Application and Validation of a Relative Relocation Technique for Explosion Monitoring

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Introduction

Relative arrival times have been used in the past to produce relative relocations of earthquakes and explosions. Precise relocations of explosions have value in the context of the Comprehensive Nuclear-Test-Ban Treaty on-site inspection when data are available for a previous event. **The Democratic People's Republic of Korea (DPRK) has now conducted 6 declared nuclear tests from 2006-2017.** After the declared test in 2009, many researchers applied relative relocation techniques to improve the accuracy and precision of the seismic event locations. Relative relocation methods require multiple events with arrivals from the same stations. There are few locations in which such a scenario takes place with the same source type and similar location. However, there is still the overall unknown of the exact ground truth location for these events.

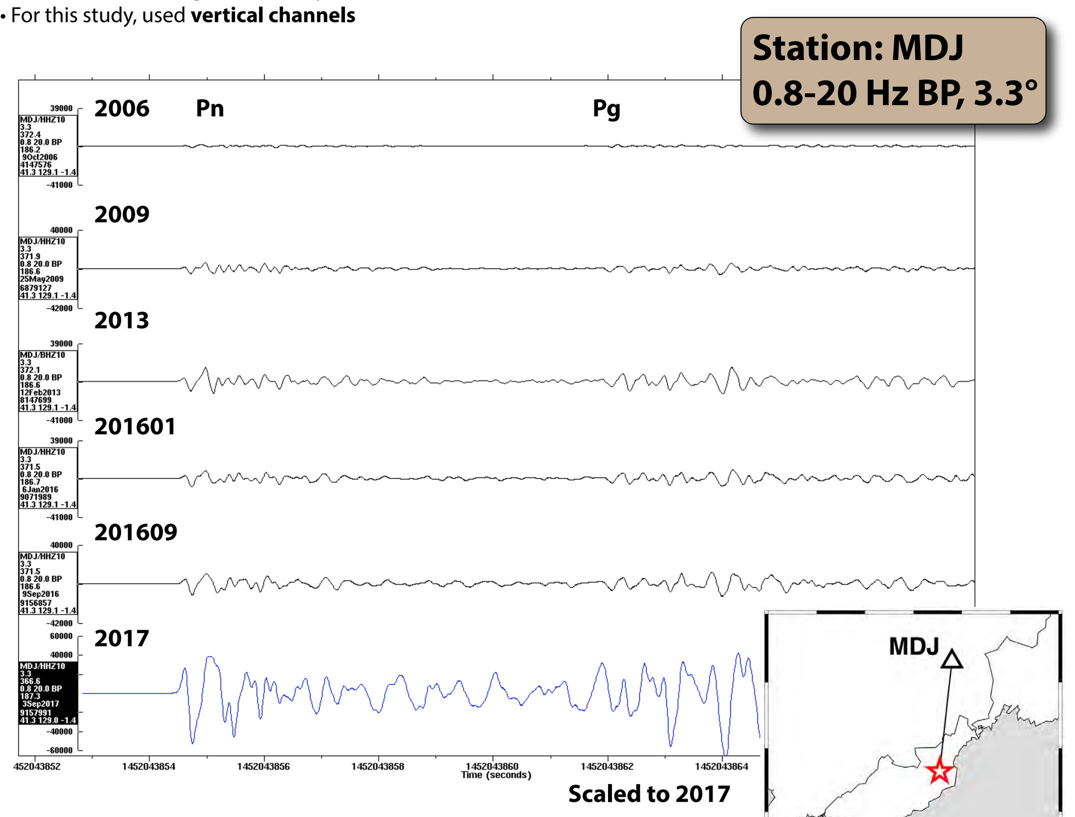
We will demonstrate the application of a straight-forward master event methodology for doing relative relocations for DPRK events, modified for a simultaneous, maximum likelihood solution. We also validate the standard, master event method using a data set where we precisely know the locations of multiple, similarly-located explosive events with arrivals from common stations.

Taking advantage of readily available waveforms, we are able to make relative picks for many stations at local, regional, and teleseismic distances, depending on the particular event and data set. Waveforms are manually-aligned on the first few cycles in order to match the initial arrival information. We will compare the relative relocations with those obtained using more recent techniques that involve simultaneous inversion of data from multiple events. The application of the standard master event method consistently provides high relative accuracy and precision, even when the master and test events are separated by tens of kilometers.

