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Matched-Filter for detecting aftershocks of the 2014 Mormori-Ilam earthquake

Iman Kahbasi, Ehsan Karkooti, Saeed SoltaniMoghadam

International Institute of Earthquake Engineering and Seismology

International Institute of Earthquake Engineering and Seismology (IIEES)

INTRODUCTION

The detection of earthquakes with magnitudes less than the Mc is a challenging task, because of seismic waves attenuation and unavoidable noise levels at seismic stations.

Consequently, many earthquakes with magnitudes less than the Mc value of a given seismic network may remain undetected.

METHODS/DATA

The Matched-Filter (MF) technique is a signal processing approach, which makes it possible to identify seismic phases even with very low SNR in case of repeating events.

We utilized the MF method on 95 days of continuous data with 13 temporary seismic stations installed by the IIEES to monitor the aftershock sequence of the August 2014 ML 6 earthquake in Mormori, Ilam province.

START

RESULTS

Using the MF method and 838 reference earthquakes (REQ), 3575 aftershocks were detected (4.27 times the REQ).

The detected aftershocks are classified and interpreted based on the quality of location.

CONCLUSION

Because each REQ can detect new ones with maximum quality and number of phases similar to its own, the MF method shows its best performance when REQ's phases are picked completely and accurately.

Due to the accuracy of phase determination in this method, its processing time is very suitable.

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Introduction

Why we used Matched-Filter?

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The detectability of seismic events in a seismographic network depends on inter-station spacing (network density) and the level of noise at each station. When seismic waves propagate, the amplitude of the waves decreases over time and distance from the epicenter due to the seismic attenuation. This effect, together with the unavoidable noise level in the seismic stations caused seismic waves of many earthquakes with magnitudes less than the Mc of the network, buried in the noise. So, the buried seismic phases are undetectable by observation or detectors that rely on signal energy. As a result, many small earthquakes remain undetected in the network. So, it is very advantageous to use improved signal processing techniques to increase the efficiency and detectability of a seismological network.

We will explain why we are interested in the Matched-Filter (MF) technique:

1. The Matched-Filter method (using waveform Cross-Correlation as an identifier) enables the identification of seismic phases below the noise level in known source conditions (Schaff and Richards 2014).
2. The waveform Cross-Correlation technique can determine seismic phase time with great accuracy. Even phases with very low SNR or buried in the noise are detectable accurately.

Considering the ambient vibrations as random or Gaussian seismic wave fields and the unique features of the earthquake waves, these waves are distinctive from other waves (natural or artificial). Therefore, any significant similarity resulting from the correlation of seismic waves and recorded earthquake data indicates a seismic wave with similar characteristics (Schaff and Waldhauser 2010).

Energy detectors and manual event identification by specialists do not require prior information about the events. Unlike these methods, a priori information is crucial for using the Matched-Filter technique, and identifying seismic phases is possible in the case of known sources. In other words, the reference signal utilized for similarity detection acts as a filter on data, identifying bits of the continuous data that are similar to prior earthquakes.

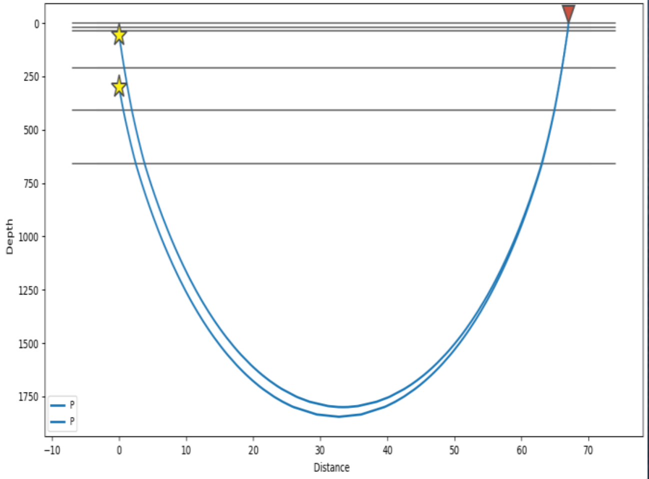
The recorded seismic signal by a seismographic station is the result of the convolution of the instrument response, seismic attenuation, Green's function, and source function. So, these parameters control the similarity of the two seismic data.

