Nuclear test depth determination with synthetic modelling: global analysis from PNEs to DPRK-2016

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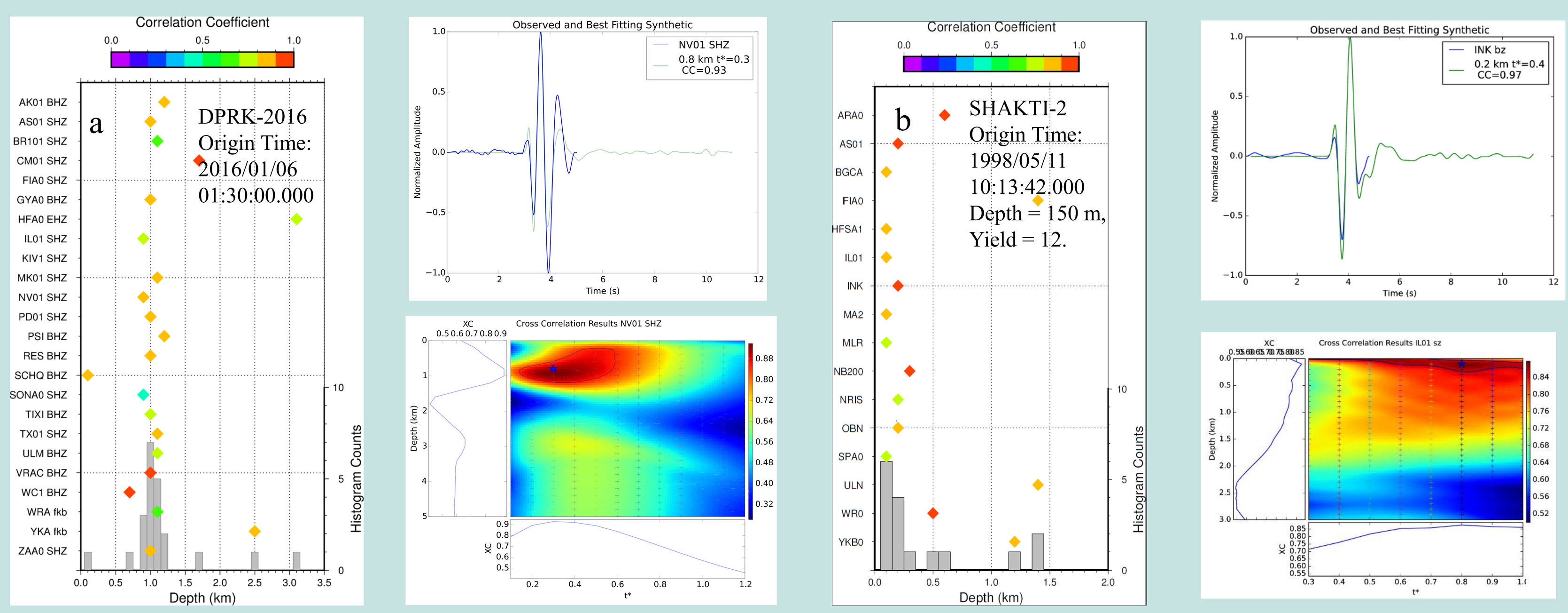
Introduction. Seismic event depth determination is a part of Special Studies and Expert Technical Analysis (ETA) specified in Comprehensive Nuclear Test Ban Treaty (CTBT). We have studied a number of approaches aimed at depth determination and designed a prototype software. Since the shape of the first few seconds of signal of very shallow events is very sensitive to the depth phases, cross correlation between observed and theoretic seismograms can provide a basis for the event depth estimation, and so an expansion to the screening process. We applied this approach mostly to events at teleseismic and partially regional distances. The approach was found efficient for the seismic event screening process, with certain caveats related mostly to poorly defined source and receiver crustal models which can shift the depth estimate. An adjustable teleseismic attenuation model (t*) for synthetics was used since this characteristic is not known for most of the rays we studied. We studied a wide set of historical records of nuclear explosions, including so called Peaceful Nuclear Explosions (PNE) with presumably known depths, and recent DPRK nuclear tests. The teleseismic synthetic approach is based on the stationary phase approximation with hudson96 program, and the regional modelling was done with the generalized ray technique by Vlastislav Cerveny modified to account for the complex source topography. The software prototype is designed to be used for the Special Studies and Expert Technical Analysis at the IDC. With this, the design effectively reuses the NDC-in-a-Box code and can be comfortably utilized by the NDC users. The package uses Geotool as a front-end for data retrieval and pre-processing. The modules are mostly Python coded, C-coded (Raysynth3D complex topography regional synthetics) and FORTRAN coded synthetics from the CPS330 software package by Robert Herrmann of Saint Louis University. The extension of this single station depth determination method is under development and uses joint information from all stations participating in processing. It is based on simultaneous depth and moment tensor determination for both short and long period seismic phases. A novel approach recently developed for microseismic event location utilizing only phase waveform information was adapted by us to a global scale. It should provide faster computation as it does not require intensive synthetic modelling, and might benefit processing noisy signals. A consistent depth estimate for recent nuclear tests was produced for sufficient number of IMS stations (primary and auxiliary) used in processing. All techniques are in a development or/and testing stage.

