T3.5-P19

Finding aftershocks with waveform cross correlation

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Abstract

For the International Monitoring System (IMS) it is difficult to find low-magnitude aftershocks of small underground nuclear tests using only standard detection and phase association methods. At the same time, signals from thousands of aftershocks per day following Mw8+ earthquakes are difficult to separate, and thus, to recover the whole sequence. Both tasks are important for the International Data Centre (IDC) of the Comprehensive Nuclear-Test-Ban Organization. The underlying problems can be better solved with waveform cross correlation (WCC), which is most suitable for repeating events. The WCC method can reduce detection threshold and enhance phase association fully utilizing the similarity of waveforms generated by spatially close seismic events. In addition, the use of WCC at seismic arrays of the IMS can reduce station-specific detection thresholds, allow accurate estimate of signal attributes, including relative magnitude, and effectively suppress irrelevant arrivals. Here, we test an aftershock tool matching the IDC requirements for seismic events. It includes creation of waveform templates for master-events, cross correlation (CC) of real-time waveforms with these templates, association of arrivals detected at CC-traces in event hypotheses; building events matching the IDC event definition criteria; and resolution of conflicts between events hypotheses created by neighboring master-events.

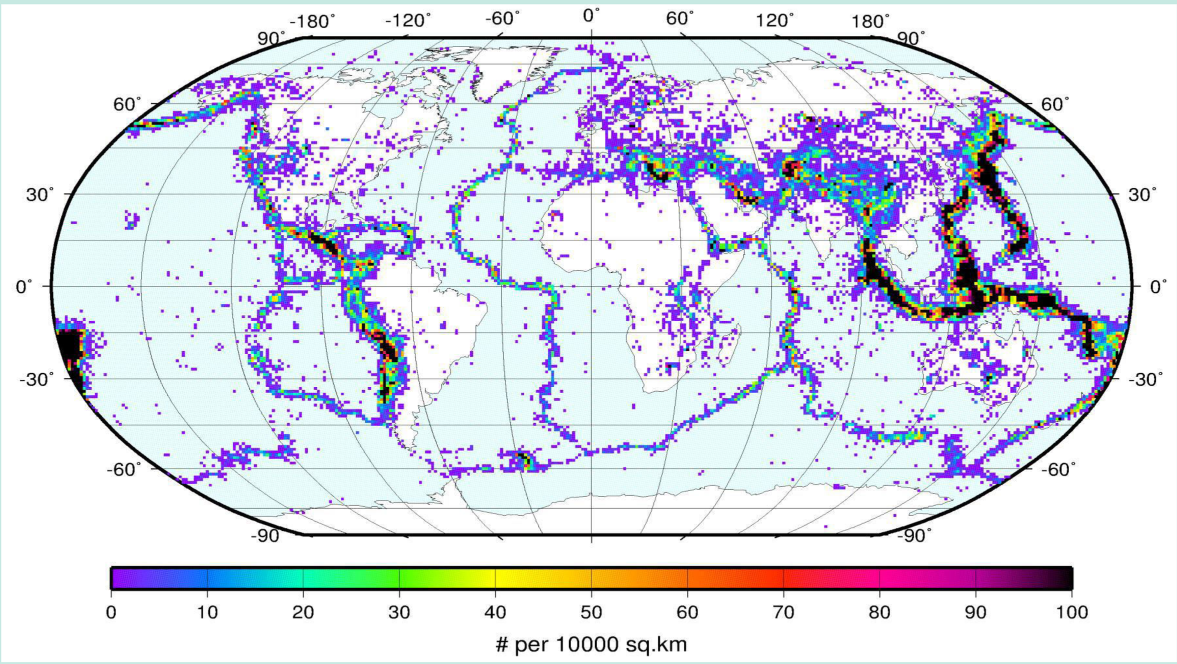
Conclusion

Bigger aftershock sequences and the smallest aftershocks are a challenge for IDC automatic and interactive processing.

- Waveform cross correlation is an effective technique to accurately recover even the biggest aftershock sequences with thousands of events.
- Cross correlation bulletin (XSEL) includes only REB-compatible (EDC) events.
- XSEL provides more REB-compatible events than GA.
- XSEL provides higher quality and consistency (more arrivals primary IMS stations) for the REB events.
- XSEL completeness grows with time as new and higher quality master events are available.
- XSEL events need no global location and have smaller confidence ellipses as related to the accurately located master events.
- The analysts' workload may be reduced by several times with higher location accuracy and bulletin completeness.
- WCC is a powerful tool for REB quality check and expert technical analysis.
- WCC works best with arrays.
- WCC is an effective monitoring method for weak aftershock activity.

