ANALYSIS OF THE 2008 CHINESE EARTHQUAKE AFTERSHOCKS USING CROSS-CORRELATION

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ABSTRACT

Our objective is to assess the performance of a cross-correlation technique as applied to automatic and interactive processing of aftershock sequences at the International Data Centre (IDC). This technique allows a flexible approach to time windows, frequency bands, correlation thresholds and other parameters controlling the flux of detections. For array stations, we used vertical channels to calculate a unique cross-correlation coefficient. All detections obtained by cross-correlation were then used to build events according to IDC definitions. To investigate the influence of all defining parameters on the final bulletin, we selected the aftershock sequence of the March 20, 2008, earthquake in China with m_b(IDC) = 5.41. As templates, fragments of P- and Pn-waves from two sets of the IDC Reviewed Event Bulletin (REB) events were selected: all 19 events from the second and third hour after the main shock and 50 events from the entire sequence with m_b between 3.0 and 4.0. By varying the threshold of correlation coefficient and F-statistics which were applied to original waveforms and to the cross-correlation time series, we obtained several bulletins with different numbers of events, which could be compared to the original REB and also checked manually. These events were split into four categories: (1) new events having a counterpart (origin time within 10 sec) in the REB, (2) new valid events not having a counterpart in the REB, (3) valid REB events not having counterparts in any bulletin created by cross-correlation, and (4) bogus (invalid) events created by cross-correlation and which are in the REB.

OBJECTIVE

Our objective is to assess the performance of the cross-correlation technique as applied to automatic and interactive processing of aftershock sequences at the IDC. This technique allows a flexible approach to time windows, frequency bands, correlation thresholds and other parameters controlling the flux of detections. For International Monitoring System (IMS) array stations, we used vertical channels to calculate cross-correlation coefficients. Then, all qualified detections obtained by cross-correlation were used to build events according to the IDC event definition criteria (EDC).

RESEARCH ACCOMPLISHED

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) obligates each State Party not to carry out any nuclear explosions, independently of their size and purpose. The Technical Secretariat (TS) of the Comprehensive Nuclear-Test-Ban Treaty Organization will carry out the verification of the CTBT. The IDC is an integral part of the (currently Provisional) TS. It receives, collects, processes, analyses, reports on and archives data from the IMS. The IDC is responsible for automatic and interactive processing of the IMS data and for standard IDC products. The IDC is also required by the Treaty to progressively enhance its technical capabilities.

The methods based on cross-correlation have recently shown the possibility of significant improvements in many seismological applications such as detection of low magnitude seismic events (Gibbons and Ringdal, 2006; Harris and Paik, 2006; Schaff, 2008; Schaff and Waldhauser, 2010), location of seismic events (Schaff et al., 2004; Schaff and Waldhauser, 2005; Schaff and Richards, 2011), phase identification and characterization (Gibbons, Ringdal, and Kvaerna, 2008; Harris and Dodge, 2011), event size characterization (Schaff and Richards, 2011) and event clustering (Harris and Dodge, 2011). All these improvements are potentially of crucial importance to IDC routine processing, both automatic and interactive, and also for expert technical analysis of specific events as provided for under the Treaty. In this study, we focus on detection and event building/clustering in automatic processing. All new events have to be tested manually in accordance with IDC rules of interactive analysis and thus standard location algorithm was used.

The cross-correlation technique can be a powerful tool for detection of similar signals. For 3-C stations, similar signals on vertical channels may come from any azimuth and may have any slowness. The use of all three components puts some constraints on the difference between azimuth and slowness for two signals to have a high correlation coefficient. For array stations with many individual sensors at distances from few hundred metres to tens of kilometres, similar signals should have similar vector slownesses: the signals from different azimuths and with different apparent velocities across arrays with an aperture of several kilometres are well suppressed by destructive interference.

A powerful way to test the cross-correlation technique is to use a set of events which are close in time and space. A natural candidate is the aftershock sequence of a large shallow event. After catastrophic earthquakes, aftershocks are distributed over larger territory and their signals are not necessarily well correlated, whereas swarms and aftershock sequences of small and moderate events usually consist of small events not recorded at teleseismic distances. It is therefore preferable to choose a sequence of intermediate size.