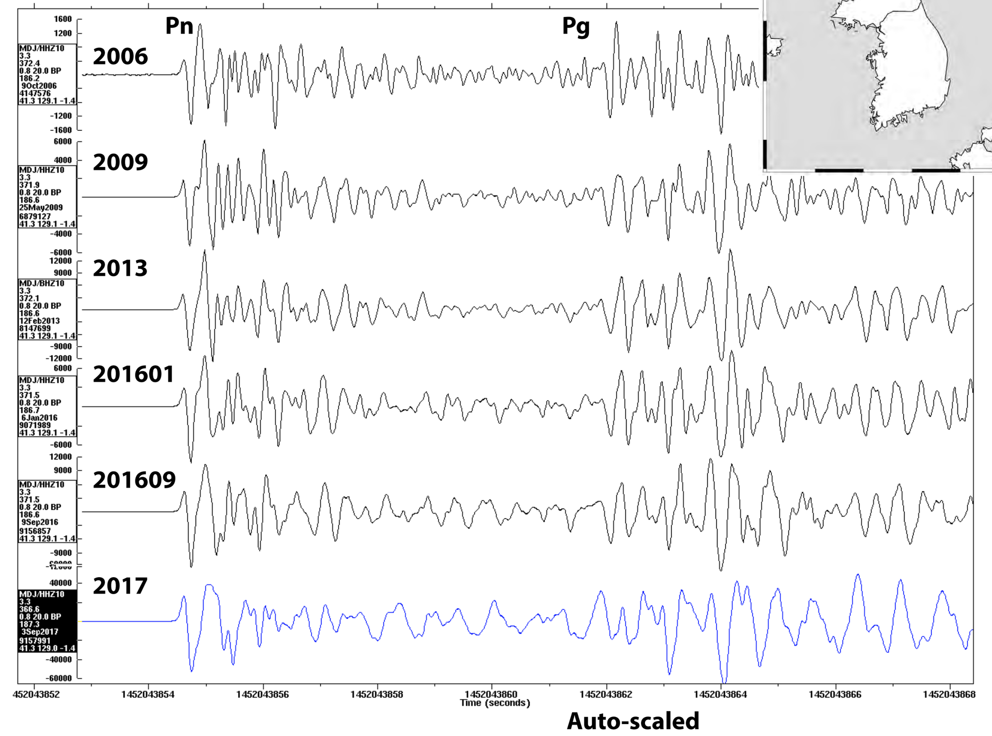
Relative Arrival Picks

For relative relocations, the arrival times are generally obtained from standard first arrivals (P) or other standard phase picks. We general relative arrival picks by **manually aligning waveforms on "features"** (i.e., peaks or troughs) than are common to the same station for different events (e.g., Fisk (2002)).

- Similar to waveform cross-correlation, but the analyst identifies the feature to use to align near a predicted phase arrival.
- Use the same **sample rate**, **filter** and **channel** (there is some leeway on how rigid similar channels must be)
- Allows for more precision in the waveform alignment and a more narrow pick uncertainty window (e.g., half-width, half-height)
- Must assume the events have a similar source mechanism
- Most useful when signals are noisy (low SNR)
- For this study, used **vertical channels**



Scaled to 2017



Auto-scaled

Joint Master Event Method (JMEM)

The **Master Event Method** (MEM) has been used for relative relocation for decades (e.g., Evernden (1969)). The method is a simple correction of the travel time for a station/phase based on a previous, co-located event with the same station/phase. It allows very precise timing of the arrival times and can provide an accurate location when the master event location is known. Combining the MEM with the relative arrival picking technique outlined below allows for conservative relocation.

We modify the standard MEM to include a maximum likelihood grid search, using each event as a Master Event for every other event. This allows for an iterative, **jointly-determined solution**, as each event corrects all others for similar station/phases (JMEM). Use a standard gaussian with respect to the residuals and uncertainty.

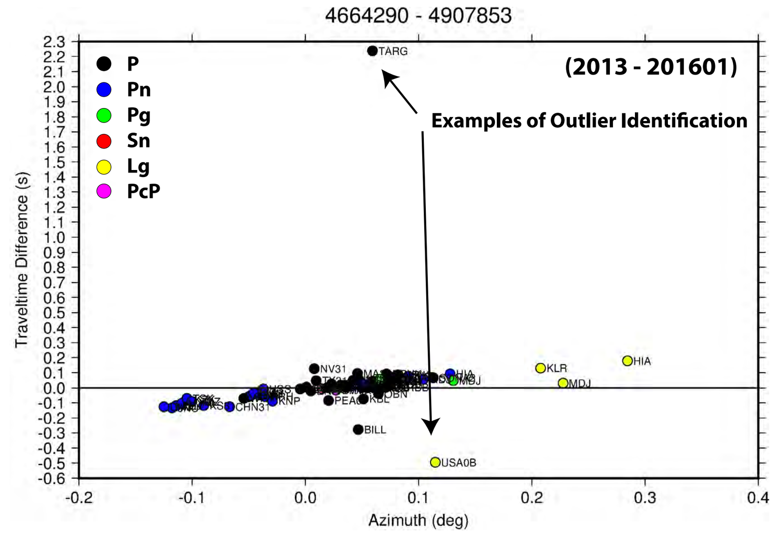
Various earth models can be used. For the majority of the work, the simple **1D ak135** model (Kennett et al., 1995) works well. For the JMEM and other relative relocation techniques, the choice of the model is not as crucial, but can still provide additional path accuracy. For the relocations below, we used the **SALSA3D model** (Ballard et al., 2016) for Pn, P, Sn, S and **RSTT** (Myers et al., 2010) for Pg and Lg. Other phases still used **ak135**.

Relative Relocations of the DPRK Announced Nuclear Tests

We relocate the 6 announced nuclear tests of the Democratic People's Republic of Korea (DPRK) using the JMEM and arrival picks from regional and global stations from various networks (e.g., International Monitoring System, Global Seismic Network, etc.).

The goal was to find arrival picks from stations in roughly equal azimuthal distances and at regional and teleseismic distances. Thus, we could be selective on which stations/waveforms we chose to use based on waveform quality and azimuthal distribution.