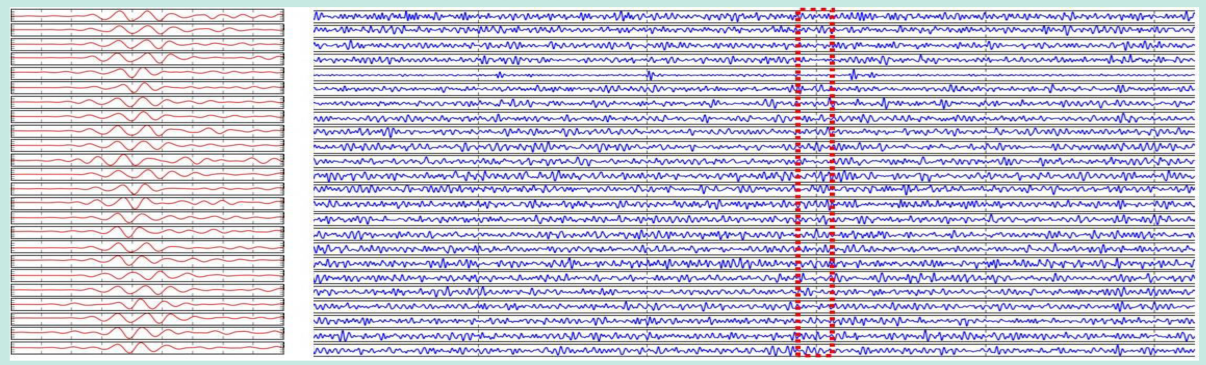
WAVEFORM CROSS CORRELATION AND AFTERSHOCKS

GLOBAL SEISMICITY MEASURED BY IMS NETWORK



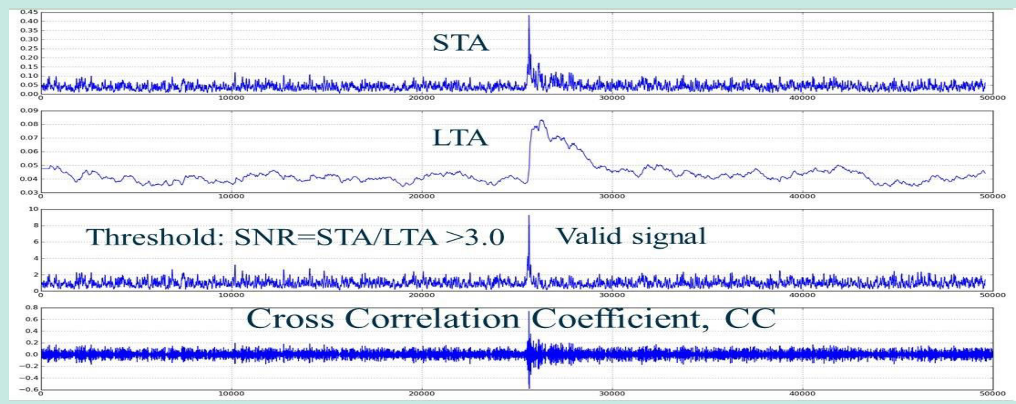
Global seismicity is unevenly distributed with a few zones, where catastrophic earthquakes with Mw>7 can happen. Such events are usually accompanied by extensive aftershock sequences (black areas in the map), which are repeated events with similar signals within a relatively small territory. The method of waveform cross correlation (WCC), i.e. the matched filter method, is natural for aftershock signals detection and association them with event hypotheses.

WAVEFORM CROSS CORRELATION



We select high quality waveform templates (*e.g.*, high SNR) measured at primary IMS stations from a number of representative master events and run cross correlation over real-time signals. For an array, we calculate cross correlation coefficient, ***CC***, on each channel separately and then average them *without* any time shifts over all channels to get the aggregate ***CC***. Selection of high quality and representative master events is crucial for the WCC method.