We have chosen an earthquake in China that occurred at 22:32:56 on 20 March 2008. This earthquake was detected by many primary and auxiliary IMS stations and starting from the automatic location an event was built by IDC analysts with body wave magnitude m_b(IDC)= 5.41. The event had a short but prominent aftershock sequence also recorded by the IMS. There are 146 events in the Reviewed Event Bulletin (REB) during five days after the earthquake. Cross-correlation is a technique which requires computation resources and we have limited our testing to five full days including the day of the main shock.

The aftershocks located by IDC provide several opportunities to test cross-correlation as a method for signal detection and event building. First, we must endeavour to reproduce the existing REB using only a few master events or waveform templates. Secondly, we can check the REB aftershocks for internal consistency in terms of cross-correlation. Thirdly, we should check for new events (not in the REB) which match the IDC event definition criteria (in short, at least three IMS primary stations with defining arrival time, azimuth and slowness). Fourthly, we must determine those parameters of detection which provide the highest resolution with a relatively low false alarm rate.

As a start point, we use as templates 19 REB events within 50 km of the main shock detected during two hours after the main shock: between 23:00 20 March and 01:00 21March. These events have magnitudes m_b(IDC) between 3.00 and 4.58. Generally, earthquakes with larger magnitudes (say, > 4.0) provide very poor templates for much smaller events (~3.0). Since we are interested in the smallest sources it was reasonable to compile another set of 50 events with magnitudes between 3.0 and 4.0 and to use their records as templates.

The primary IMS network includes many array stations and only few 3-C stations. Theoretically, an array allows signal amplification proportional to the square root of the number of elements, when signals are spatially well-correlated and noise is uncorrelated. Therefore, array stations are more efficient in detection of weaker signals and smaller events world-wide. However, all IMS 3-C stations are very important for detection of low-amplitude signals when array stations are not available at local and regional distances. Without loss of generality, we use only primary array stations in this study. There is no primary 3-C station at regional distances from the aftershock sequence and auxiliary IMS stations provide data only by request and thus their waveforms are not continuous.

For the studied aftershock sequence, several primary stations report detections at teleseismic distances: ZALV, SONM, CMAR, FINES, ARCES, NOA, GERES, and YKA. There is only one primary station at a distance below 20^o - MKAR. It regularly reported detections of the Pn-phase. The length of seismic signal recorded at teleseismic distances depends on magnitude: smaller events are characterized by shorter visible signals. In addition, smaller earthquakes produce signals enriched by higher frequencies due to higher corner frequencies. Here, we are looking for the smallest events which are likely to be missed by standard detection algorithms and event building tools used at the IDC. Therefore, the length of template widows should not be large, and should only include valid signals from small and moderate-size events. The difference in frequency content of microseismic noise and signals at IMS stations requires a number of filters covering the whole spectral range of seismic signals from 0.8 Hz to 6 Hz.

Table 1 lists time windows and frequency bands of eight templates used in this study. All templates include several seconds of P- or Pn-wave signal and a short time interval before the signal (lead), which provides additional flexibility in onset time. The length of a given window depends on its frequency band. For the low-frequency (BP, order 3) filter between 0.8 Hz and 2.0 Hz, the length is 6.5 s and includes 1 s before the arrival time. For the high-frequency filter between 3 Hz and 6 Hz, the length is only 4.5 s. For Pn-waves, the length is 11 s and does not depend on frequency. The Pn templates also include 1 s of preceding noise. Figure 1 illustrates the selection of a template for the example of IMS station PS2 (WRA).