We checked for arrival outliers by comparing each event and plotting travel time differences relative to a "Directivity Parameter" from finite fault modeling studies (Cleveland and Ammon, 2015). These were removed from the arrival data set.



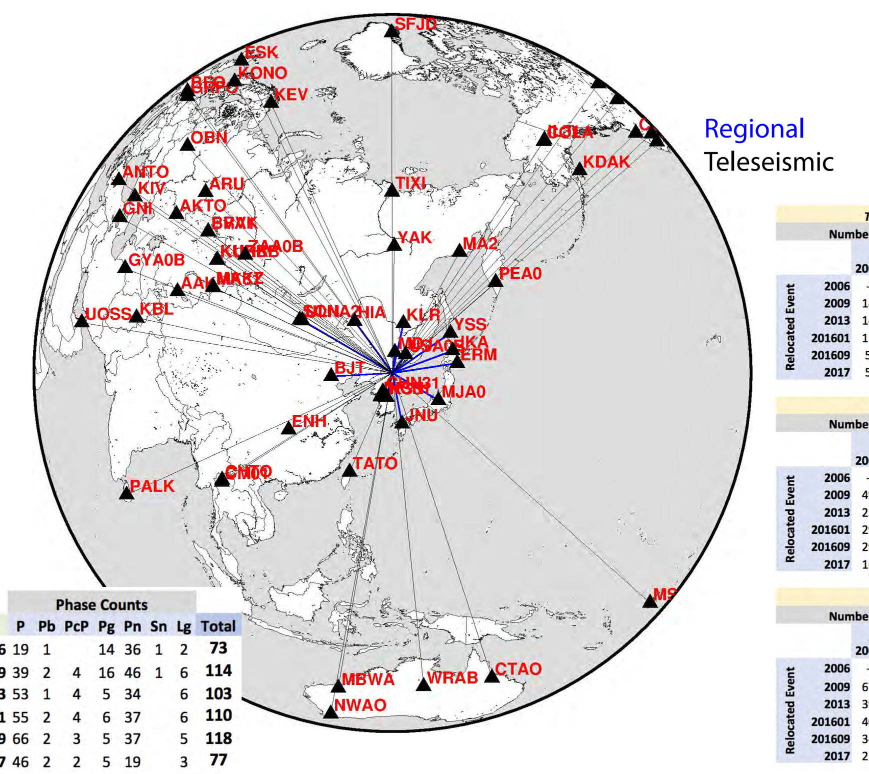
<u>Grid Search and Uncertainty Parameters:</u>

Lateral Grid Bin: 0.0005 deg
Origin Time Grid: -0.2 to +0.2 seconds @ 0.1 sec
Depth: Fixed at -1.5 km (approximate elevation of portals, based on Google Earth)
Residual (r) with respect to velocity model assigned to a phase

Uncertainties (σ^2):
(1) Pick error
(2) Pick error of master event for same Station/Phase
(2) Variance of Master Event Corrections for each Station/Phase

$$\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{r^2}{2\sigma^2}}$$

Arrival Paths for 201709 (DPRK6)



Event	P	Pb	PcP	Pg	Pn	Sn	Lg	Total
2006	19	1		14	36	1	2	73
2009	39	2	4	16	46	1	6	114
2013	53	1	4	5	34		6	103
201601	55	2	4	6	37		6	110
201609	66	2	3	5	37		5	118
2017	46	2	2	5	19		3	77

Teleseismic Phases Only — Number of Common Defining Phases (Relocated Event vs. Master Event)

Relocated Event	2006	2009	2013	201601	201609	2017
2006	-	18	14	11	5	5
2009	18	-	31	31	19	16
2013	14	31	-	45	43	30
201601	11	31	45	-	44	28
201609	5	19	43	44	-	49
2017	5	16	30	28	49	-

Regional Phases Only — Number of Common Defining Phases (Relocated Event vs. Master Event)

Relocated Event	2006	2009	2013	201601	201609	2017
2006	-	49	25	29	29	16
2009	49	-	44	45	43	24
2013	25	44	-	42	40	22
201601	29	45	42	-	47	29
201609	29	43	40	47	-	27
2017	16	24	22	29	27	-

All Phases — Number of Common Defining Phases (Relocated Event vs. Master Event)

Relocated Event	2006	2009	2013	201601	201609	2017
2006	-	67	39	40	34	21
2009	67	-	75	76	62	40
2013	39	75	-	87	83	52
201601	40	76	87	-	91	57
201609	34	62	83	91	-	76
2017	21	40	52	57	76	-

Absolute Location Constraints

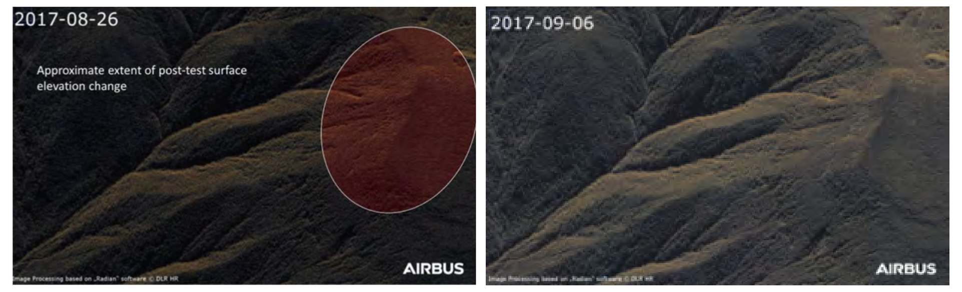
In order to determine absolute locations, we **must tie at least one of the locations in an absolute sense.** Before the 2017 event, we generally used the topography and assumption of maximum overburden to tie the relative locations to absolute positions. This lead to some uncertainty in the north-south positions for absolute locations, given the orientation of canyons and ridges in the area of the DPRK test site.