DETECTION USING CROSS CORRELATION COEFFICIENT



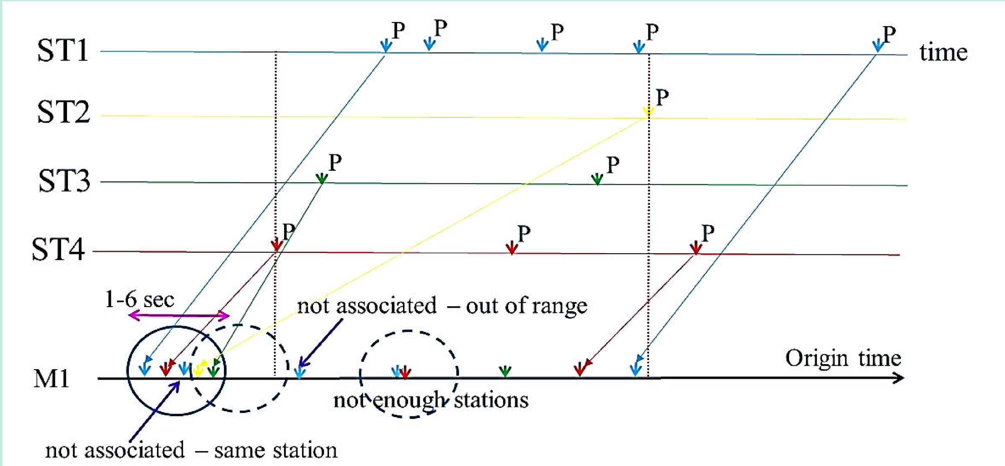
Detection is carried out with STA/LTA method adapted at the IDC. Detection threshold depends on station (3-C, array). When detected on a CC-trace, all signals are processed by standard procedures to estimate their attributes,

PHASE ASSOCIATION, CONFLICT RESOLUTION

For all valid arrivals at **primary stations**, which are found with a given **master event**, origin times, OT_{ij}, are calculated. Empirical travel times from the master event to the relevant primary stations, TT_{ij}, are subtracted from the arrival times, AT_{ij}:

$$\mathbf{OT}_{ij} = \mathbf{AT}_{ij} - \mathbf{TT}_{ij} \textit{ and } \mathbf{TT}_{ij} = \mathbf{TT}_j \ !$$

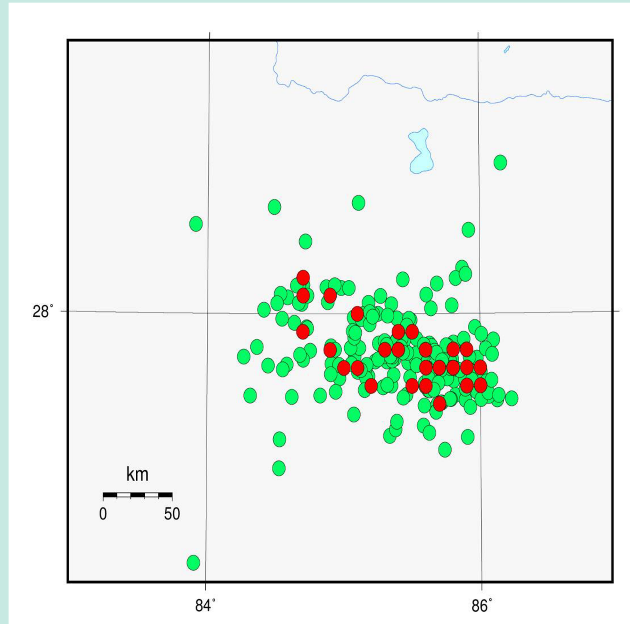
These empirical travel times from a master event to seismic stations are characterized by **ZERO** modelling errors and very low measurement errors. These conditions allow extremely accurate ***relative*** location.



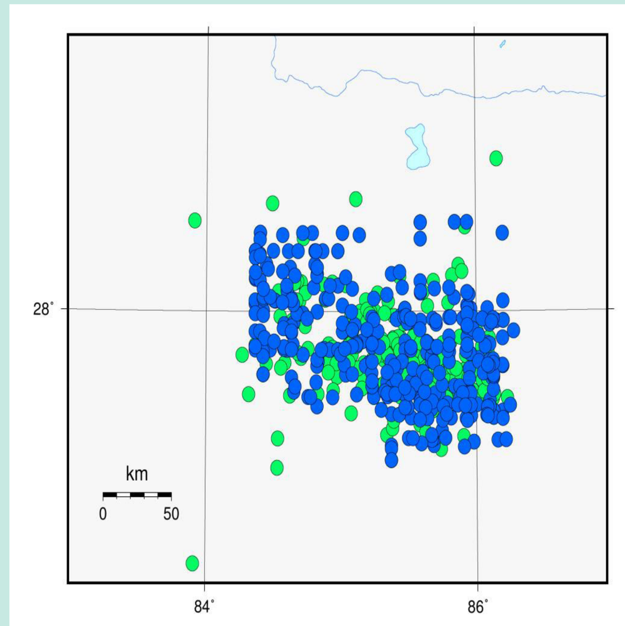
After extensive quality checking, all valid detections are tested for possible association with event hypotheses as based on a Local Association (LA) procedure using the calculated empirical origin times. The IDC event definition criteria (EDC) are applied to these event hypotheses. When several masters compete for the same physical arrival, a conflict resolution (CR) procedure is applied as based on the event quality, i.e. the number of phases and then the RMS origin time residual.

