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Relative Location Analysis of DPRK Test Events

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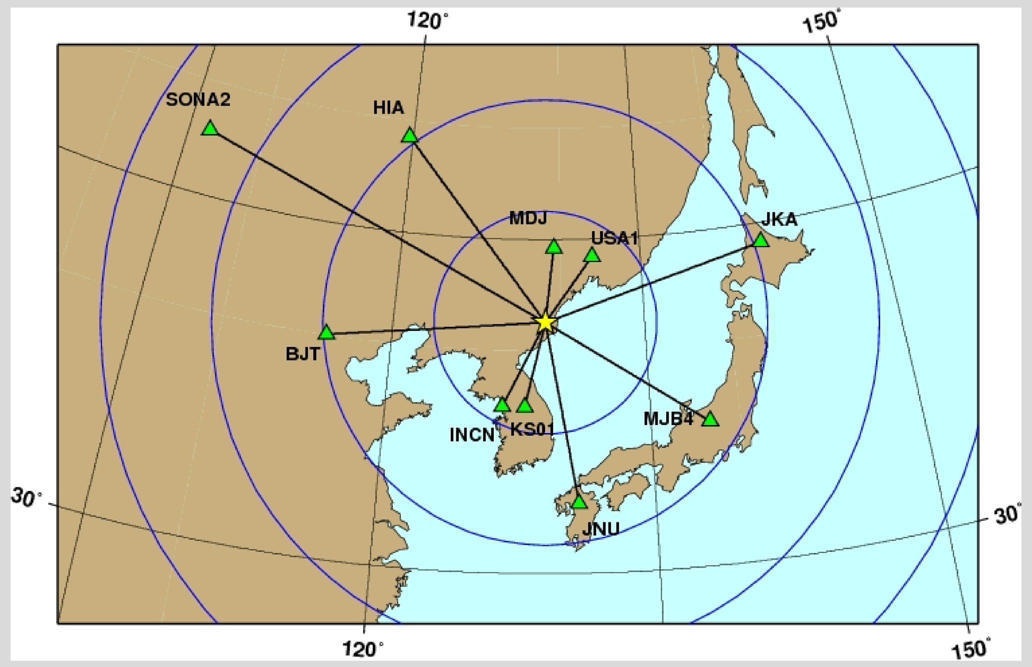
ABSTRACT

Relative location analysis of the last five declared DPRK nuclear test events is presented. Given a well azimuthally distributed regional dataset of common stations, each with sufficient time-bandwidth product, precise relative arrival times are produced through manual alignment (*e.g.*, Fisk, 2002). These relative arrivals are subsequently passed to a multiple event locator based on Pavlis and Booker's Progressive Multiple Event Location technique (1983), which produces relative locations of the test events. In an effort to better understand how station distribution affects the relative locations we calculate numerous location realizations with varying station sets. We then assess the how the number of defining phases (NDEF), as well as the resultant length of the station set affect each location solution.

DATA

The panel (right) shows the geographic distribution of observing stations (triangles), used for this analysis, with respect to the test-site (star). Blue ellipses denote 5 arc-degree intervals from the test-site. The data set is comprised of IMS and openly available stations.