Conclusions. We are in a process of development of preliminary methodological and technological frameworks of the Special Studies and Expert Technical Analysis to be established at the International Data Center and conducted as an on-demand service for the Provisional Technical Secretariat and State Parties in a routine manner after entering the Treaty into force. A number of case studies were explored and suggested as services, and a software environment design for these cases was developed, taking into account current IDC software status and its prospect. In this presentation we consider a shallow event depth determination with different approaches: (1) synthetic modeling and cross-correlation, (2) Statistically Optimal Phase Method, and (3) method based on moment tensor estimation. They all utilizes historical nuclear test seismograms for wide range of depths, yields and distances for both the weapon tests and so called ground truth Peaceful Nuclear Explosions. We explored explosions for different site topography and geology and receiver stations at teleseismic distances. The simultaneous determination of event depth and moment tensor estimation will provide expanded knowledge of the source properties and allow further analysis of uncertainties. Initial implementation yields efficient and reliable results using teleseismic P arrivals and future work will include additional phases and first motion information for further constraints.

Depth determination of the announced DPRK-2016 explosion and Indian SHAKTI-2 with synthetic modeling.

We use a synthetic modeling approach to shallow event depth determination based on teleseismic observations. hudson96 program [Herrmann and Ammon, 2002] was used as it's allowed for specific velocity models for the source and receiver as well as the propagation model in between. The source and receiver velocity models are obtained from Crust1.0 (or specific model if known, like in DPRK case, see also our poster 6620) and the global reference model ak135 is used for the teleseismic propagation path. To assess the dependency of the amplitude and frequency content of the arrivals, a range of attenuation operators (t*) are chosen and the synthetic waveforms are calculated for a range of source depths from the surface to 4 km, every 100 meters. Synthetic waveform with the highest cross correlation with the observed signal corresponds to the appropriate depth of the event.

Figures a and b shows depth distribution (km) vs stations. Colored diamonds indicate depth corresponding to maximum cross correlation coefficient for search of t* and source depth. Depth histogram shown at bottom of figure. Figures to the right of a and b show examples of the depth determination procedure for selected stations and events. Top Figures: waveform fitting for the indicated station. Observed waveform and best fitting synthetic shown along with optimal depth and t*. Bottom Figure: Cross correlation map for range of depths and t*. Warmer colors show higher cross correlation with star indicating highest value. Black contour approximates region of 95% confidence. Cross marginal profiles through depth and t* shown to the side and below.



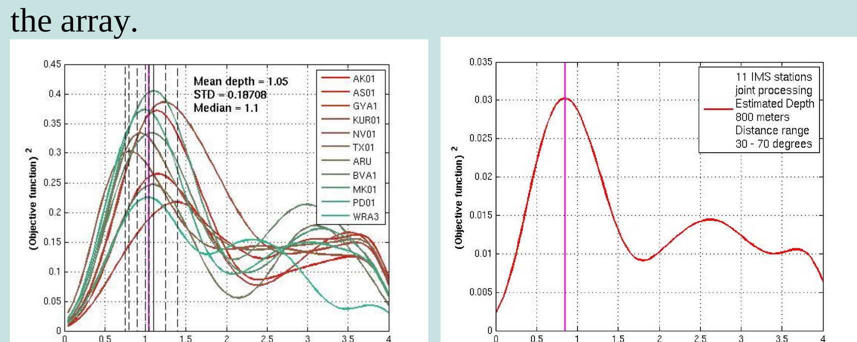
Depth determination with the Phase Method

This statistically optimal (SO) method is based on joint determination of hypocenter coordinates and fault plane solution of the microseismic source during hydraulic fracturing. It utilizes only phase information of the signal and disregards amplitudes and was found robust in noisy environment when mapping hypocenters of sources with signals having SNR << 1 (Kushnir, et al., Geophysical Prospecting, 2014). In this research the method was adapted to global network instead of array (see also our poster 6620 of current EGU session with the adapted formula and results of the method applied to other DPRK explosions).