AUTOMATIC RECOVERY OF THE BIGGEST AFTESHOCK SEQUENCIES

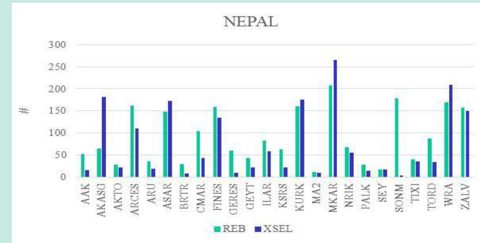
Nepal 2015, day 115



Selection of master events (red circles) from the REB

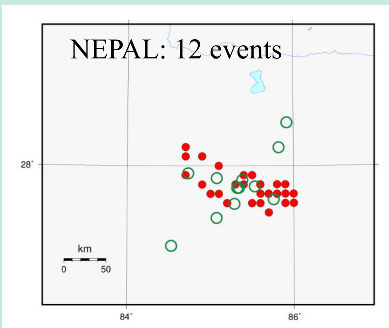


Recovery of the aftershock sequence (blue circles)



Nepal 2015: input of IMS stations to XSEL and REB

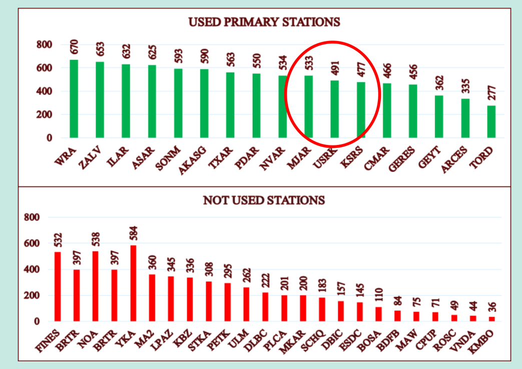
NOT FOUND REB EVENTS



STATISTICS OF PERFORMANCE

	NEPAL (2015115)	SUMATRA (2004361)
REB ALL	286	724
REB aftershocks	209	625
REB with SEL3 evid's	132	497
SEL3 ALL	262	910
SEL3 in AREA	109	526
XSEL	362	1459
REB FOUND	197	592
REB NOT FOUND	12	33

Tohoku 11.03.2011 (725 aftershocks)



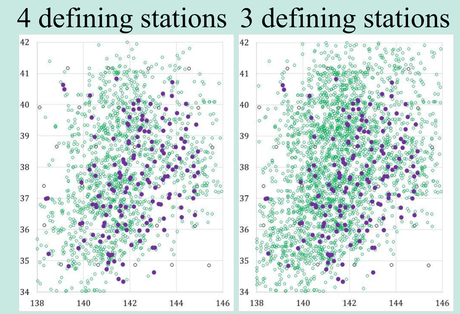
Tohoku 2011: input of IMS stations to the REB. MJAR is not the be best station. Many stations are not used.

The pipeline based on the waveform cross correlation method is more effective in automatic finding real event hypotheses matching the IDC Event Definition Criteria and creates much less invalid event hypothesis. Overall, the completeness of the REB increases (REB vs. XSEL) with decreasing analyst workload.

By design, the WCC method is also characterized by higher potential of adjustment to specific sources, *e.g.*, to earthquakes and explosions. When recovering intensive aftershock sequences (hundreds of events per day) with standard seismological methods based on detections related to the change in energy flux one might miss bigger man-made events. Fine tuning of waveform templates to specific sources is capable to reduce the threshold of detection for the events of interest.

Recovery with historical master events

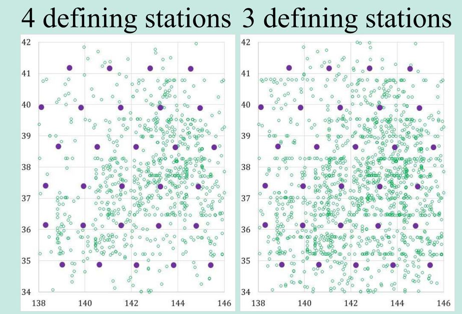
4 defining stations 3 defining stations



1411 XSEL events 2554 XSEL events

Regular grid (corrected TT_j)

