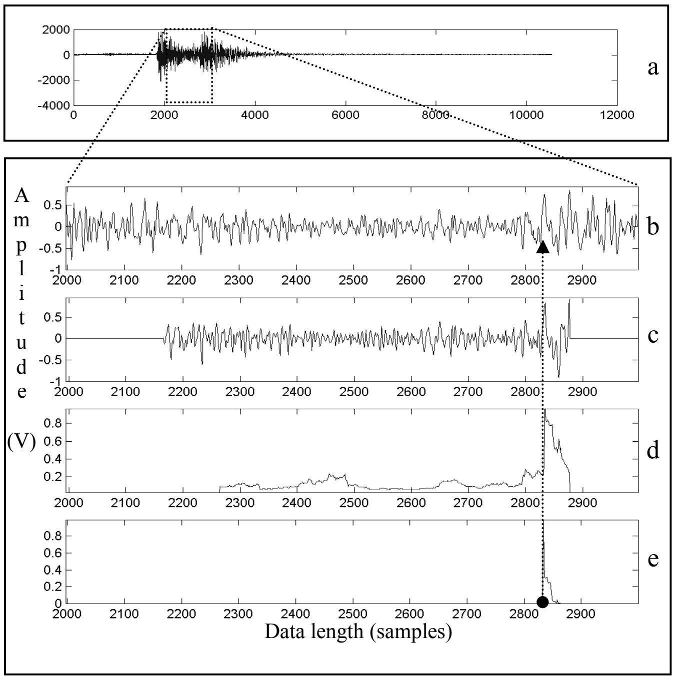

Figure 4: (a)-(e) Similar to Fig. 3. The deviation from the analyst's estimation is –10 samples.

CONCLUSIONS

In this work, an automatic S-phase picker using a WT-based nonlinear filtering combined with HOS has been developed. The proposed scheme has considerable results, some of which very impressive. It has low computational complexity and real-time implementation is feasible due to its fast performance. It is robust to noise contamination and results in an automated S-phase identification, even in cases where the analyst is difficult to identify. Long scale tests of the proposed algorithm are included in an on going project.

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