$$CC(O1, O2) = CC(I1 * A1 * G1 * M1,\ I2 * A2 * G2 * M2)$$

Two earthquakes with neighboring epicenters whose waves were detected using the same seismographic stations might be assumed for this purpose. In this configuration, the effect of attenuation, Green's function, and instrument response are identical on both signals. So, the source parameter of two earthquakes controls the degree of similarity between their signals. (Zhang and Wen, 2015)

$$CC(O1, O2) = CC(M1, M2) = CC(S1, S2)$$

Therefore, having prior seismic phase data in a region as the references signal and calculating its correlation with the continuous data in the same network, will make it possible to identify new seismic phases.



In this study, we have implemented the Matched-Filter method in the Python environment with EQcorrscan library (Chamberlain et al. 2017)

INTRODUCTION
OBJECTIVES
METHODS/DATA
RESULTS
CONCLUSION

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Objectives
How to we selected parameters of Matched-Filter?

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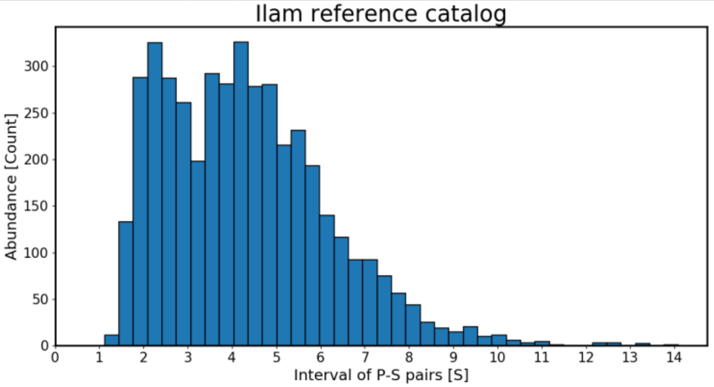
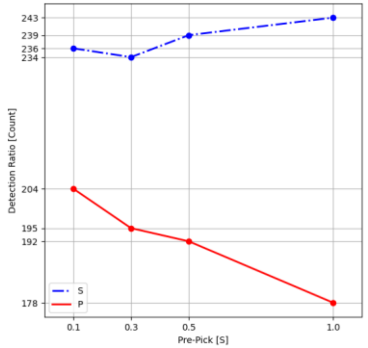
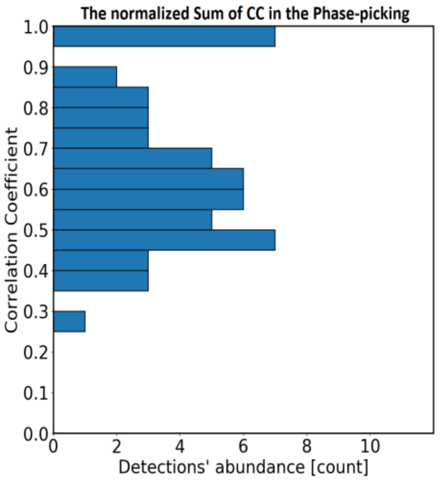


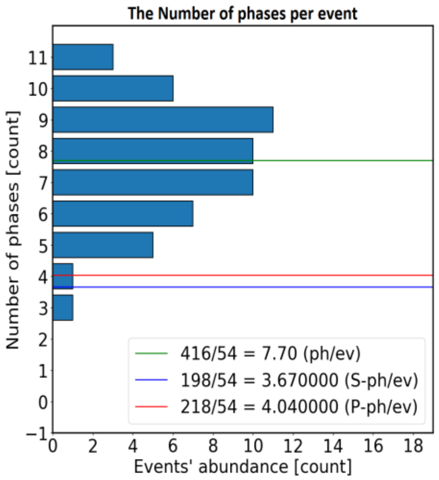
* Template length:
Because local earthquakes have a high-frequency content, a short data duration can cover the entire P or S seismic phases. Selecting disjointed templates of P and S phases is essential to accurately pick the onset of seismic phases in the phase-picking stage. This study proposes developing a histogram of the S-P time differences of the REQ to take a vision of how long time could produce a disjointed template of P and S phases. We decided to select 1 s length of data as a template.