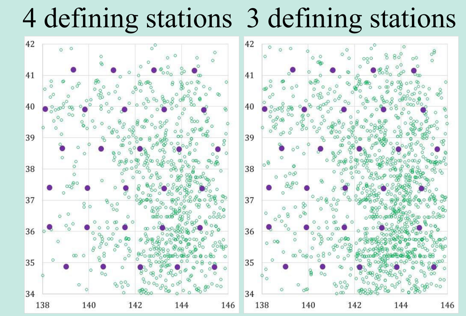
4 defining stations 3 defining stations



834 XSEL events 1522 XSEL events

Grand Master, 29 Nodes x 10 GM

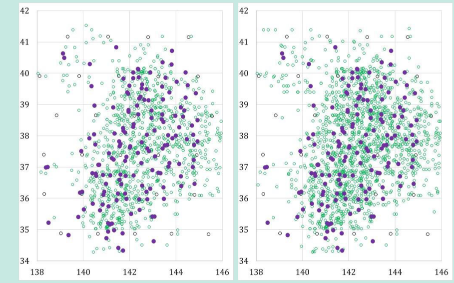
4 defining stations 3 defining stations



995 XSEL events 1520 XSEL events

Recovery with 162 aftershocks as master events

4 defining stations 3 defining stations

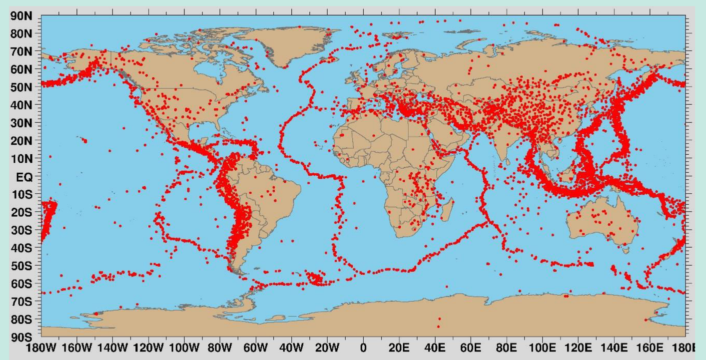


944 XSEL events 1530 XSEL events

ME Set	# defining stations	XSEL	REB by time (12 s)	REB by 2 sta (4 s)
Tohoku aftershocks, dense set - 162 ME	3	1530	725	654
	4	944	711	621
Tohoku aftershocks, sparse set - 69 ME	3	1682	723	660
	4	980	711	615
Historical, sparse set - 109 ME	3	1590	725	670
	4	1411	721	633
Regular Grid, 29 ME	3	1522	720	611
	4	834	675	538
Grand Master, 10 GM, 29 ME	3	1520	722	572
	4	995	702	524

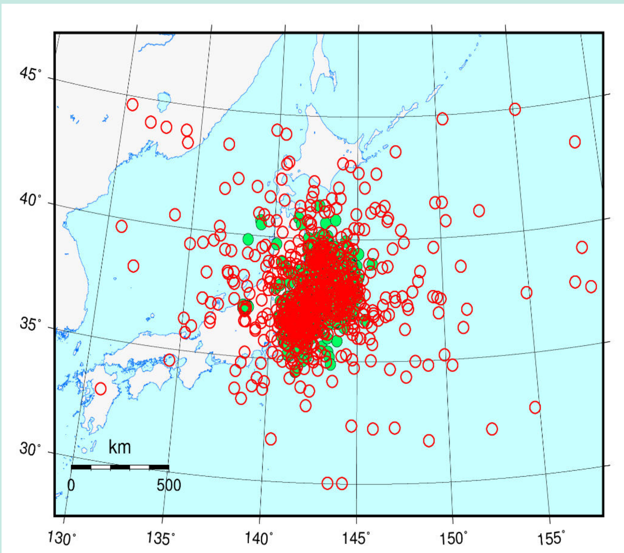
SELECTION AND CREATION OF MASTER EVENTS

HISTORICAL MASTER EVENTS



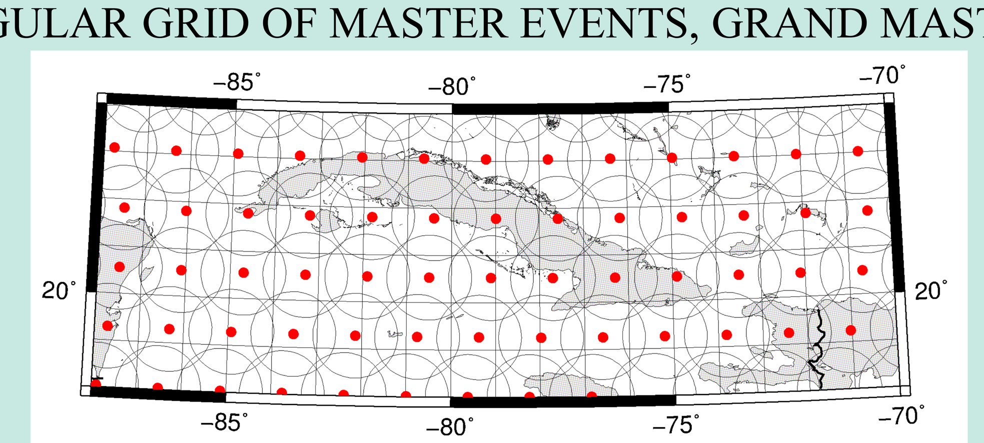
Currently, the IDC database includes more than 500,000 (REB) events with seismic phases. Using the level of cross correlation between signals at primary IMS stations from these REB events within 1 degree from each other, we have selected approximately 2,000 master events with depth from 0 to 700 km, to cover the whole area with the observed historical seismicity. This set is extended by selected events in low seismicity areas and events from mines. The total number of master events is approximately 6000.