The statistically optimal phase algorithm finds an estimate $\hat{\mathbf{r}}_{ph}$ of hypocenter coordinates $\mathbf{r}=(x,y,z)$ as an argument in the maximum of the cost function, depending on complex coherence functions $\dot{K}_{k,l}\left(f_j \mid \dot{\mathbf{X}}_N\right)=C_{k,l}\left(f_j\right)exp\left\{i\psi_{k,l}\left(f_j\right)\right\}$ calculated using observations of different pairs $k,l\in(1,\dots,K),\, k\neq l$ of array channels (Kushnir, Rozhkov and Tagizade, 2012; Varypaev, 2012):

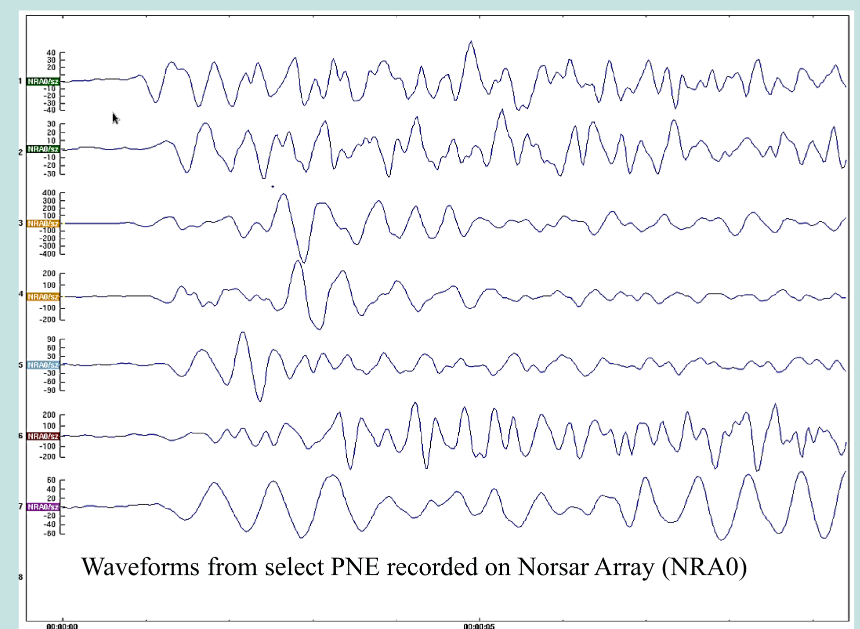
$$\hat{\mathbf{r}}_{PH}\left(\dot{\mathbf{X}}_N\right)=\underset{\mathbf{r}\in Q,\, s\in\{1,\dots,S\}}{arg\,max}\ \Phi_s\left(\dot{\mathbf{X}}_N,\mathbf{r}\right),\ \text{ where }\ \Phi_s\left(\mathbf{X}_N,\mathbf{r}\right)=\sum_{f_j\in\Delta_s}\sum_{k\neq l}^{K}a\left(C_{k,l}\left(f_j\right)\right)b\left(\varphi_{k,l}(f_j,\mathbf{r})-\psi_{k,l}\left(f_j\right)\right),$$

In the cost function $a(C)$ is a contrasting tuning function of the algorithm; $C_{k,l}\left(f_j\right)$ is the modulus of estimated complex coherence $C_{k,l}\left(f_j\right)exp\left\{i\psi_{k,l}\left(f_j\right)\right\}$ for different array channels; $\psi_{k,l}\left(f_j\right)$ is the argument of this coherence estimate; $\varphi_{k,l}\left(f_j,\mathbf{r}\right)$ is the theoretical difference of spectral phases (at frequency f_j) for pure signals generated by the source with the coordinates $\mathbf{r}$ in channels k and l, $k\neq l$; $b(\delta_{k,l})$ is a function of residuals $\delta_{k,l}=\varphi_{k,l}(f_j,\mathbf{r})-\psi_{k,l}\left(f_j\right)$ of the theoretical and observed phase differences between k and l channels; Δ_s, $s\in(1,\dots,S)$ is the set of possible frequency bands of source time function. Theoretical phase differences $\varphi_{k,l}\left(f_j,\mathbf{r}\right)$ are calculated from the known seismic velocity model of the earth beneath the array.