Table 1. Time windows and frequency bands of the templates for P- and Pn-waves

Phase	*Filter*				*Window, s*	
	Low (Hz)	*High (Hz)*	*Type*	*order*	*Lead*	*Signal*
P	0.8	2.0	BP	3	1.0	5.5
P	1.5	3.0	BP	3	1.0	4.5
P	2.0	4.0	BP	3	1.0	3.5
P	3.0	6.0	BP	3	1.0	3.5
Pn	0.8	2.0	BP	3	1.0	10.0
Pn	1.5	3.0	BP	3	1.0	10.0
Pn	2.0	4.0	BP	3	1.0	10.0
Pn	3.0	6.0	BP	3	1.0	10.0

Overall, we have designed the following procedure for event building. As a first step, correlation coefficients were calculated for all master events/templates. For a given master event, correlation coefficients were calculated only for primary seismic arrays with a defining P-wave (or Pn-wave in the case of MKAR). Therefore, bigger master events may have more stations. Then, we tried to associate all detections obtained from cross-correlation with events. For a given master event, we calculated approximate origin times for all detections by subtracting the travel time from the master event to a given station from the relevant arrival time. A cluster of origin times obtained from three or more stations was interpreted as a new event.

Following Gibbons and Ringdal (2006), we use a normalized cross-correlation function. Both time series must have the same sample rate. This condition seems to be trivial for the same seismic station but when decimation is used for reduction of the overall computation time one should be careful to use the same rate. The notation $_{N,\Delta t}(t_0)$ is used to denote the discrete vector of N consecutive samples of a continuous time function (t), where t_0 is the time of the first sample and Δt is the spacing between samples:

$$\omega_{N,\Delta t}(t_0)=[\omega(t_0), \omega(t_0+\Delta t),..., \omega(t_0+(N\text{-}1)\Delta t)]^T$$

The inner product of $_{N,\Delta t}(t\ )$ and $_{N,\Delta t}(t\ )$ is defined by

$$\langle\ (t\ ),\ \ (t\ )\rangle_{N,\Delta t} = \sum_{i=0}^{N-1}\ (t\ + i\Delta t)\ \ (t\ + i\Delta t)$$

and the normalized cross-correlation coefficient by

$$CC[\ (t\ ),\ \ (t\ )] = \frac{\langle\ (t\ ),\ \ (t\ )\rangle_{N,\Delta t}}{\sqrt{\langle\ (t\ ),\ \ (t\ )\rangle_{N,\Delta t}\langle\ (t\ ),\ \ (t\ )\rangle_{N,\Delta t}}}$$

Figure 1. IMS seismic array PS2 (WRA). Waveforms recorded on vertical channels and an example of waveform template (right panel). One correlation coefficient is calculated over the entire template with all channels aligned in one record. In the template, individual channels are shifted in time according to theoretical travel time residuals defined by azimuth and slowness of the origin (source/receiver) beam. All waveforms are also shifted by the same time delays between individual channels. Hence, the empirical time delays between the channels are retained when the template is convolved with the waveforms.

For a given master event, we use all primary array stations providing time defining P- or Pn-wave arrivals. According to IDC rules, any time defining arrival must be within a 2 s window around the computed P-wave arrival time (2.2 s for Pn-wave). Similar rules are applicable to defining azimuth and slowness, with their uncertainty bounds dependent on phase and array type. Individual channels of an array are aligned in one record and create a waveform template. In order to retain the signal inside the template window individual channels are shifted in time according to the theoretical travel time residuals defined by azimuth and slowness of the origin (source/receiver) beam. All waveforms are also shifted by the same time delays between individual channels. The empirical time delays between the channels are retained when the template is convolved with the waveforms. Therefore, time delays between arrivals on the channels are real and should not cause any additional energy loss in beam forming.

When a master event and corresponding template is selected, normalized cross-correlation coefficients are calculated for all discrete times in the predefined time window of 5 days. By definition, this window includes all master events used in the study. Previously, we have defined four different frequency bands and thus four *CC(t)* time series are calculated for each involved station for the selected master event. All four *CC* time series for a given station are used to detect new arrivals. Then all valid arrivals at all stations related to the master event are used to build new events.

There is no theoretically justified unique *CC* threshold used to define a new arrival; rather appropriate thresholds must be determined empirically. These thresholds are likely to be station dependent and vary with geographical coordinates and depth. For two neighbouring events, the level of cross-correlation coefficient depends on the distance between them and the similarity of source functions, as well as upon signal frequency. As a rule, the larger the distance, the lower the corresponding *CC* as caused by degrading coherency of arrivals on various channels. The similarity of source functions can also deteriorate with the difference in magnitude, especially for short time windows used in our templates. Shallow earthquakes usually generate emergent signals. For larger events, an early part of the signal may become tangible and used in corresponding template, and it is not seen from smaller events. As a result, the level of cross-correlation may decrease even for collocated events.