AUTOMATIC EVENTS (SEL3)



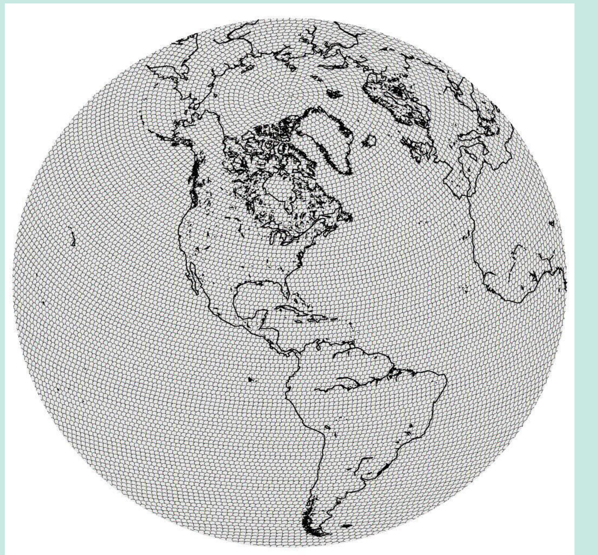
IDC produces an automatic event list, SEL3, which may contain a number of quality event hypothesis, which can be used as master events. Example of the SEL3 created for the Tohoku 2011 aftershocks - open red circles. Green circles - IDC interactive events.

REGULAR GRID OF MASTER EVENTS, GRAND MASTER



When historical or automatic (SEL3) events are not available in the zones of interest (*e.g.*, for seismic monitoring) one (Grand Master) or several high quality seismic events can be moved from their estimated positions to the nodes of the Global Grid to cover these blind spots. Grand Master creates a uniform master set with uniform resolution over the studied area and can be extended to global level.

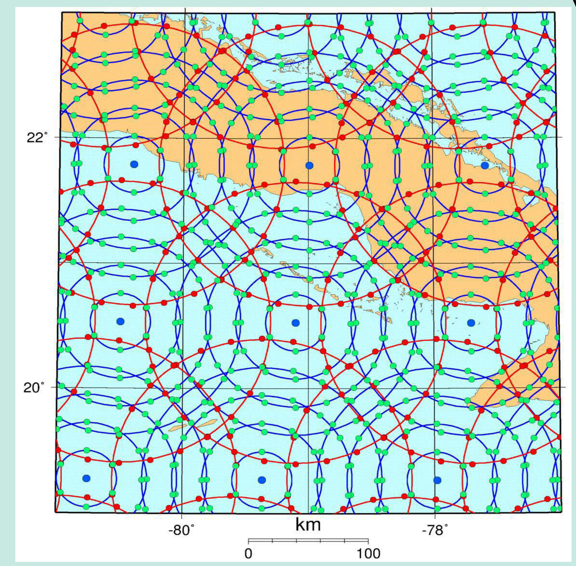
GLOBAL GRID (DETECTION)



The Global Grid of Master Events (ME) is designed for finding and location of seismic events based on waveform cross correlation. The whole globe is covered by cells, also at different depths, surrounding the uniformly spaced grid points. The primary network of IMS seismic stations consider hypotheses of signal detection from slave events within these cells using the matched filter with waveform templates from a set of master events placed in the nodes of the Global Grid. In addition to multi-channel waveforms, these templates include meta-data on theoretical (and empirical where available) azimuth, slowness and travel times estimations for a given node (master)/station pair, ME magnitude and depth, and defining parameters for cross correlation – frequency band, length of template, detection threshold, etc. When signals are detected at several stations, a multi-stage phase association and location procedure is started.

The choice of best templates is one of the key points of the detection and location/phase association procedures. Waveforms from real master events work best for similar sources – earthquakes for earthquakes and explosions for explosions. At the same time, all sources and their seismograms can be simulated numerically. These synthetic master events most useful in aseismic zones, where real master events are not available and Grand Masters are not efficient.