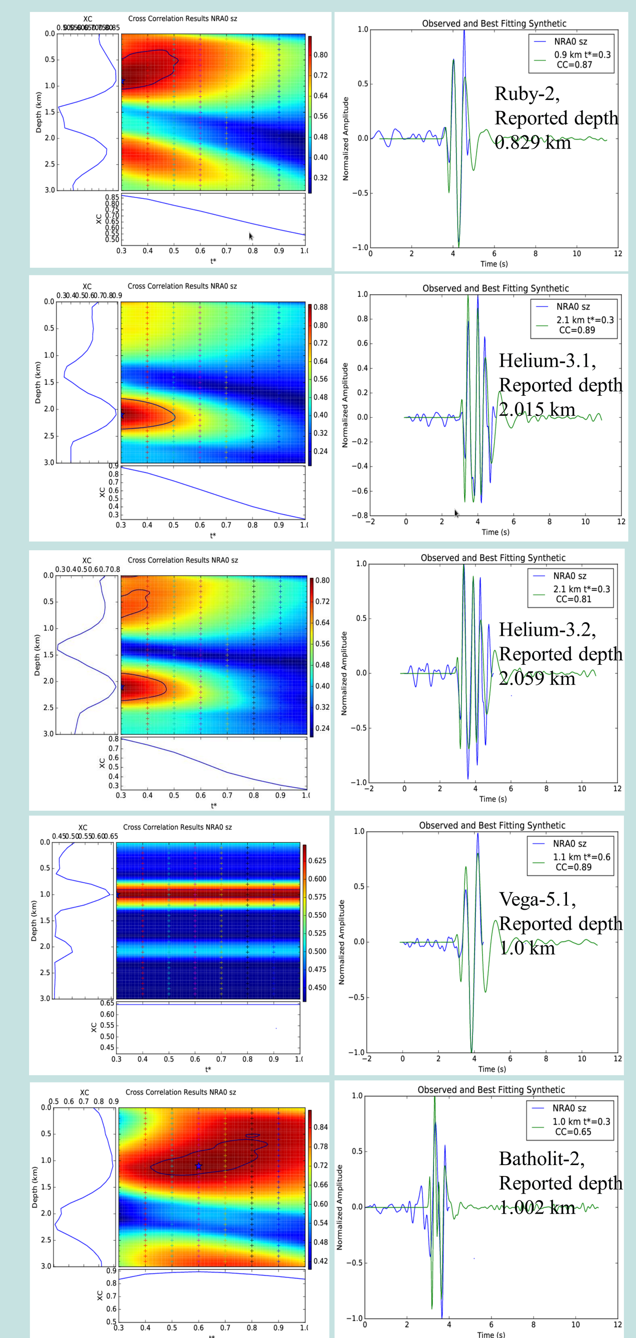
Determination of the DPRK-2016 depth with phase method. Left: The method is applied to single station with only two seismic phases used: P and pP. With the standard deviation of 187 meters mean depth is 1050 meters. Joint processing of 11 IMS stations in teleseismic range of 30-70 degrees produces an estimate of 800 m depth which correlates with the synthetic modeling results accounting for the reduced velocity in an upper layer.

Depth determination of Soviet Peaceful Nuclear Explosions: Vega-5, Helium-3, Ruby, Batholit, years 1984-1988.



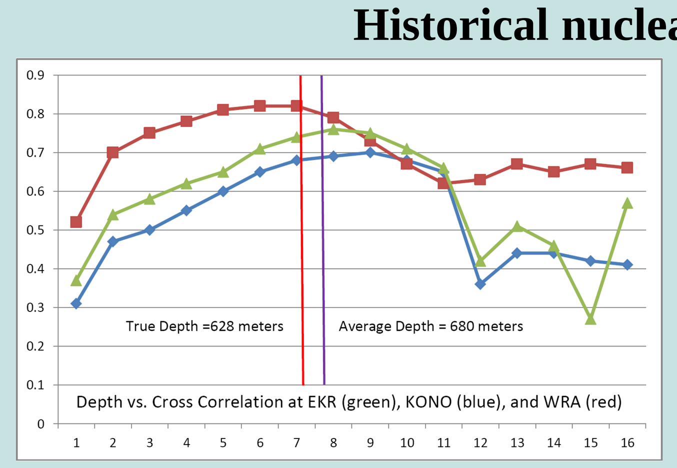
Summary of the PNE explosions as indicated at the rdss.info. Source-receiver distance is between 23 and 30 degrees.