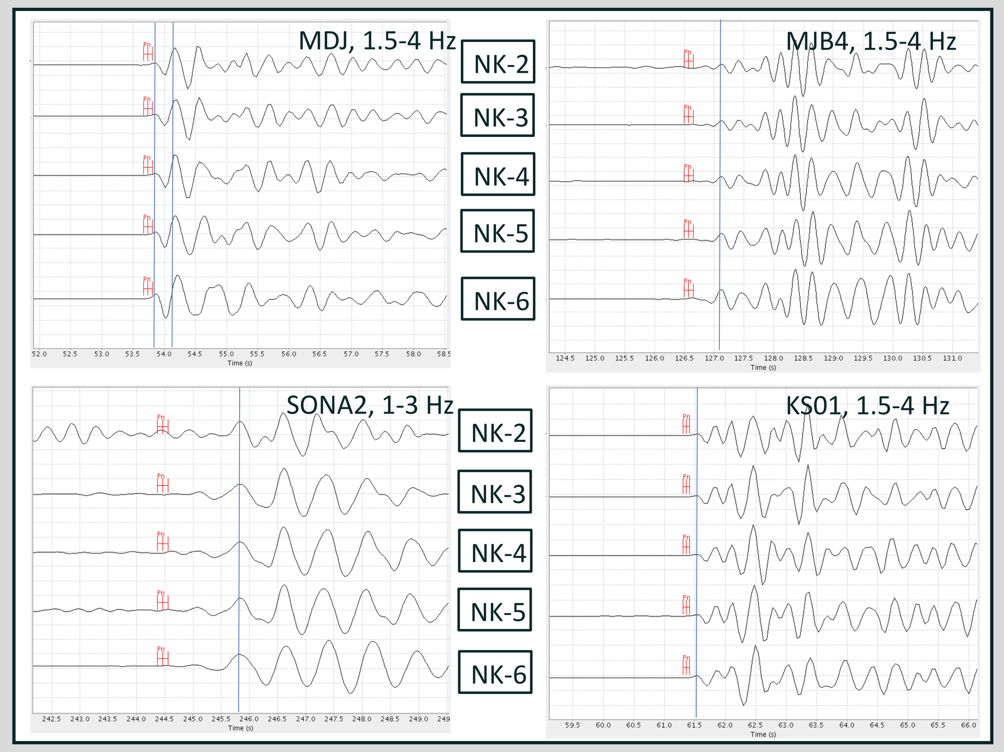


DPRK2	DPRK3	DPRK4	DPRK5	DPRK6	ESAZ	DELTA	KEY
MDJ	MDJ	MDJ	MDJ	MDJ	6.35	3.34	A
USA1	USA1	USA1	USA1	USA1	35.13	3.62	C
JKA	JKA	JKA	JKA	JKA	69.51	10.31	F
MJB4	MJB4	MJB4	MJB4	MJB4	120.75	8.56	missing
JNU	JNU	JNU	JNU	JNU	169.53	8.28	
KS01	KS01	KS01	KS01	KS01	194.01	3.95	
INCN	INCN	INCN	INCN	INCN	207.35	4.24	
BJT	BJT	BJT	BJT	BJT	266.93	9.87	
SONA2	SONA2	SONA2	SONA2	SONA2	299.83	17.37	
HIA	HIA	HIA	HIA	HIA	323.78	10.33	

The table (left) shows a quality control analysis of the station data. Each event-station waveform was graded with respect to SNR. Only those waveforms graded "A" were used in the analysis. Note that some stations were not available for all events. ESAZ and DELTA are with respect to the test-site.

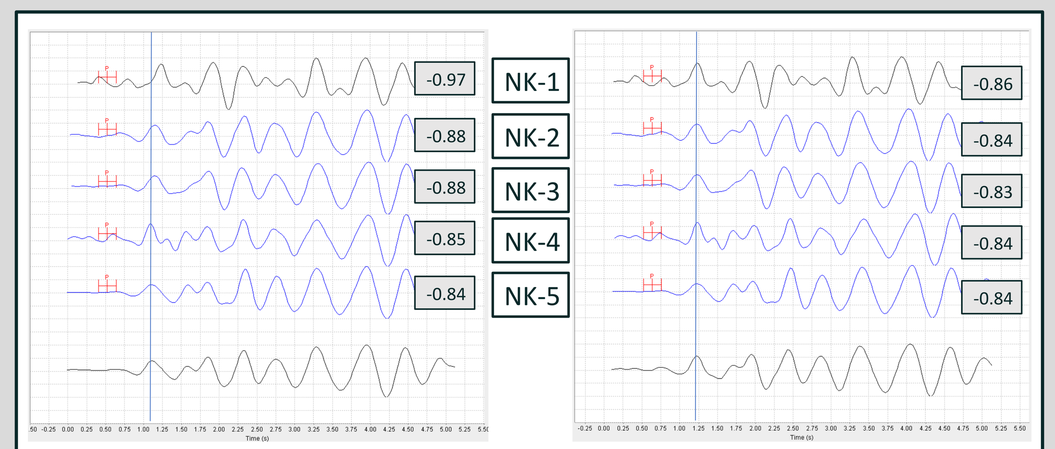
The panel (right) shows a North Korean official presenting a schematic map of the Punggye-ri Nuclear Test Site complex on the day of the public demolition (24 May 2018). The map includes administrative areas, tunnel complexes, and "ground-truth" locations of the six declared nuclear tests. These "ground-truth" locations are compared to our geolocations from this analysis.