GG (LOCATION)



For the purposes of phase association and event location, each node of the GG is extended by a sub-grid of slave event epicentres spaced by ~25 km and placed on five concentric circles. The location accuracy is 12.5 km. For each sub-grid point, the master-station travel times are corrected for the distance between the GG node and this point. These corrected travel times are used in the LA by origin times.

All GG nodes are processed individually, but may use the same set of physical signals (arrivals) obtained by the WCC method. The node with the largest number of associated stations and the lowermost RMS origin time residual wins and is saved as an event hypothesis in the cross correlation standard event list (XSEL). Other hypotheses are rejected.

The fifths circle is ~100 km in radius (*i.e.* very close to the adjacent GG nodes) and all hypotheses obtained at this circle, which are many, are rejected because they must be found by one of the adjacent GG masters.

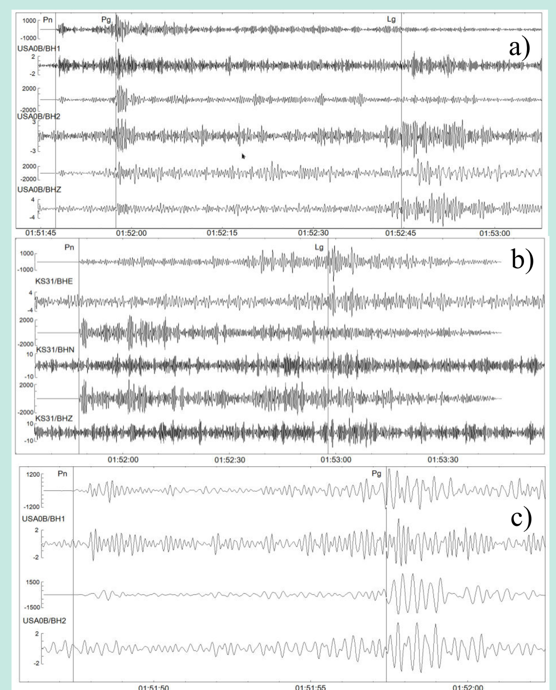
SMALL AFTERSHOCK OF THE DPRK SEPT 9, 2016 UNDERGROUND TEST

The method of waveform cross correlation (WCC) allows remote monitoring of weak seismic activity induced by moderate size earthquakes as well as underground explosions. For nuclear explosions, this type of monitoring is considered as a principal task of on-site inspection under the Comprehensive nuclear-test-ban treaty.

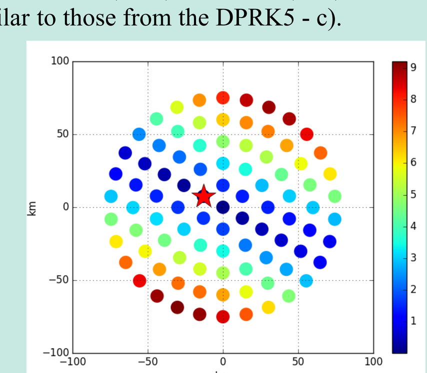
On September 11, 2016, a seismic event with body wave magnitude 2.1 was found in automatic WCC processing near the epicenter of the underground explosion conducted by the DPRK on September 9, 2016. This event occurred approximately two days after this test. The automatic procedure based on WCC was developed by the IDC and runs in testing mode since 2011.

Using the WCC method, two array stations of the International Monitoring System (IMS), USRK and KSRS, detected P_n-wave arrivals, which were associated with a unique event. Standard automatic processing at the International Data Centre (IDC) did not create an event hypothesis, but in the following interactive processing based on WCC detections, an IDC analyst was able to create a two-station event with local magnitude ML=2.4 (after magnitude correction at station USRK). Location and other characteristics of this small seismic source indicate that it is likely an aftershock of the preceding explosion.

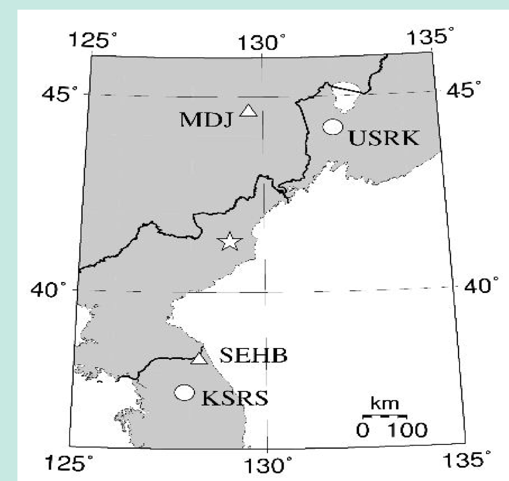
Building on the success of automatic detection and phase association, we carried out an extended analysis, which included later phases and the closest non-IMS stations. The final cross correlation solution uses four stations, including MDJ (The People's Republic of China) and SEHB (Republic of Korea), with the epicenter approximately 2 km to north-west from the epicenter of the Sept. 9 test. We also located the aftershock epicenter by standard IDC program LocSAT using the arrival times obtained by cross correlation. The distance between the DPRK and LocSAT aftershock epicenters is 25.5 km, i.e. by an order of magnitude larger than that obtained by the WCC relative location method.