For weak signals, the absolute level of correlation coefficient for collocated events can be dramatically reduced by the effect of uncorrelated seismic noise mixed with the signals. Hence, before using *CC* as a detector, one has to enhance the detection procedure. There are many possibilities and the simplest one is the STA/LTA detector. It is based on a running short-term-average (STA) and long-term-average (LTA), which is computed recursively using previously computed STA values. The LTA lags behind the STA by a half of the STA window. For a time series *x(n)*, where *n* is the sample index and *x(n)* is the amplitude at sample *n*, the initial value of the STA, *stav*, is calculated as

$$stav\left(\frac{S}{2}\right) = \frac{1}{S}\sum_{s=0}^{S-1}|x(s)|$$

where *S* is the number of samples in the STA window. Recursion is used to compute consequent values of the STA:

$$stav(k) = stav(k-1) + \frac{1}{S}\left[\left|\left(x(k+\frac{S}{2}\right)\right| - \left|\left(x(k-1-\frac{S}{2}\right)\right|\right]$$

where $(S/2) \le k \le (N-1) - (S/2)$, and N is the number of available samples in the time series. For the end-segment intervals, $k \le S/2$ and $\ge (N-1) - (S/2)$, $stav(k) = stav(S/2)$ and $stav(k) = stav((N-1) - S/2)$, respectively.

The LTA, *ltav(k)*, is computed recursively from the previous STA:

$$ltav(k) = \left(1 - \frac{1}{L}\right) ltav(k-1) + \frac{1}{L} stav(k-S)$$

where *L* is the number of samples in the LTA window.

As a rule, the length of the STA and LTA windows have to be defined empirically as associated with spectral properties of seismic noise and expected signal. We have carried out a brief investigation and determined the following windows: 0.8 s for the STA and 40 s for the LTA.

The LTA helps to distinguish valid signals from noise and to suppress undesirably high correlation coefficients in coda of valid signals, which may be incorrectly interpreted as additional detections. In the middle panel of Figure 2, the *CC/LTA* ratio is shown in red. The largest correlation coefficient was ~0.4. When divided by the *LTA*, this coefficient reached the level of 10.

Finally, the lower panel in Figure 2 shows the time history of signal-to-noise ratio, *SNR* = *STA/LTA,* as applied to the *CC/LTA* obtained previously with the same LTA window. We define a detection or an arrival of P - or Pn-wave when *STA/LTA* ≥ 3.2. This is a tentative threshold and may vary with station and geographical region. In Figure 2, there are only two valid signals which can be used for event building. Figure 3 shows the same time window but in a different frequency band. There are also two detections but they are different from those in Figure 2. This difference illustrates the importance of utilizing several frequency bands for the event building procedure.