ANALYSIS OF *Pn* ARRIVAL TIMES



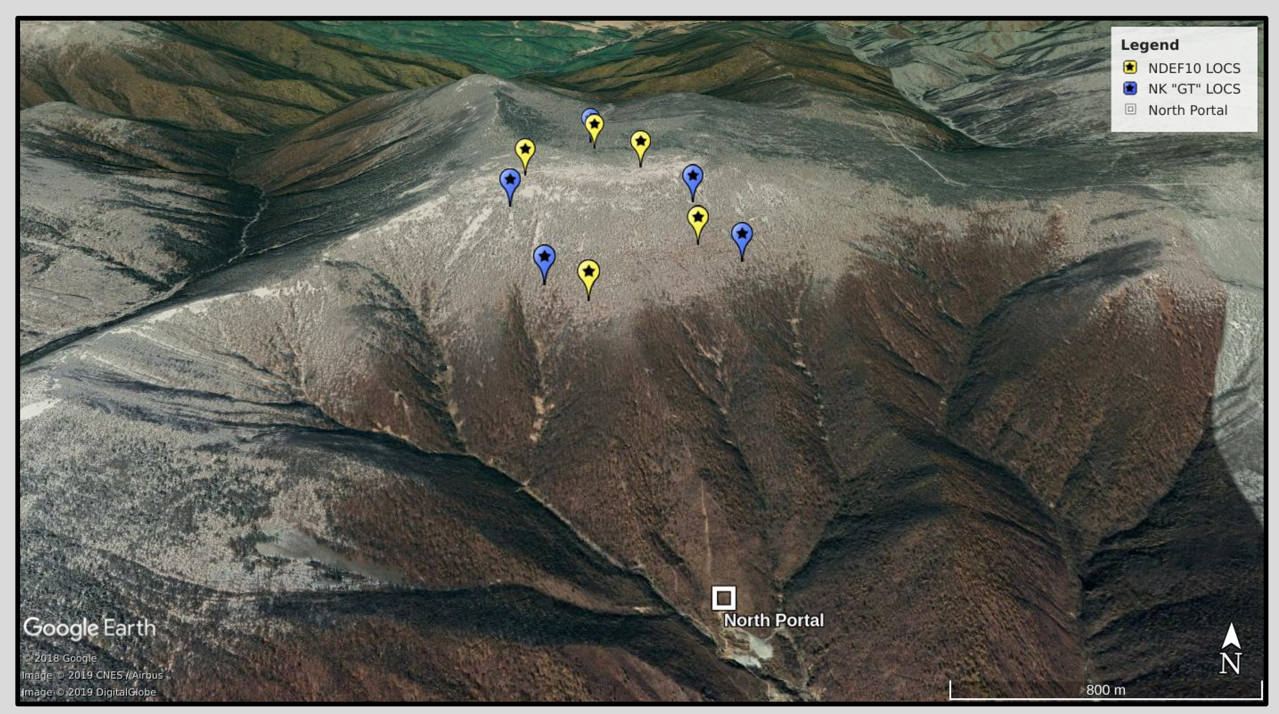
After Fisk (2002) we manually align the observed explosion waveforms at common stations. We specifically attempt to align the first few cycles of the *Pn* onset (left). We denote the alignment with a blue vertical bar. The phase onset is placed on the first discernable break on the highest SNR event and that pick is then mapped to the other events. This method is key to the success of the relative location, as it removes random pick error from the location inversion and leaves only the systematic model error of the shared travel path.

The panel (right) shows the importance of manual alignment versus that of quantitative cross-correlation (QCC). Note the difference in the travel-time residuals between the 2006 event and the remaining events when QCC is used. We noted that when the traces are aligned manually the residuals are consistent across all events.