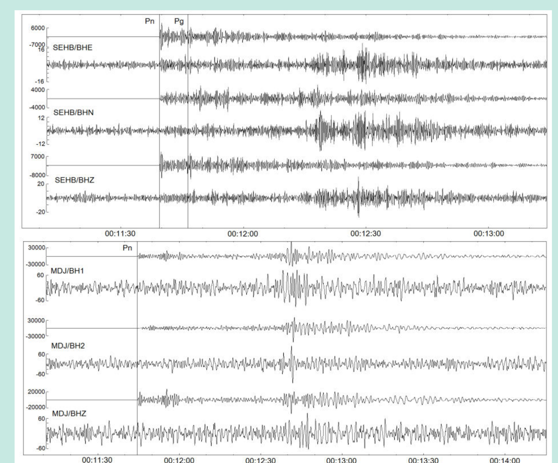
Component-to-component, E-W (H1), N-S (H2), Z, comparison of signals from the DPRK5 and its aftershock as measured at IMS stations USRK (a) and KSRS (b). P_n- and P_g-waves from the aftershock at channels H1 (E-W) and H2 (N-S) of USRK are similar to those from the DPRK5 - c).



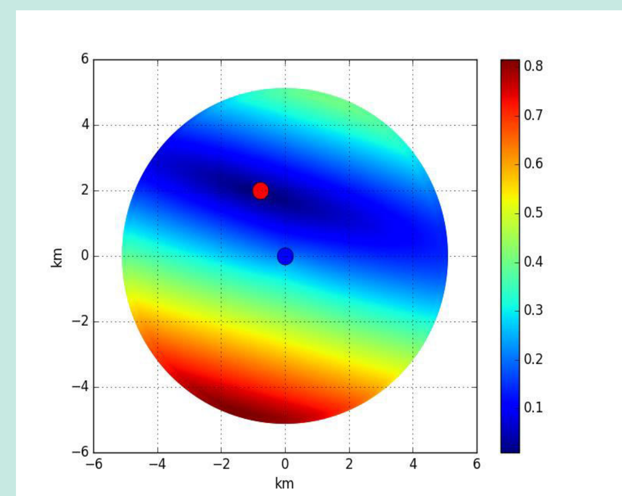
The local association grid around the DPRK4. The distance between circles and nodes is approximately 15 km. Red star shows the node with the automatically found event hypothesis. The RMS origin time residual for the two-station event is 0.054 s.



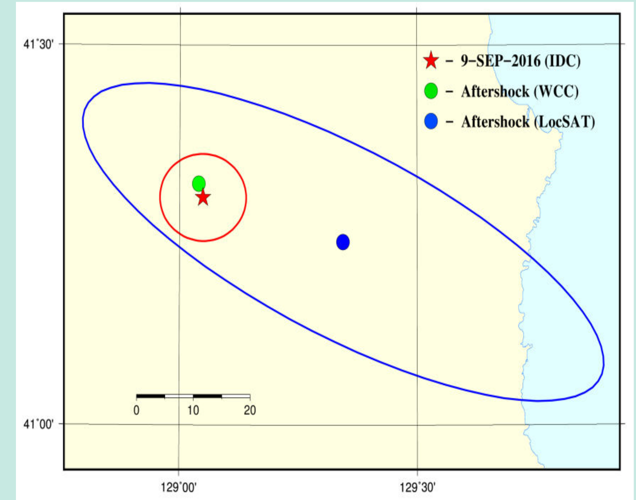
Relative positions of the test site (star), two IMS arrays (open circles), and two 3-C stations (open triangles).



Component-to-component, E-W (H1), N-S (H2), and Z, comparison of signals from the DPRK5 and its aftershock as measured at stations SEHB and MDJ. The P_n-wave arrival at SEHB is poor, nevertheless found by WCC.



The position of the aftershock (red dot) relative to the DPRK5 epicenter (blue dot). The distance between two events is ~2 km as estimated from the cross correlation arrivals at four stations. Color bar shows the RMS origin time residual measured in seconds.



Absolute locations of the DPRK5 (red star) and its aftershock (blue circle) with 90% confidence ellipses as obtained by IDC location software LocSAT. The result of aftershock relative location is shown by green circle.

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