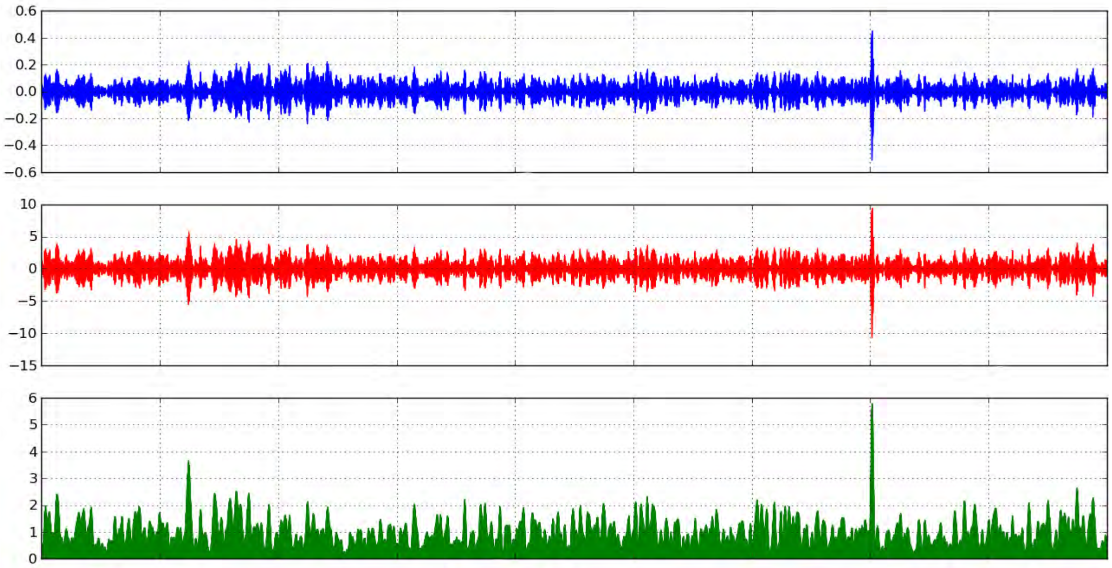

Figure 2. An example of cross-correlation analysis carried out using the template in Figure 1: blue – the normalized correlation coefficient, *CC*; red – *CC* divided by *LTA*; green – *SNR* = *STA/LTA*. The frequency band is between 2.0 Hz and 4.0 Hz. There are two detections with SNR>3.2.

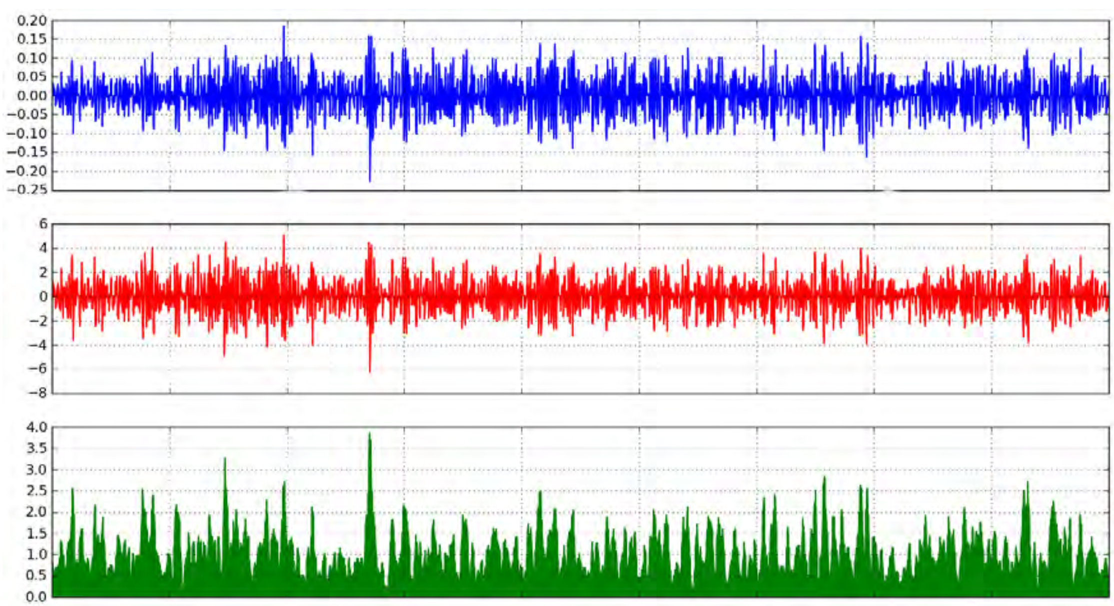

Figure 3. Same as in Figure 2 for the frequency band between 1.5 Hz and 3.0 Hz. There are two detections with SNR>3.2; both are different from the two detections in Figure 2.

When all *CCs* and *SNRs* are calculated for a master event we obtain a set of arrivals for each station. To select the best arrival time for a given detection we find the largest *CC* in the ±1s window around this detection (defined by *STA/LTA*) and consider its time as the onset time. It is important to remember that these *CCs* and *SNRs* are calculated in four different frequency bands for the same time window and some of them may be very close in time and magnitude. All of them are used for event building.