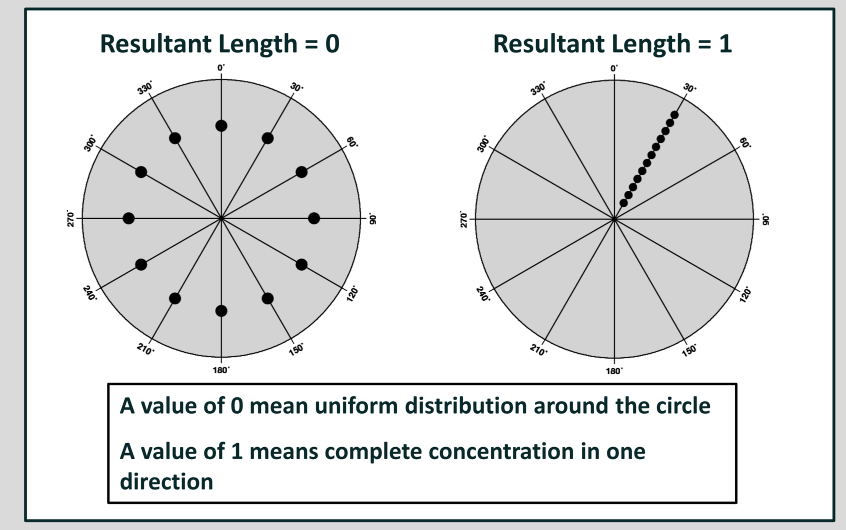
Aligned on optimal lag — Aligned by analyst

RESULTS



The panel (above) shows the results of passing the *Pn* relative arrival times for all ten stations (NDEF=10) through the Progressive Multiple Event Location (PMEL) technique (Pavlis & Booker, 1983). As the name implies PMEL uses data from multiple events simultaneously to determine each of the clustered hypocenters. Unlike single event location techniques (*e.g.*, master-event location) PMEL offers the advantage of not requiring every station to observe each event. The cluster of locations (yellow markers) has been manually shifted approximately 840m SSE to facilitate the comparison of the relative locations with the "ground-truth" locations (blue markers) provided by North Korea.

