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Relative location of North Korean nuclear tests using IMS data: Creating RELLOC, an NDC-in-a-Box friendly program for analysts

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1. Introduction

We are creating RELLOC, an 'NDC-in-a-Box'-friendly program for estimating the relative location of small groups of seismic events, such as mineblasts and nuclear tests. What makes RELLOC unique is (1) its integration with the 'Geotool' program workflow, and (2) the simple yet robust quality control step that allows the analyst to address data quality issues at the station, event, and trace level. Using only 11 regional IMS and IRIS seismic stations, we show that RELLOC produces relative locations similar in precision to those of published studies at North Korea's Punggye-ri test site.

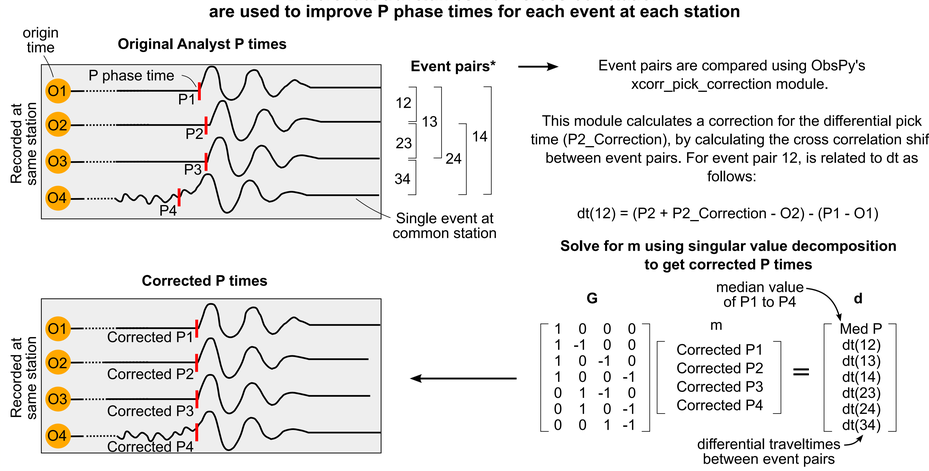
Motivation: We found it difficult to obtain a high-precision relative location program that was suitable for small seismic events clusters recorded at regional/teleseismic distances - a common situation in forensic seismology. Many seemingly suitable programs are reported in the literature, but the source code is either challenging to obtain, the program lacks critical features such as the inclusion of differential traveltimes calculated using cross-correlation, or the program is provided with insufficient documentation. This motivated us to write our own relative location program tailored to our needs.

Method: Relative location using Joint Hypocenter Determination (JHD), the master event method, and double-difference, appear broadly comparable when applied appropriately. Any of these methods combined with cross-correlation derived differential traveltimes (dt's) always perform better, and so this was chosen as a key requirement along with whatever relative location method was simplest to code (in our case, JHD).

Implementation: Our goal is to create a relative locations tool for use in the Australian NDC operations environment. We implemented a modification of Shearer's 1997 station terms method (an approximation of JHD), except that we use a single analyst phase pick for each station rather than including all the analyst picks in the results (and thus introducing picking errors into the solution). Development so far has been in Python using libraries from ObsPy. Currently all the code resides in a single Python Jupyter workbook, but later it will be written into a GUI.

2. RELLOC Method

Differential traveltimes from cross-correlation are used to improve P phase times for each event at each station

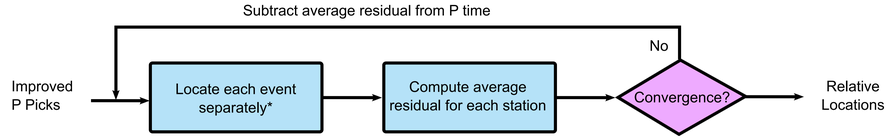


Event pairs are compared using ObsPy's xcorr_pick_correction module.

This module calculates a correction for the differential pick time (P2_Correction), by calculating the cross correlation shift between event pairs. For event pair 12, is related to dt as follows:

dt(12) = (P2 + P2_Correction - O2) - (P1 - O1)

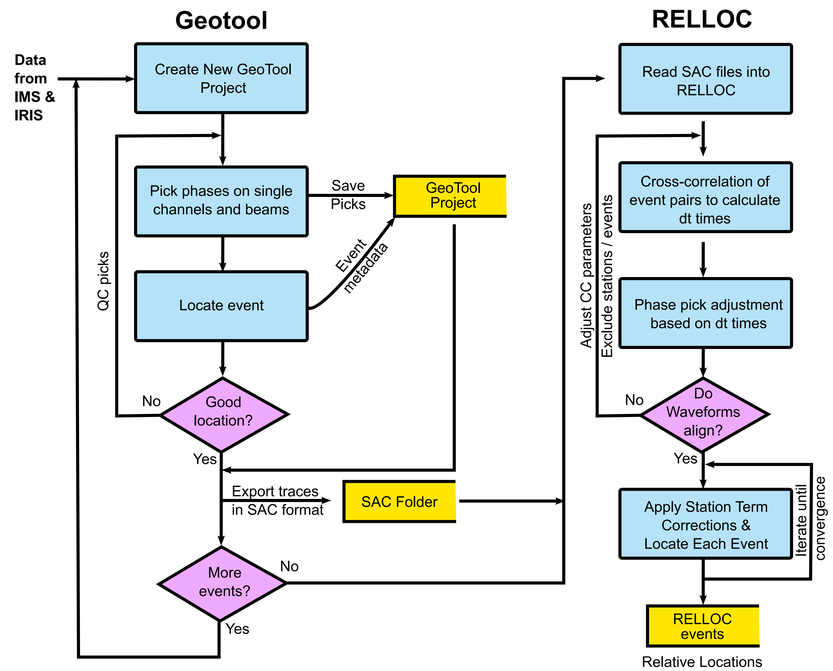
Relative locations are solved using a modification of Frohlich's (1979) JHD method



*We locate using a neighbourhood algorithm locator, based on AK135 traveltimes. But could use any suitable locator.