The possibility cannot be excluded that some higher correlation coefficients may be related to strong signals from sources far away from the master event or associated with noise. To validate the signals detected on the *CC* traces we use *F*-statistics as applied to waveforms. Specifically, we calculate maximum *Fprob* for all detections in the time window ±2 s around their onset times. For that, *F*-statistics in a running 2 s window is estimated using the approach developed by Douze and Laster (1979).

In addition to the global SNR detection threshold on the *CC* traces one can define various thresholds for the cross-correlation function for *Fprob*. The number of detections critically depends on these thresholds. Our objective is to estimate the best values which guarantee that all real events similar to the master event are detected and are built in line with IDC definitions, and that the rate of false alarms is low. We have selected the following tentative values: for *CC*: 0.15, 0.2, and 0.3; for *Fprob*: 0.01, 0.1, 0.2. Now we are ready to build events from qualified detections on the *CC* traces.

For a global network, the identification of signal detections made at number of stations as belonging to the same event is a basic task. As a rule, this “association” process is difficult. For the studied aftershock sequence, all arrivals obtained by cross-correlation should correspond to closely spaced events. The travel times obtained for a master event should not differ much from those for other aftershocks. One can subtract from all onset times at a given station the travel time for the master event in order to estimate approximate origin times. When these approximate origin times for three or more primary IMS stations create a cluster we associate these arrivals with one event. By definition, a cluster, and thus an event, is defined by the largest time difference of 5 s between any two origin times. A tentative origin time can be defined as the median amongst all relevant origin times (one station can give four different origin times as obtained from four frequency bands). This is the essence of our event building procedure using the cross-correlation method. All tentative origin times (and thus events) have to be revised manually.

Table 2 lists some principal results of the cross-correlation detection and event building as applied to the aftershock sequence of the studied earthquake sequence. There are 146 aftershocks in the REB. The number of events built in our automatic procedure depends on threshold values of *CC* and *Fprob* used for detection, and decreases with higher thresholds. For *CC* = 0.15 and *Fprob*=0.01, the number of events found by cross-correlation is 384 and 270 for 19 and 50 patterns, respectively.

The larger number of created events with 19 templates is not good news, however. Most of these events are not real (false-positive) and are related to a wider range of waveform shapes in the broader range of magnitudes. In the set of 50 master events, all are small (m_b(IDC)<4.0) and their waveforms vary less. Hence, the flux of cross-correlation detections is less dense. The probability to build a false-positive event is lower. This mechanism works for any *CC* and *Fprob* thresholds.

Table 2. Statistics of the event building procedure with various critical values of *CC* and *Fprob* for two sets of patterns.

# of templates	CC	Fprob	Total events	REB found/ not found	New events
19	0.15	0.01	384	140/6	221
19	0.20	0.10	212	135/11	60
19	0.30	0.20	175	128/18	32
50	0.15	0.01	270	139/7	117
50	0.20	0.10	192	134/12	49
50	0.30	0.20	157	129/17	20

Our first task was to repeat the REB with only a small number of master events. Column 5 in Table 2 lists the number of REB events found, and the number of REB events which were not found automatically. The term "found" means that there are one or several built events with origin times within 10s from the sought REB event. The number of matched REB events varies from 140 to 129.

The "not found" events belong to one of two separate categories. Some of them may be far away from any of the master events and the cross-correlation technique failed to detect corresponding signals. This is a fundamental problem, especially for the largest earthquakes. In general, the solution of this problem is in a more careful selection of master events, which should cover as large area as possible (these master events have to be built by analysts), and in the usage of various extrapolation and interpolation schemes for templates. For example, one can use subspace detectors (Harris and Paik, 2006). The second category consists of events in the REB which may not be real. Superficial inspection of a few "not found" events by an experienced analyst has revealed some problems in phase interpretation in the REB event, and all events in this category will be carefully inspected according to the rules of interactive analysis.

Most of the REB events in Table 2 are matched by various numbers of events obtained by cross-correlation. The largest number of "hits" for the 50-event set is 33. Figure 4 depicts the overall distribution of hits for the 129 REB events in line 6 of Table 2. It is worth noting that 72 from 129 events are matched by 10 or less templates from 50. Only 9 events are matched by 25 and more templates.