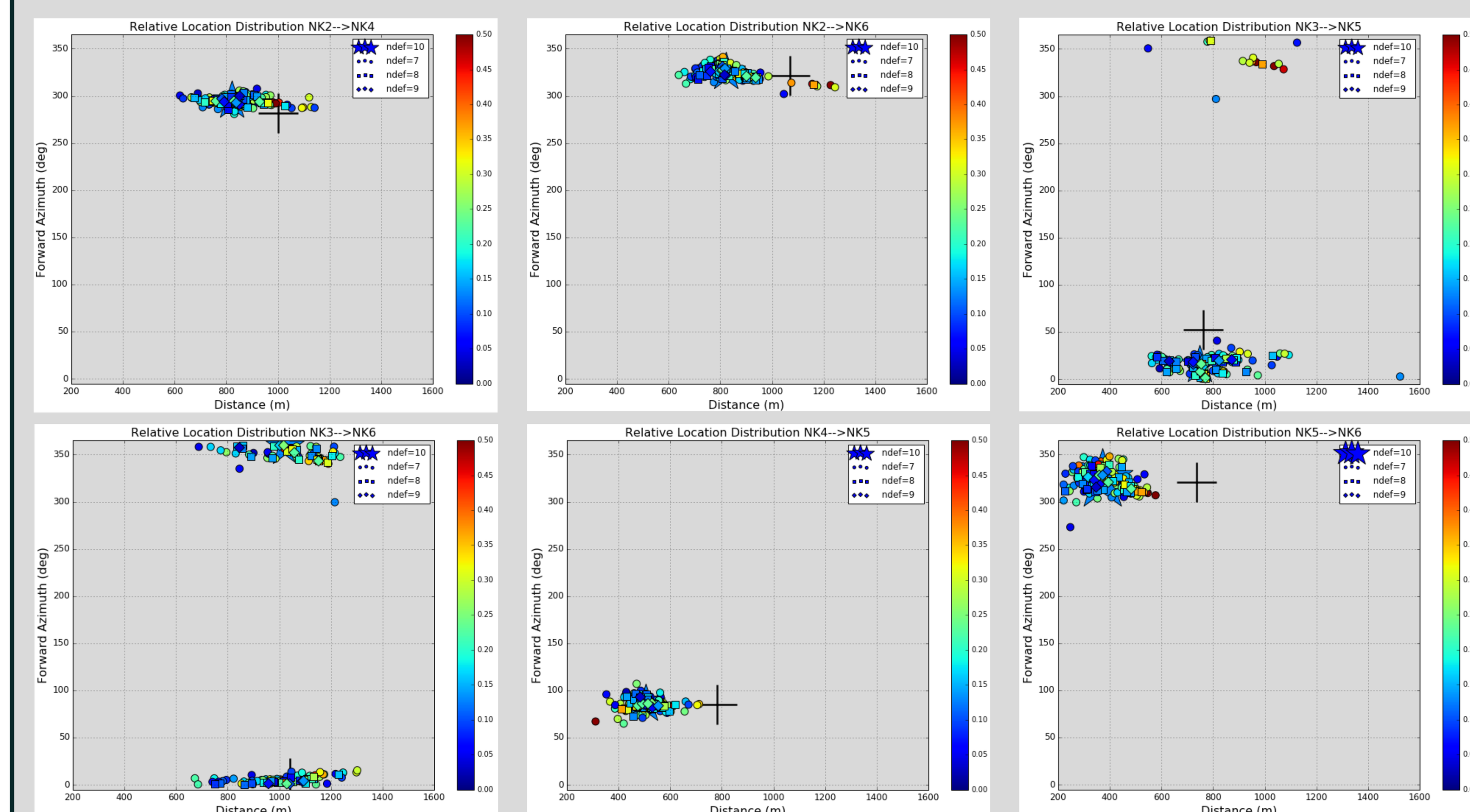
RESULTANT LENGTH



We borrow the "resultant length" (RL) statistic from the field of circular data analysis and use it as a proxy to measure the azimuthal distribution of our station set with respect to the North Korean test site. As seen on the panel (left) a perfectly uniform station set would give us a RL = 0. As reference the RL of the 10 station dataset shown in the DATA section is equal to 0.13.

Details: https://ncss-wpengine.netdna-ssl.com/wp-content/themes/ncss/pdf/Procedures/NCSS/Circular_Data_Analysis.pdf

EFFECT OF RL & NDEF



Each panel (above) shows the relative location results from 176 realizations in distance-azimuth space for a specific event pair. These realizations represent all possible station combinations from NDEF=7 to NDEF=10. Different markers represent NDEF values, while the color represents the resultant length value. The black cross represents the "ground-truth" ("GT") dist/az with respect to the test locations provided by North Korea. As expected there are systematic biases between the "GT" values and each cloud of locations. We note a distinct correlation between increasing NDEF and the location collapsing to the center point of the cluster, and a weaker correlation between decreasing RL statistic and the location collapsing to the center.

DISCUSSION / FUTURE WORK

The analysis presented here shows that it is possible to produce reasonably precise relative locations given a well azimuthally distributed station set at regional distances. The manual alignment of waveforms, while time consuming, seems to afford more precise relative arrival times than automated cross-correlation methods. This is highlighted when event sizes within a cluster vary by orders of magnitude. The use of a multiple event locator, such as PMEL has an advantage over single-event techniques, primarily due to its ability to handle incomplete data sets, where some stations do not observe all events. In the future, we will apply this dataset to other well know locators (*e.g.*, HypoDD, BayesLoc) to assess the dependency of these results on the location algorithm. Our location realizations illuminate the correlation between location, NDEF, and RL. However, a more complete data set is needed to better understand this relationship.

REFERENCES:

Fisk, M. D. (2002). Accurate locations of nuclear explosions at the Lop Nor Test Site using alignment of seismograms and IKONOS satellite imagery, Bull. Seism. Soc. Am., 92, 2911-2925.

Pavlis, G. L., and J. R. Booker (1983). Progressive multiple event location (PMEL), Bull. Seism. Soc. Am.,73, 1753-1777.