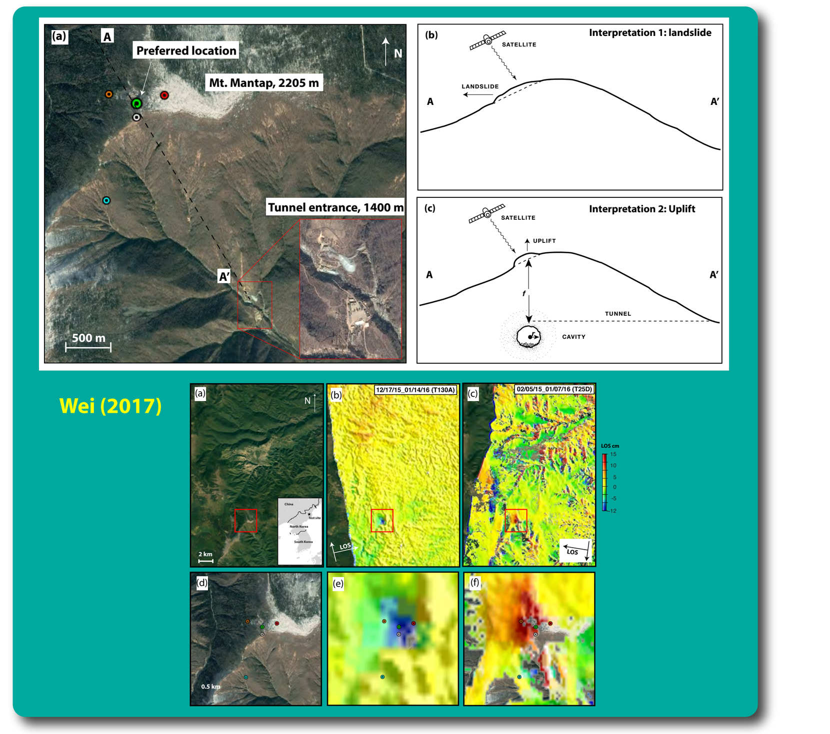
Wei (2017) used interferometric synthetic aperture radar (InSAR) data from Japan Aerospace Exploration Agency ALOS-2 satellite to show possible deformation associated with the January 6, 2016 announced DPRK test.

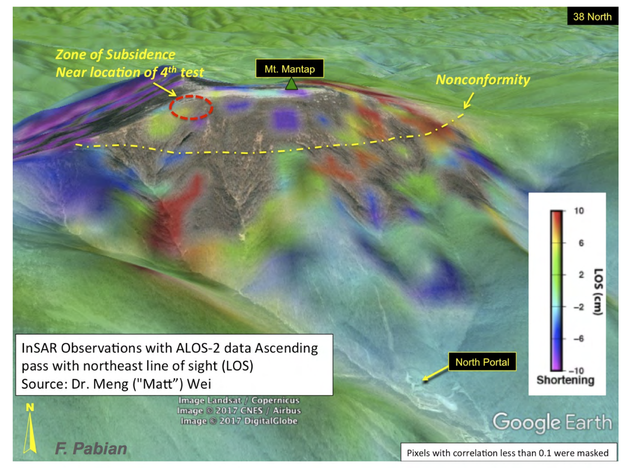
Airbus produced images before/after the 2017 event, indicating an apparent rise at the top of the mountain. InSAR observations with ALOS-2 data Ascending pass shows significant movement, centered at the peak of the mountain.

We decided to use the extent of the Airbus image to constrain the location of the 2017 event with an ellipse shown in the image below.

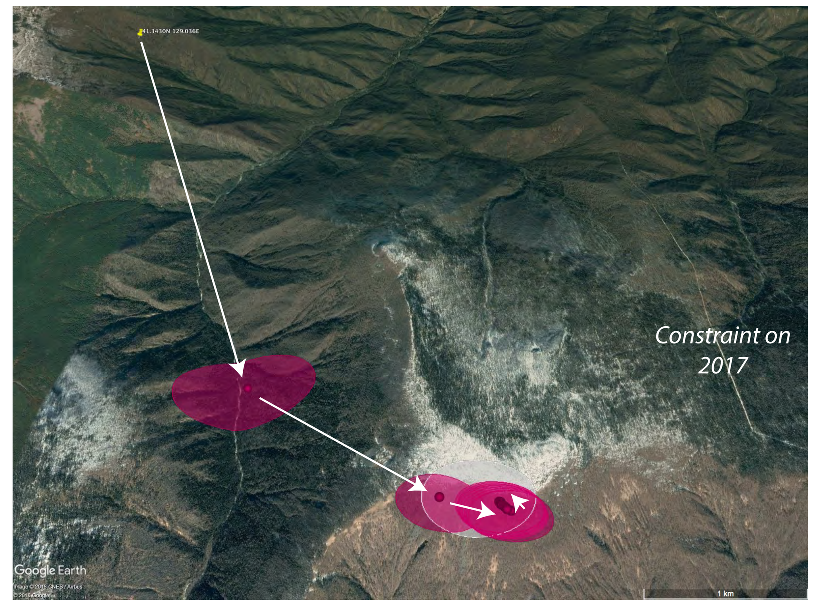
Center of rise approximately
41 17 51.90N, 129 04 40.64E
Ellipse oriented roughly E-W; major axis of 670m; minor axis of 425m
Material that moved up mostly involved the volcanics and not the basement