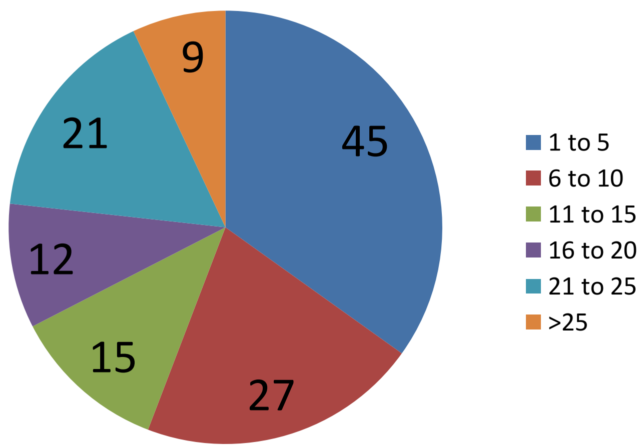

Figure 4. Distribution of the number of hits for the 129 REB events matched by cross-correlation.

When several events obtained by cross-correlation match the same REB event, we do not consider them as "new" events. Therefore, column 6, "new events," counts only those events which do not match any of the 146 REB events. The number of new events varies from 221 to 20. We would like to automatically find all valid events and reject all events which are not real.

The third task is to check that new events meet the IDC definition criteria for REB events. We started with 20 events from line 6 in Table 2. Only several new events were matched by two or more templates, with 13 events matched by only one template. Manual analysis is a time consuming procedure but we have tested all 20 events. Seventeen events from these twenty are new and meet all REB criteria. Two events were valid REB events but mislocated by about 100 km due to the input of auxiliary IMS station AAK, which is closest regional station. This mislocation is directly mapped into the difference between origin times larger than 10 s and these two events are considered as new ones. The latter event is a valid one but was located in the REB about 2000 km far from the main shock. The REB event was big enough to generate waveforms of twenty and more seconds at teleseismic distances. It was wrongly built by cross-correlation as an aftershock because all three primary IMS stations were close (NOA, FINES and ARCES) and at the same great circle with the main shock and the REB event. Figure 5 presents two new events with very low magnitudes. The largest magnitude among all manually checked events is m_b(IDC) = 3.7.

Task four also needs considerable human resources. We have checked several events with low *CC* and *Fprob* at two or more defining stations. It was expected that such arrivals are poorly defined and thus build events which are not real. From 10 randomly selected events none satisfied the REB event definition criteria. The problem of optimal *CC* and *Fprob* thresholds will be investigated in more detail.