1. Western USSR, Event *Batholith-2* Origin Time = 1987/10/03 15:15:00.030 Depth = 1.002 Yield = 8.5
2. Western USSR, Event *Helium 3-1* Origin Time = 1987/04/19 Depth = 2.015 Yield = 3.2
3. Western USSR, Event *Helium 3-2* Origin Time = 1987/04/19 04:04:59.980 Depth = 2.055 Yield = 3.2
4. Western USSR, Event *Vega 5-1* Origin Time = 1984/10/27 06:00:00.100 Depth = 1.000 Yield = 3.2
5. Eastern USSR, Event *Ruby-2* Origin Time = 1988/08/22 16:20:00.070 Depth = 0.829 Yield = 15

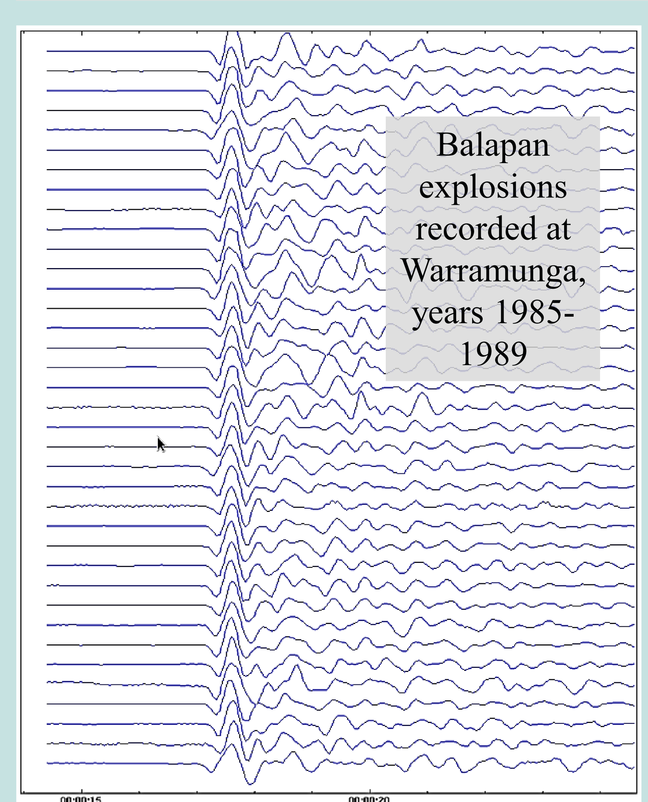


Left: examples of the depth determination procedure for PNE events for station.channel NRAO.SZ. Right figure: waveform fitting for the indicated station. Observed waveform and best fitting synthetic shown along with optimal depth and t*. Left figure: Cross correlation map for range of depths and t*.

Historical nuclear tests processing with synthetic modeling



Left: example of depth determination for Semipalatinsk (Balapan site) Oct-19, 1989 explosion. Reported depth is 628 m, reported yield is 80 kT. Maximum cross-correlation between raw (non filtered) and synthetic seismograms (convolved with instrument response) are 0.82 for WRA, 0.7 for KONO and 0.76 for EKR. Average depth for 3 stations is 680 meters. The depth increment for modeling (horizontal axis) is 100 meters between 0 and 1 km, then depths are 2, 4, 10, 20, 30 and 40 km.