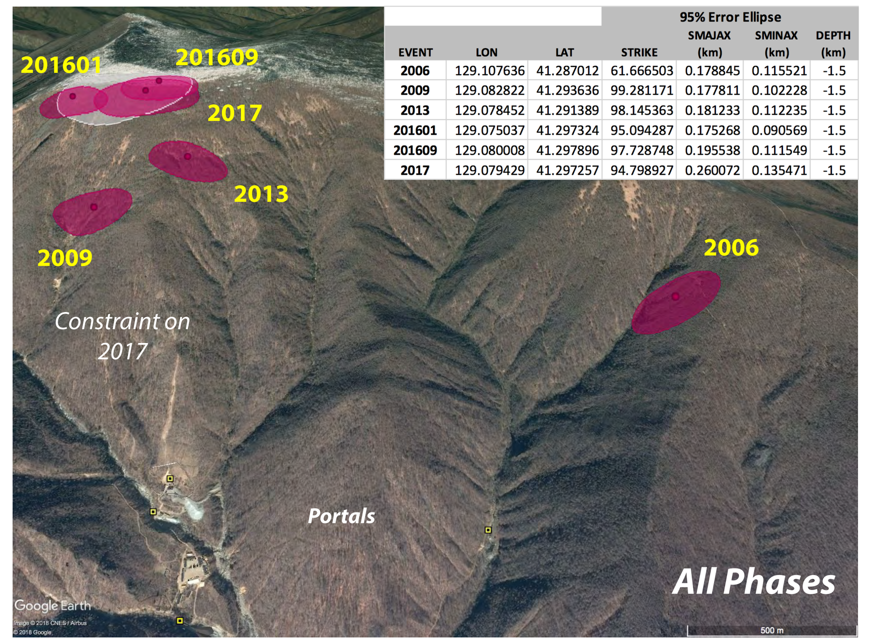




Migration of 2017 Location from Starting USGS Epicenter

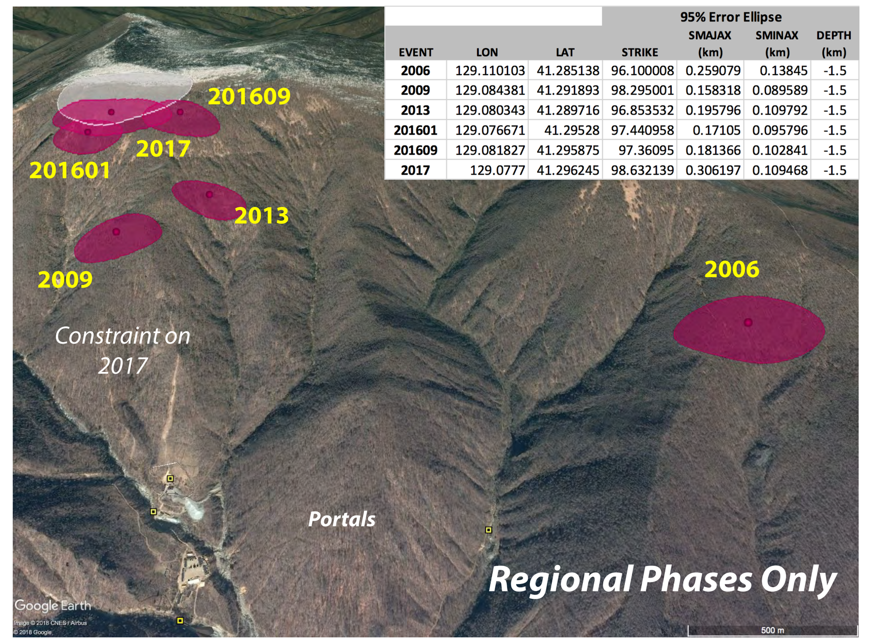


Relative Relocation Results -- All Phases



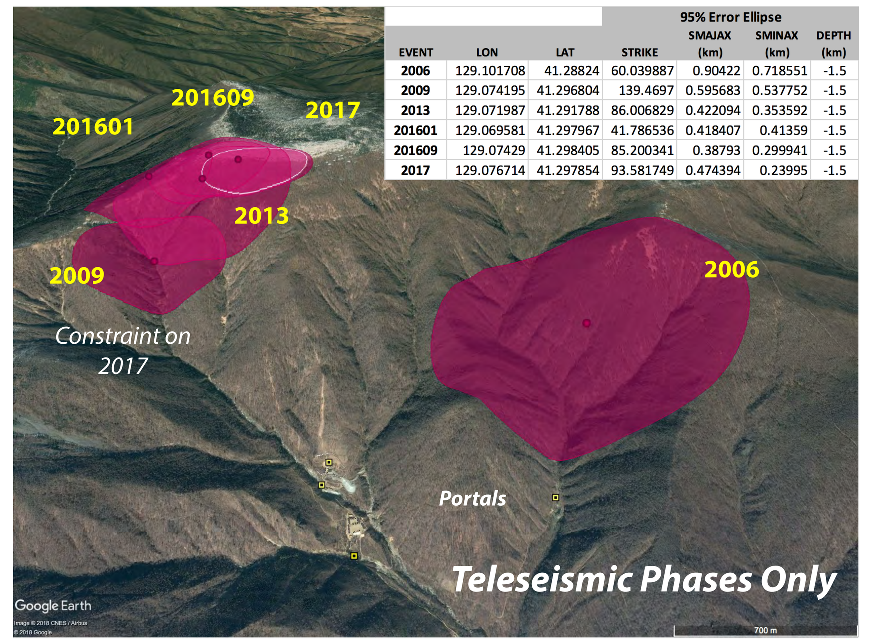
EVENT	LON	LAT	STRIKE	95% Error Ellipse SMAJAX (km)	SMINAX (km)	DEPTH (km)
2006	129.107636	41.287012	61.666503	0.178845	0.115521	-1.5
2009	129.082822	41.293636	99.281171	0.177811	0.102228	-1.5
2013	129.078452	41.291389	98.145363	0.181233	0.112235	-1.5
201601	129.075037	41.297324	95.094287	0.175268	0.090569	-1.5
201609	129.080008	41.297896	97.728748	0.195538	0.111549	-1.5
2017	129.079429	41.297257	94.798927	0.260072	0.135471	-1.5

Relative Relocation Results -- Regional Only



EVENT	LON	LAT	STRIKE	95% Error Ellipse SMAJAX (km)	SMINAX (km)	DEPTH (km)
2006	129.110103	41.285138	96.100008	0.259079	0.13845	-1.5
2009	129.084381	41.291893	98.295001	0.158318	0.089589	-1.5
2013	129.080343	41.289716	96.853532	0.195796	0.109792	-1.5
201601	129.076671	41.29528	97.440958	0.17105	0.095796	-1.5
201609	129.081827	41.295875	97.36095	0.181366	0.102841	-1.5
2017	129.0777	41.296245	98.632139	0.306197	0.109468	-1.5

Relative Relocation Results -- Teleseismic Only



EVENT	LON	LAT	STRIKE	95% Error Ellipse SMAJAX (km)	SMINAX (km)	DEPTH (km)
2006	129.101708	41.28824	60.039887	0.90422	0.718551	-1.5
2009	129.074195	41.296804	139.4697	0.595683	0.537752	-1.5