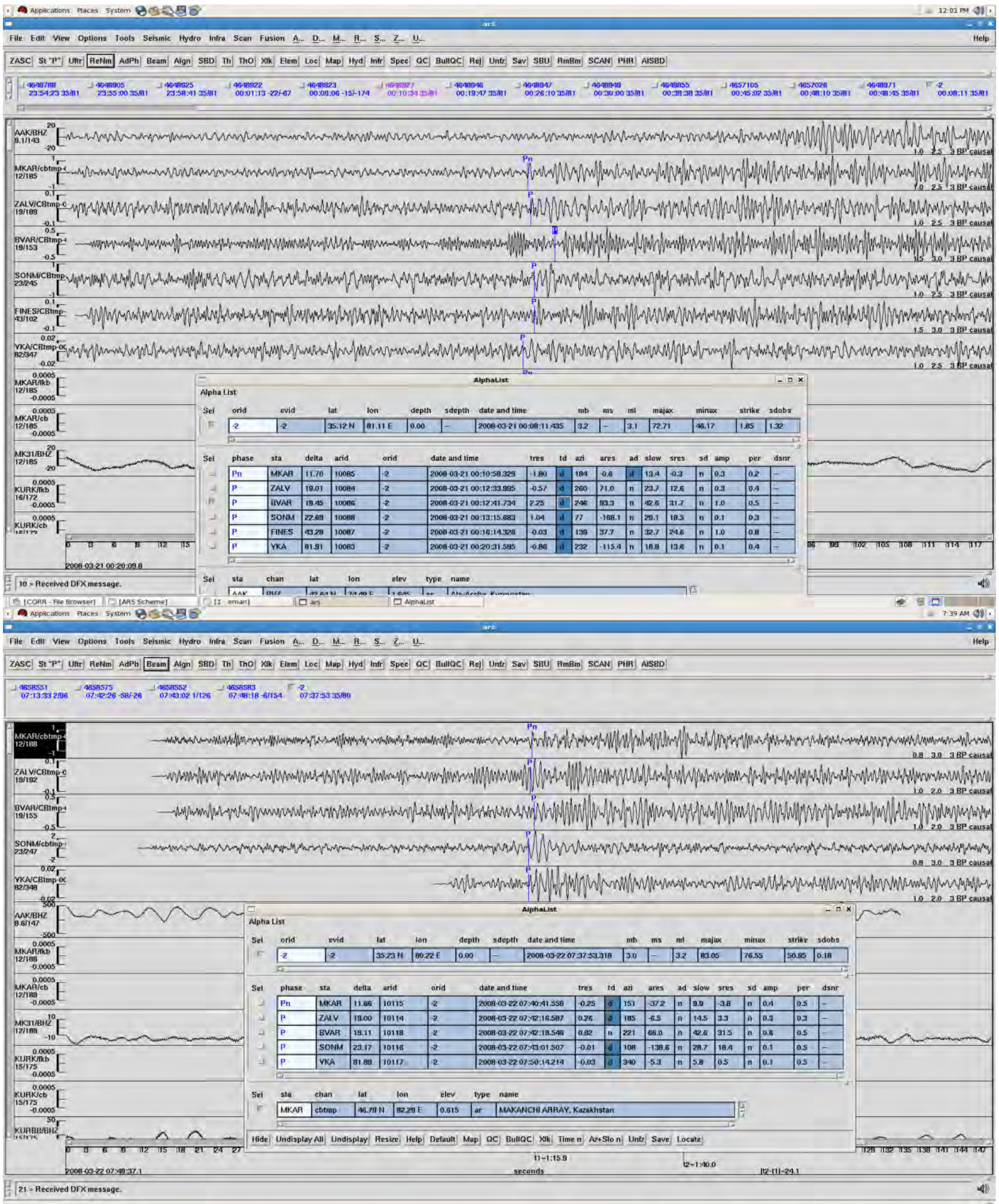

Figure 5. Two new events with 6 and 5 defining phases and magnitudes of 3.2 and 3.0, respectively. These events were built using detections obtained from the correlation coefficients. Both events match the IDC event definition criteria.

CONCLUSIONS AND RECOMMENDATIONS

The cross-correlation technique is a powerful tool for detection of signals from close events. It allows finding valid arrivals of P- and Pn-waves and building events which have been missed from the REB. Moreover, cross-correlation helps to check the quality of previously built REB events.

For the largest earthquakes, the zone of aftershocks may cover tens thousands of square kilometres and the distance between most remote aftershocks may reach several hundred kilometres. In this situation, the set of event templates has to cover the entire area. In some cases, there are no events built by analysts in specific areas. One may try to find new events using cross-correlation and templates at the boarders of the blank areas and/or build synthetic templates by extrapolation of the existing templates.

The cross-correlation technique may reduce the detection threshold for aftershock sequences of nuclear tests when continuous waveform data from regional stations are available. At regional distances, the duration of correlated signals may be between 10 s (Pn) and 60 s (Lg) which allows gathering substantial integral energy as expressed by higher correlation coefficients. In the best case, the detection threshold might be reduced by an order of magnitude relative to the standard threshold guaranteed by the IMS network. At teleseismic ranges, one should not expect any significant reduction in the detection threshold since the duration of correlated P-wave signals from weak sources does not allow enough energy to be gathered.

For depth defining phases pP and sP, cross-correlation could also improve detection and characterization because of their similarity to the primary P-wave. This technique works better for events in the lower crust and below when the surface reflected phases are far enough in time from the primary phase. For shallow events, cross-correlation cannot distinguish between P-wave coda and surface reflections.

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DISCLAIMER

The views expressed in this paper are those of the authors and do not necessarily reflect the views of the CTBTO Preparatory Commission.

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