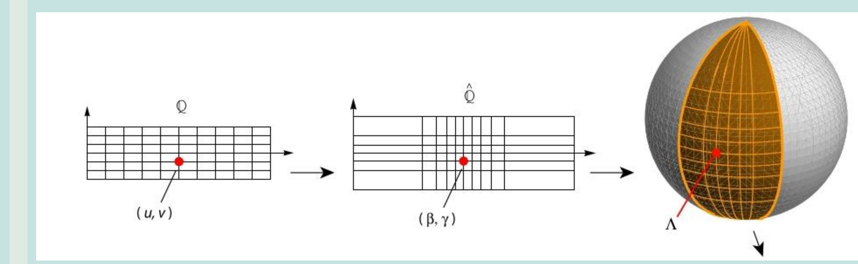
Data used for the research

1. Underground nuclear explosions (UNE), Semipalatinsk (Balapan) recorded at WRA, Australia, dist 85 degrees, baz=129 degrees
2. UNE, Balapan, recorded at Eskdalemuir Array (EKR), Scotland, dist 47.3 degrees, baz=310 degrees
3. UNE, Balapan, recorded at Urumqi 3C Station (WMQ), China, dist 8.6 degrees, baz=131 degrees
4. UNE Degelen, recorded at Talgar station, Kazakhstan (TLG)
5. UNEs SHAKTI, India, recorded at IMS and IRIS/GSN stations.
6. Peaceful Nuclear Explosions (PNE) at Eastern and Western Russia sites recorded at NORSAR, ANMO, CHTO, CTAO, etc.
7. DPRK-2006 through 2016 tests recorded at IMS stations

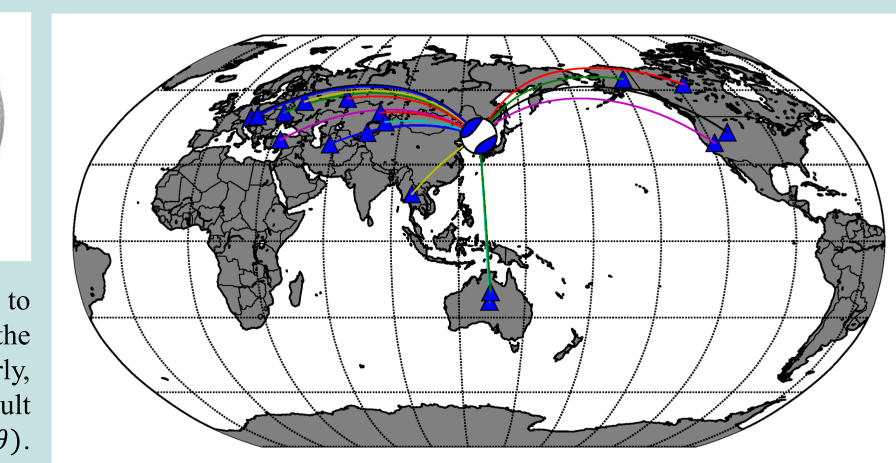
Left: Semipalatinsk nuclear test seismograms (Balapan site) recorded at Warramunga array. 30 events were processed. Though no depths were reported in event bulletins, the yield reported/estimated was between 7 and 150 kt which corresponds to detonation depths at Balapan between 200 and 700 meters. Our estimated depths were well constrained within the range of 100 to 800 meters

Depth determination with moment tensor estimation

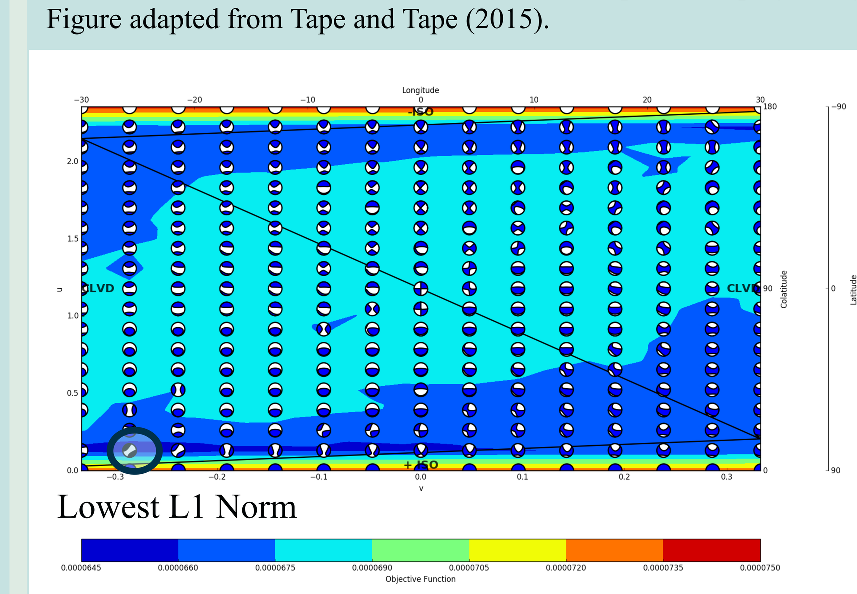
The depth determination procedure is being improved by also estimating the source properties via grid search over moment tensors. We implement the method of Tape and Tape (2015) to uniformly discretize the moment tensor space, then determine the optimal moment tensor and depth by comparing observed seismograms with synthetic waveforms. Several waveform similarity measures can be used, here we show results from the DPRK2016 event using a lagged 1-Norm objective function where the L1 norm is calculated while shifting the observed trace up to one second in time to simultaneously find the minimum misfit and best waveform alignment. Here, source location is kept fixed and we use teleseismic P waves windowed -4.3/+3.7 seconds around an analyst picked first arrival. Waveforms are filtered 0.5 - 4.5 Hz. Greens Functions are calculated using hudson96 (Herrmann, 2002) with the AK135 velocity model for the propagation path and CRUST1.0 for the source and receiver locations. The attenuation parameter (t*) is kept fixed at 0.5 for all source-receiver paths.