2013	129.071987	41.291788	86.006829	0.422094	0.353592	-1.5
201601	129.069581	41.297967	41.786536	0.418407	0.41359	-1.5
201609	129.07429	41.298405	85.200341	0.38793	0.299941	-1.5
2017	129.076714	41.297854	93.581749	0.474394	0.23995	-1.5

Validation of the Master Event Method Using a Known Explosion Dataset

The use of the MEM for the DPRK test site has suggested high levels of accuracy and precision, even with poor network geometry. In order to validate the use of the MEM, we selected an alternate data set to test the accuracy and precision of the method. **The Bighorns experiment** (Worthington et al., 2012) was a series of explosive tests in the Bighorns, Wyoming area between July 19 and August 6, 2010. The shots varied from ~113 to 900 kg of explosive and were generally much farther apart from each other than typically used for relative relocation studies. In order to test the MEM event with a similar event separation to the DPRK announced tests, we chose to test only the central five events in the Bighorns experiment (identified with a rectangle in the figure). The event information and separations are shown in Table 1 and Table 2. Picking styles were the same as for the DPRK events.

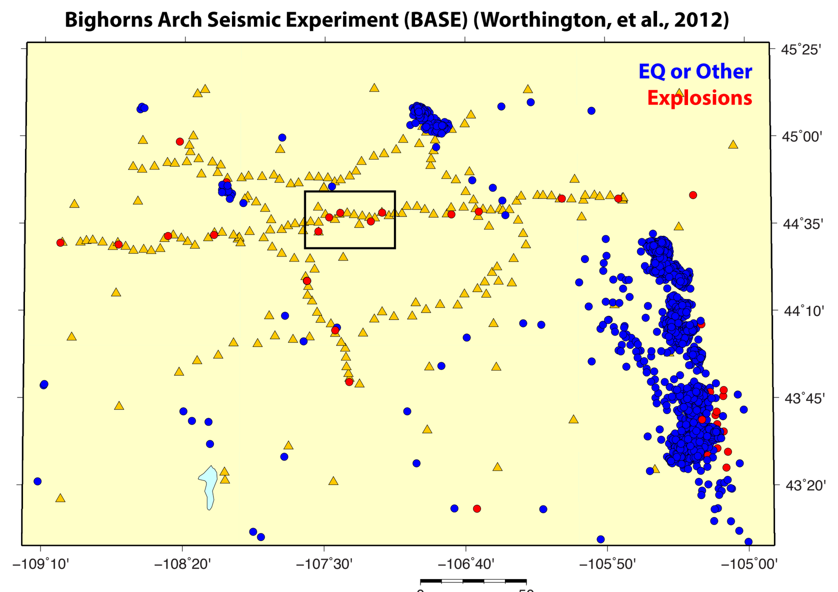
Because there are stations between the 5 selected events, we limited stations to those outside the event area.