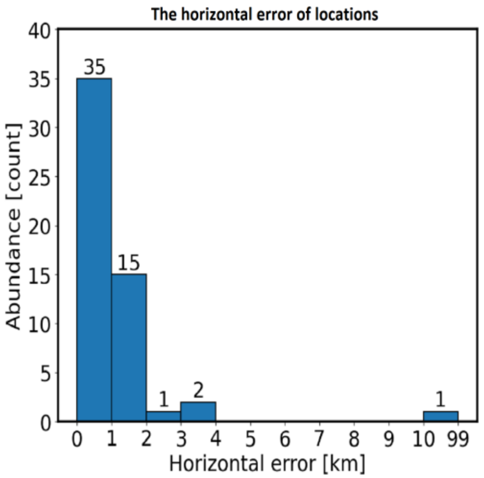
* Minimum time intervals between sequential identifications:
The presence of duplicated identifications by different references leads to considering the minimum time interval between the adjacent detections to remove duplicate ones. We set this parameter to 10 seconds, by considering the S-P histogram.

* Length of pre-phase:
The pre-phase parameter of earthquake templates is necessary to decrease the uncertainty of phase unset. To evaluate the effect of it on the power of detections, we selected the references in four groups of pre-phase duration, including 0.1, 0.3, 0.5, and 1 second of pre-phases and 1 second of after-phase time. Based on the findings, as the pre-phase time increases, the ability to identify P phases decreases, while the ability to identify S phases increases. We utilized 0.1 s pre-phase in order not to lose the desirable ability to identify the P phases compression of S phases.









* Frequency range of the filter:
Selecting an efficient filter is highly influenced by the frequency content of the earthquake data and the ambient noise. We tested some range of frequency filters on one day of data and selected 2-8 Hz with the best performance, considering maximizing correlation values and the number of phases per event and minimizing the location's error.

* Detections thresholds:
The fluctuation range of correlation signals and their superposition is unpredictable due to employing multiple references with varying phases and the daily variation in station noise level. So, for each REQ and day of data, a threshold sets to 10 times the Median Absolute Deviation (MAD) of the stacked CC.

INTRODUCTION
OBJECTIVES
METHODS/DATA
RESULTS
CONCLUSION

Methods/data (1/2)