3. RELLOC Workflow

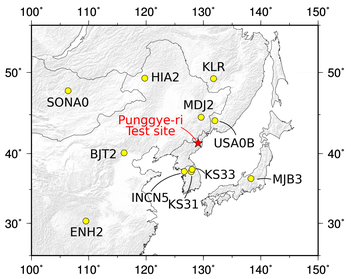
Analyst workflow to produce RELLOC relative locations



4. DPRK Example

North Korean example: We apply RELLOC to relatively locate the announced North Korean nuclear tests from 2009-2017. The 2006 event was not included in this example due to its poor S/N ratio.

Stations used for solution



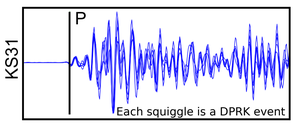
We used 11 regional stations to locate the 2009-2017 North Korean nuclear tests (map above). Single elements were used, and the best elements identified during the initial location process in GeoTool.

Regional/teleseismic beams could also have been used.

5. DPRK Quality Control

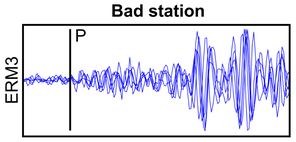
Quality Control in RELLOC: The cross-correlation QC stage is critical, as a single error can significantly reduce the quality of a relative location estimate. With RELLOC, it is possible to inspect every input trace at every station, and iteratively optimize the cross-correlation parameters. Below are example plots showing what a 'good' and 'bad' station looks like after the P times were corrected, as well as two example QC tasks used to improve cross-correlation results.

Good station



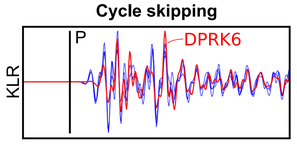
This is what a good result in a relloc QC plot looks like. The peaks and troughs align for all 5 DPRK events.

Bad station



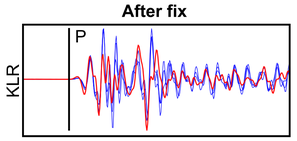
This is what a bad result in a relloc QC plot looks like. The peaks and troughs of the five events do not align. This station could not be improved, and was removed from the solution.

Cycle skipping



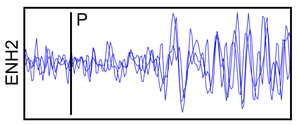
At KLR, DPRK6 did not align with the others due to cycle skipping. The trace in question is highlighted in red.

After fix



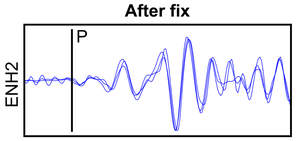
Reducing the maximum shift allowed (max_gap parameter) fixed this issue. This would have been easily missed if manual QC had not taken place.

Bad filter



By default, all stations were filtered from 2-6 Hz prior to cross-correlation. This was not a good filter for ENH2.

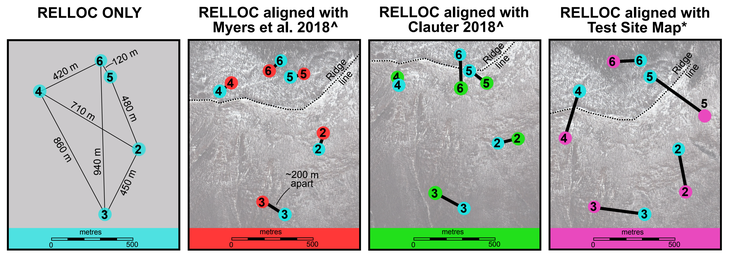
After fix



Changing the filter to 1-3 Hz produced a much better waveform alignment.

6. DPRK Results

RELLOC relative locations versus those from other sources



RELLOC relative locations are comparable with other published studies, especially Myers et al. 2018, and are broadly consistent with the map publically released by North Korean authorities.

^ RELLOC locations are bulk shifted to minimise misfit with published results.

* Interpreted absolute locations from the North Korean test site map publically revealed by North Korean authorities.

RELLOC Relative Locations

Event	Lat	Lon
DPRK2	41.2965	129.0830
DPRK3	41.2929	129.0805
DPRK4	41.2997	129.0757
DPRK5	41.3005	129.0809
DPRK6	41.3014	129.0802

Locations above are intended to be accurate in a relative sense only.

7. Future work

Planned work

- Convert Python workbook into interactive GUI.
- Use a non-approximate JHD algorithm for relative locations.
- Add a measure of uncertainty.

Aspirational

- Calculate phase pick corrections using GrowClust technique (use only the highest CC picks)
- Add master event location as an option.
- Share program with other interested NDC's

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Myers, S. C., Ford, S. R., Mellors, R. J., Baker, S., Ichinose, G., 2018, Absolute Locations of the North Korean Nuclear Tests Based on Differential Seismic Arrival Times and InSAR. Seismological Research Letters, 89(6), pp. 2049-2058.

Shearer, P. M., 1997, Improving local earthquake locations using the L1 norm and waveform cross correlation: Applications to the Whittier Narrows, California, aftershock sequence, 12(B4), pp. 8269-8283.

Frohlich, C., 1979, An efficient method for joint hypocenter determination for large groups of earthquakes, Computers & Geosciences, 5(3-4), pp. 387-389.

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Disclaimer: The views expressed on this poster are those of the author and do not necessarily reflect the view of the CTBTO

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