Table 1. Information for selected events in Bighorns Experiment for Master Event validation (see right). The number of common stations is the number of stations with arrivals from the common 18 stations selected.

Event	Lat	Lon	Depth (km)	Yield (kg)	Number of Common Stations
6	44.5906	-107.2266	0.0198	454	17
7	44.6321	-107.1604	0.0198	454	14
10	44.5424	-107.5371	0.0223	454 (blew out)	10
11	44.6096	-107.4742	0.0197	454	15
12	44.6312	-107.4077	0.0174	227	13

Table 2. Separation of selected Bighorns experiment events (see right) for Master Event validation.

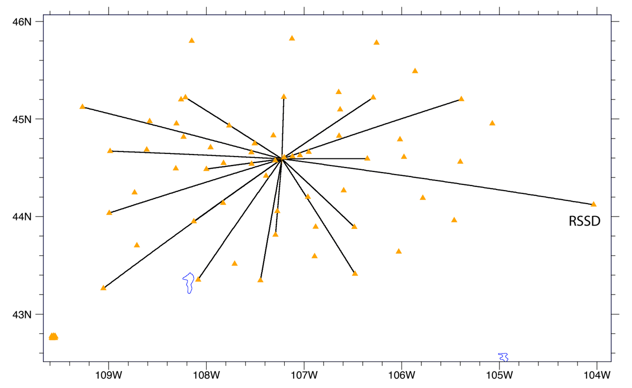
Event1	Event2	Separation (km)
6	7	7.0
6	10	25.3
6	11	19.8
6	12	15.1
7	10	31.5
7	11	25.0
7	12	19.6
10	11	9.0
10	12	14.2
11	12	5.8

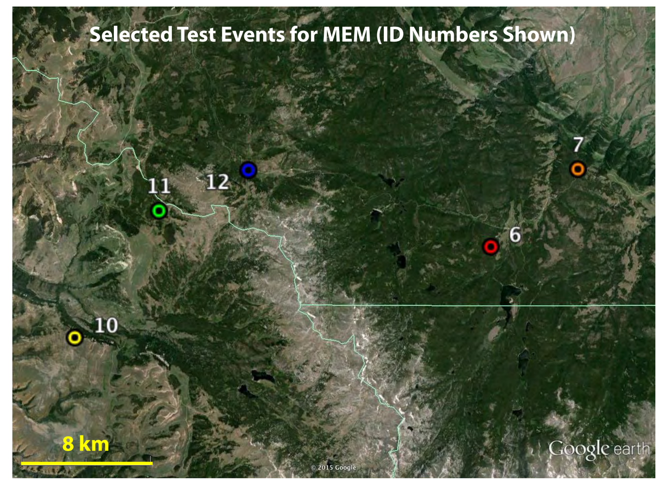


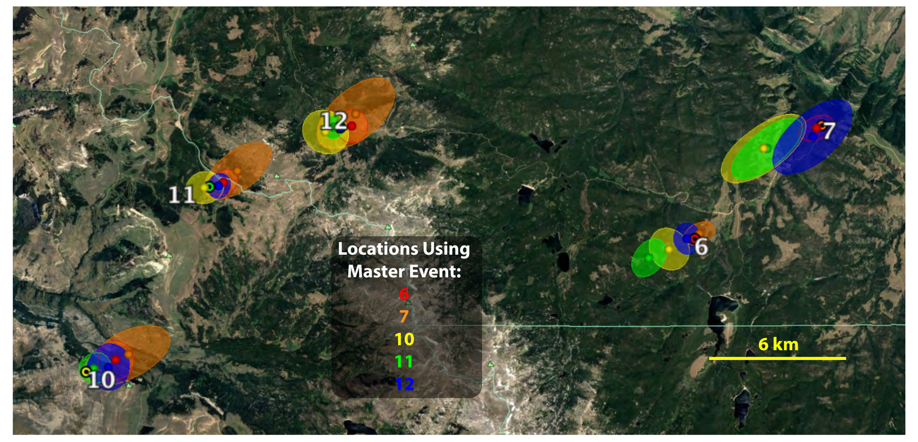
Shots of the Bighorns Experiment from July 19 to August 6, 2010. The shot locations are significantly farther apart than typically used for relative relocation studies. To test shots of similar distance between the DPRK announced tests, we selected the five central events that are clustered more closely (rectangle and bottom figure).

During the relocation procedure (**using ak135 model**), any obvious residual outlier was removed and the event relocated. There were several common stations with residual outliers, with the most common being station RSSD, which is the farthest from any of the validation events. The RMS of the travel time residuals per relocation varied from 0.043 s to 0.131 s, with the relocations with the larger number of arrivals also having the lower RMS residuals.