Ilam network and data

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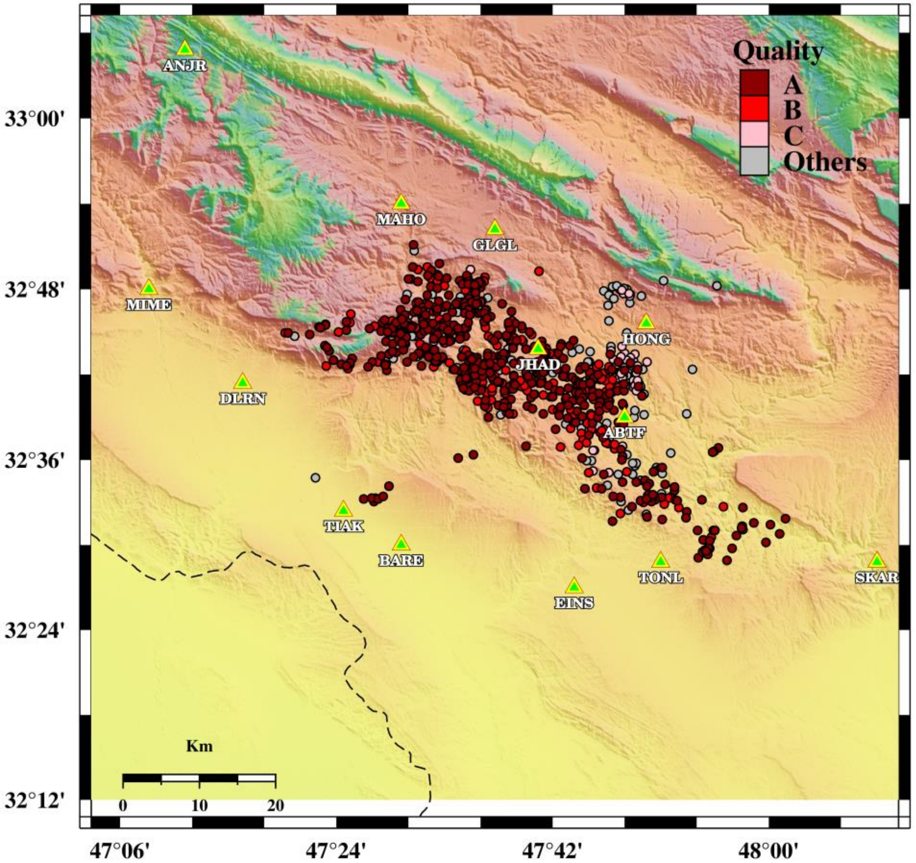
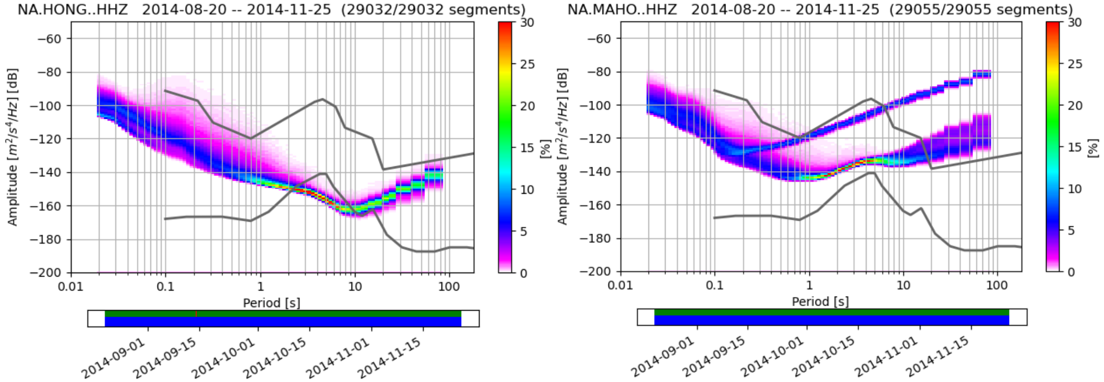
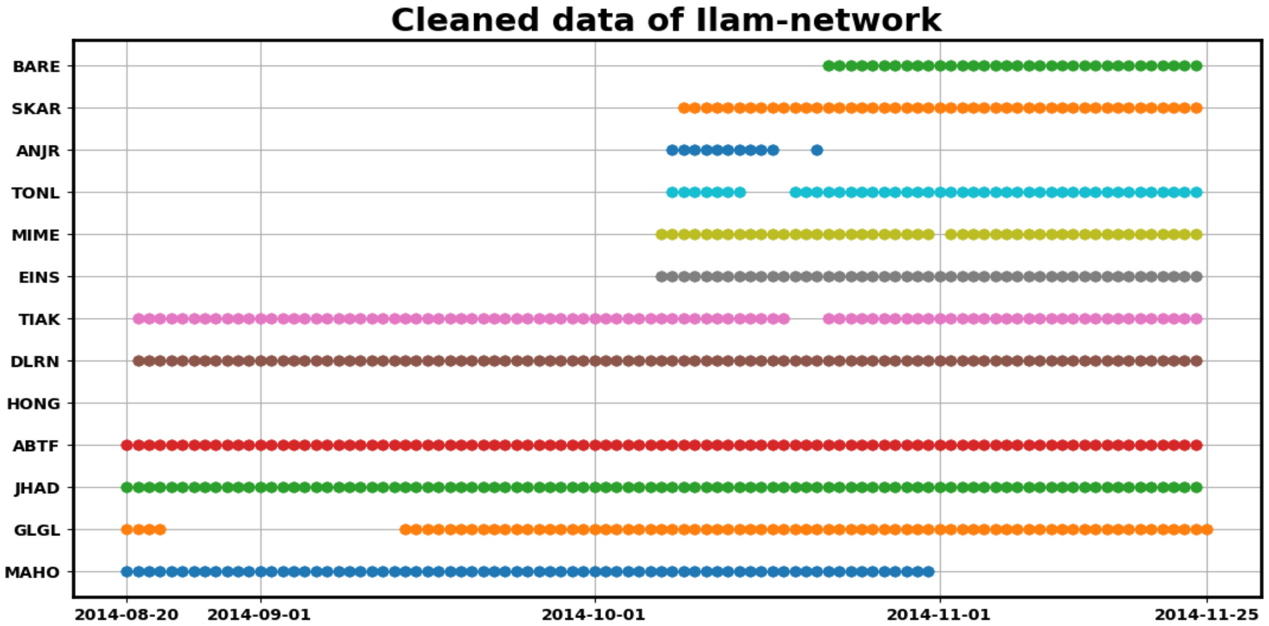
This study investigates the recorded data from the temporary seismographic network installed after the 2014 earthquake in the Ilam region in Iran. This network has included 13 seismograph stations, which recorded seismicity activity for about three months. Although, in the first half of this period, the network was active with only 7 stations, so most of the aftershocks were detected and located with this number of stations.
838 detected aftershocks were determined manually, and considered as the reference earthquakes (REQs).