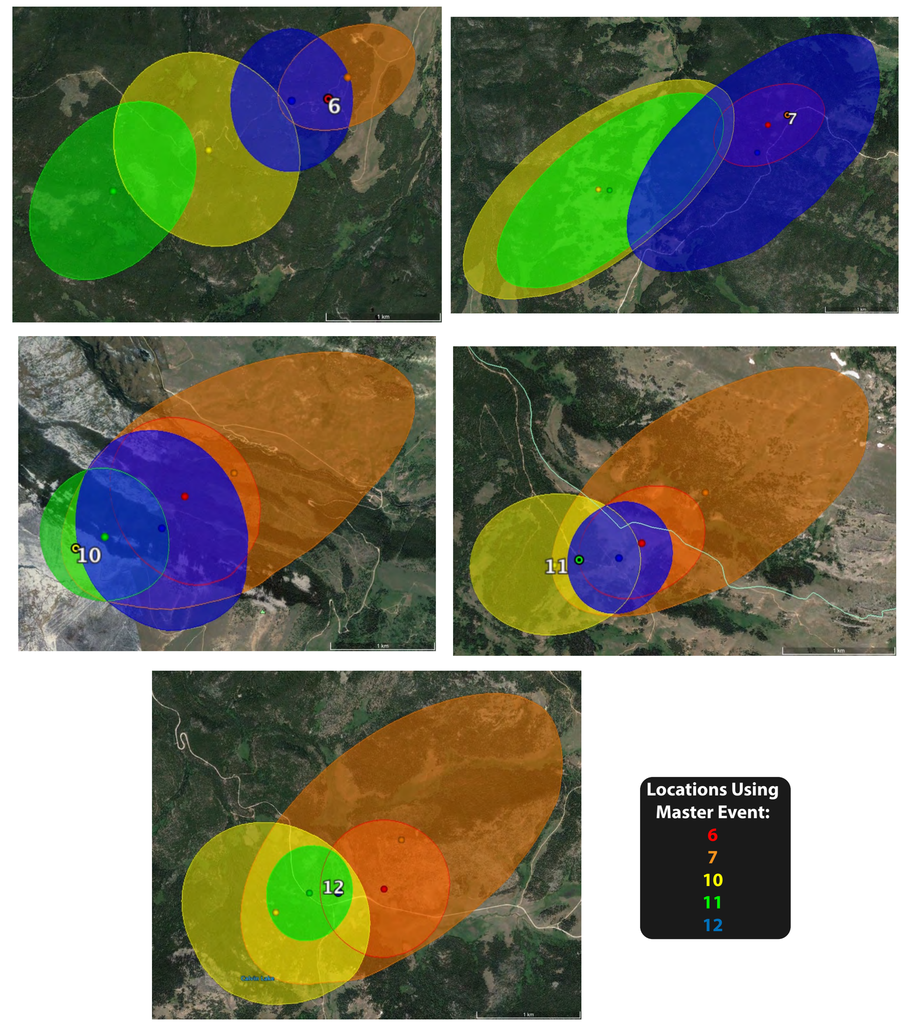
Paths for Event 6 that had picked arrivals for at least two of the Bighorns Experiment validation events. All the arrivals picked on all validation events were Pg, except for station RSSD (the farthest east) that also had a Pn arrival on several validation events. Other possible stations are also shown, but paths were selected based on common stations between validation events and common distances and azimuths.

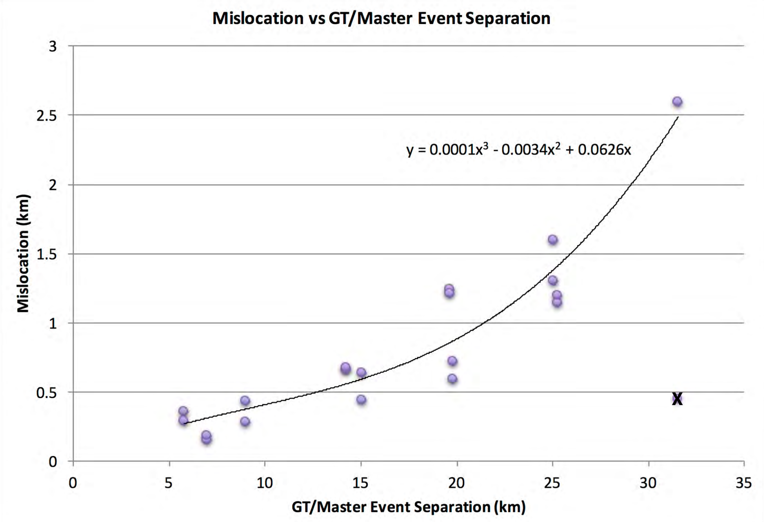






Master events (filled circles) and relocations using the MEM (colored spheres with 95% confidence ellipses). Colors correspond to which Master Event was used for the separate relocations: Red = 6, Orange = 7, Yellow = 10, Green = 11, Blue = 12. The ak135 model was used. Note how the relocated events are biased towards the Master Event, with the relocation positions following the same general location pattern of the Master Events.





After all event-master event (ME) combinations were processed, we plotted the mislocation related to the ground-truth (GT)-master event separation. The mislocation follows a pattern related to the GT-ME separation distance, with increasing mislocation with increasing separation. For these five validation events, the maximum mislocation is 2.6 km at a separation of 31.5 km, a far greater distance than is typically used for a ME relocation (usually on several kilometers). This suggests, that the ME method is valid to at least this separation and can produce a mislocation of around 4.5% of the separation distance on average.

One point in the above figure appears to be an outlier and has a mislocation much too small for the separation distance. When that point is removed and a trend line is produced, the "best" line fit appears to be a third-order polynomial line. To preserve a zero mislocation at zero separation, a third-order polynomial fit with a zero intercept fits the data well.

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