We plot the PSD of data to identify the time intervals when each station recorded incorrect data and removed them. This stage shows that the HONG station work incorrectly all of the time.



The state of the network data after removing inappropriate data is shown in the figure below.



Methods/data (2/2)

Applying Matched-Filter method

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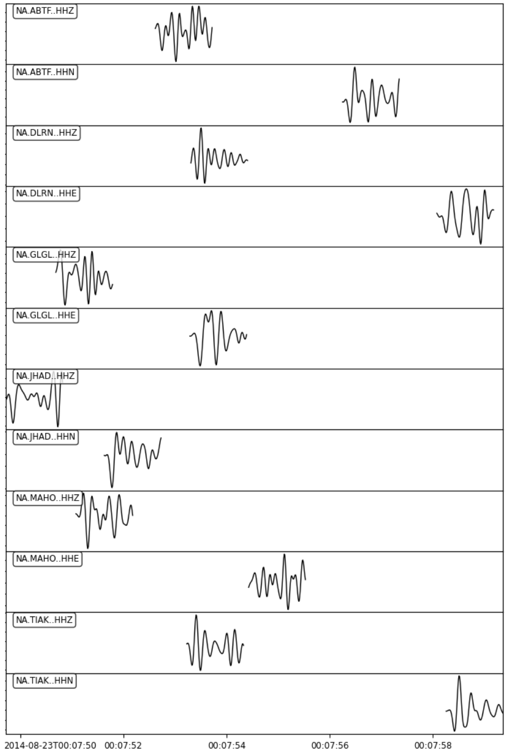
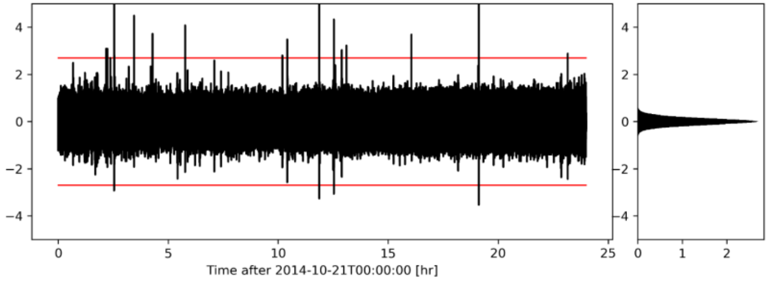
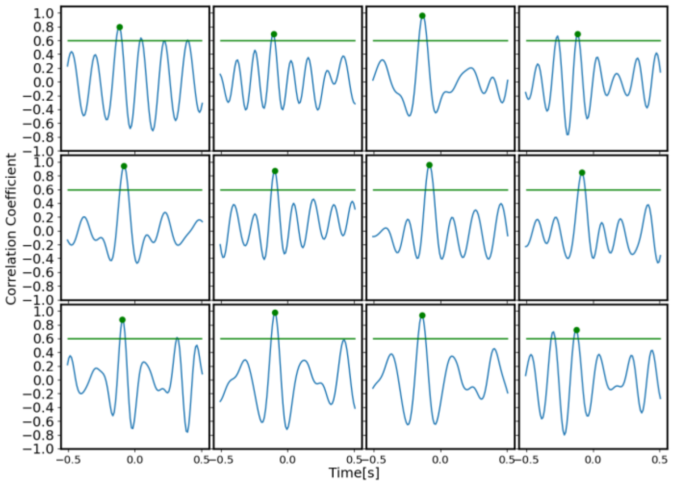
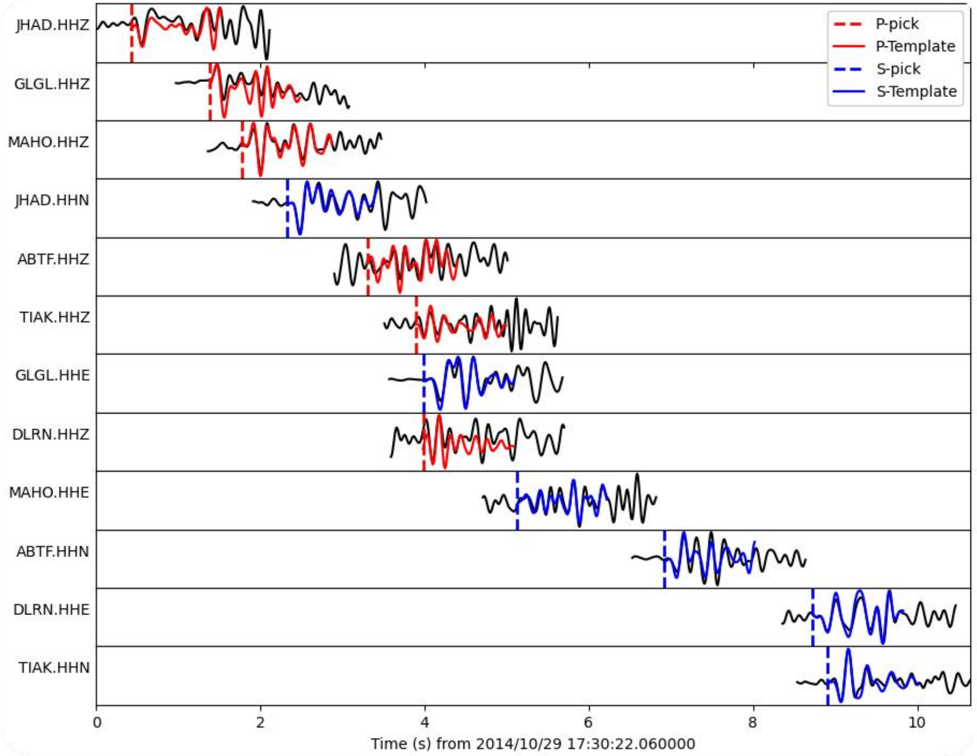
Stages of the processing:

1) Daily data grouping.
2) Necessary data pre-processing. [100 SPS, 2-8 Hz, Filling gaps]
3) Selecting reference earthquakes (REQ).
4) Extracting templates. [0.1 s pre-phase, 1 s after phase]
5) Calculating the CC of templates with continuous data on equivalent stations.
6) The CC data shifted based on the relative time difference between the REQ's phases.
7) Stacking the shifted CC.
8) Calculating the detection threshold. [10 × MAD = 6.745 × σ]
9) Eliminating duplicate detection by considering minimum time intervals between sequential identifications. [10 s]
10) Recalculating CC of Detection for phase-picking.
11) Locating new detections.









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Results

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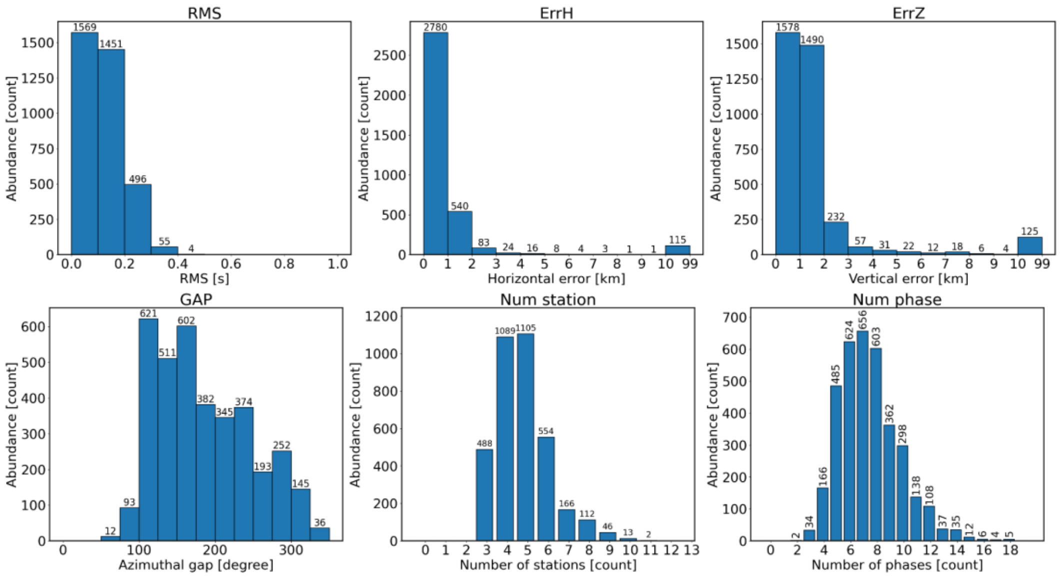
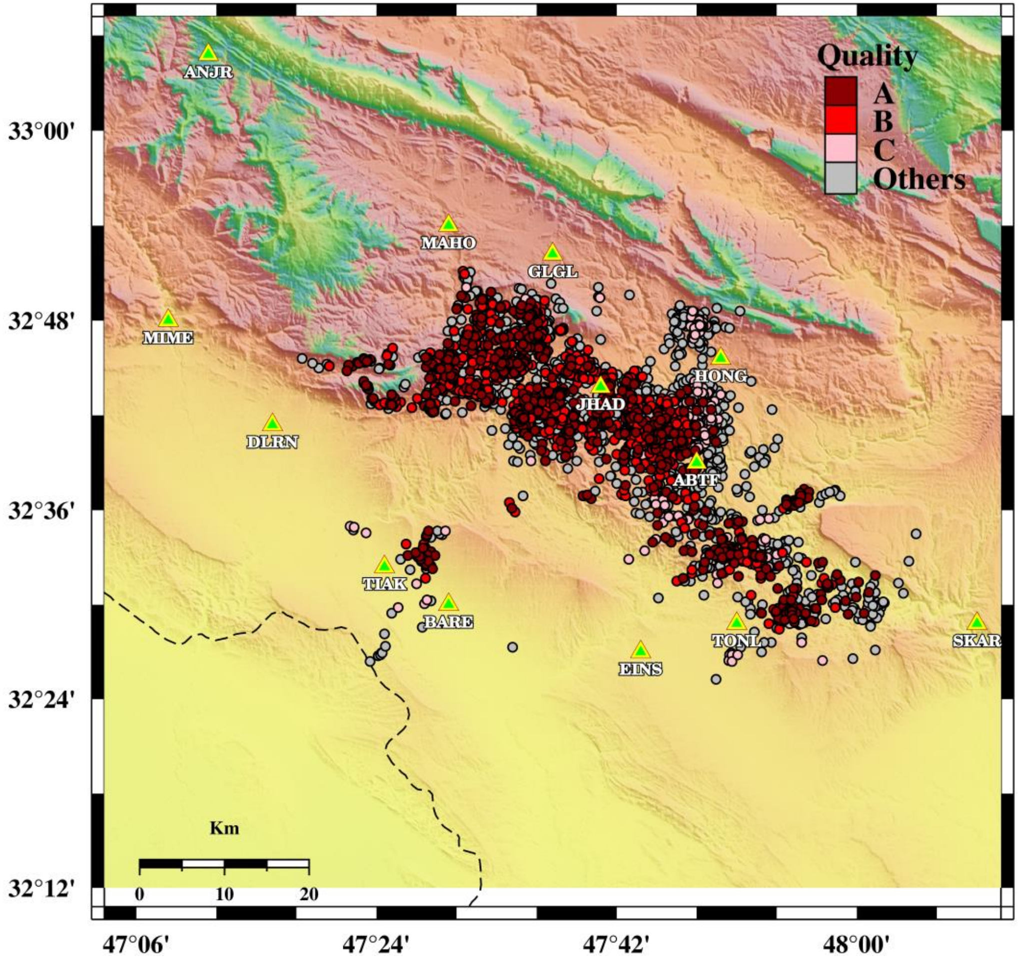
Finally, after finding the optimum parameters for using the matched-filter technique, we identified 3575 aftershocks (4.27 times the references) by the 838 reference earthquakes on the 95 days of continuous data.

We evaluated the location quality of the detected aftershocks using the effect of the azimuthal gap, the number of stations and phases, and error parameters. Compared to the reference catalog, there is an increase in the numbers of A- and B- grade locations. However, It's apparent that despite the low values of time residual, epicentral error, and depth error, a large part of these earthquakes were placed in the C and others group, just because of the number of stations.

Table: Classification of the 838 reference earthquakes (REQ) and the 3575 detected aftershocks (MF) according to the location quality.

Group	RMS	GAP	Num Stations	ErrH	ErrZ	REQ	MF
A	rms ≤ 0.3	gap ≤ 180	6 ≤ n-st	ErrH ≤ 3	ErrZ ≤ 3	458	637
B	rms ≤ 0.4	gap ≤ 200	5 ≤ n-st	ErrH ≤ 5	ErrZ ≤ 5	662	1436
C	rms ≤ 0.5	gap ≤ 250	5 ≤ n-st	ErrH ≤ 7	ErrZ ≤ 7	714	1768
Others	rms > 0.5	gap > 250	3 ≤ n-st	ErrH > 7	ErrZ > 7	124	1807





INTRODUCTION
OBJECTIVES
METHODS/DATA
RESULTS
CONCLUSION

Conclusion

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The ability and performance of the waveform cross-correlation detector compared to the energy detectors were demonstrated in this study, and the capacity of this technique to reliably recognize tiny earthquakes and investigate the seismicity of the region is highly remarkable.

1. The significant increase in the detected earthquakes reflects the high efficiency of using the MF approach for aftershock studies.
2. Because each REQ can detect new ones with maximum quality and number of phases similar to its own, the MF method will show its best performance when REQ's phases are picked completely and accurately.
3. The parameters of the MF method should be selected based on the data type and the target of the study.
4. Selecting each parameter is a trade-off between maximizing the number of detections and minimizing the rate of false detections.
5. The time accuracy of the detected phase using the waveform cross-correlation controlled with the time accuracy of REQs.
6. It revealed that the effect of increasing the pre-phase of templates on the power of detection is not identical for the P and S seismic phases due to the different nature of the pre-phase signal.
7. Due to the accuracy of phase determination in this method and no need to revise manually, its processing time is very suitable. (e.g. using 838 REQs and 13 stations (~18240 hours continuous data) consumes less than 48hr processing time 12-core CPU with 32GB RAM. It is noticeable that if the REQs contain more phases, the processing time will increase.)

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INTRODUCTION
OBJECTIVES
METHODS/DATA
RESULTS
CONCLUSION