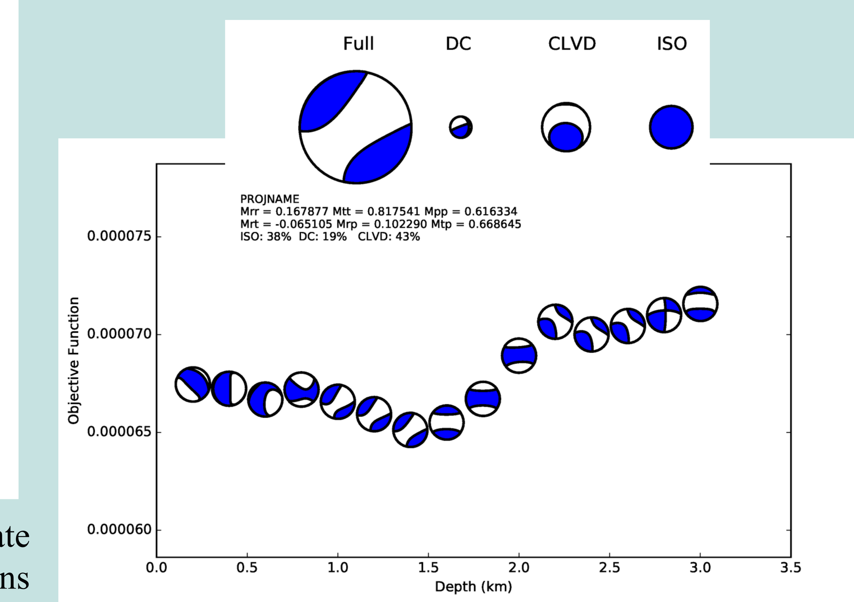
Summary of the mapping from the uniform space in (u,v,κ,σ,h) to the moment tensor. The (u,v) coordinates map to locations on the lune expressed in terms of co-latitude, β, and longitude, γ. Similarly, (κ,σ,h) are mapped to the fault orientation (κ,σ,θ). The fault orientation is described in terms of strike, slip, and dip (κ,σ,θ). Figure adapted from Tape and Tape (2015).



Global map showing 22 stations used (triangles) and optimal moment tensor at 1.4 km depth.

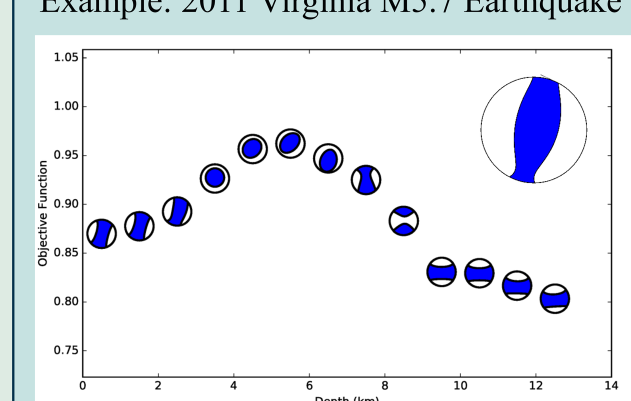


Above: Moment tensor grid search results in (v, u) coordinate system at 1.4 km depth. At each grid node, 800 combinations of strike, dip, and rake are searched. The best solution at each node is plotted. The objective function value for that optimal solution is used to create the background colormap. Pure isotropic (ISO) and CLVD shown for reference.

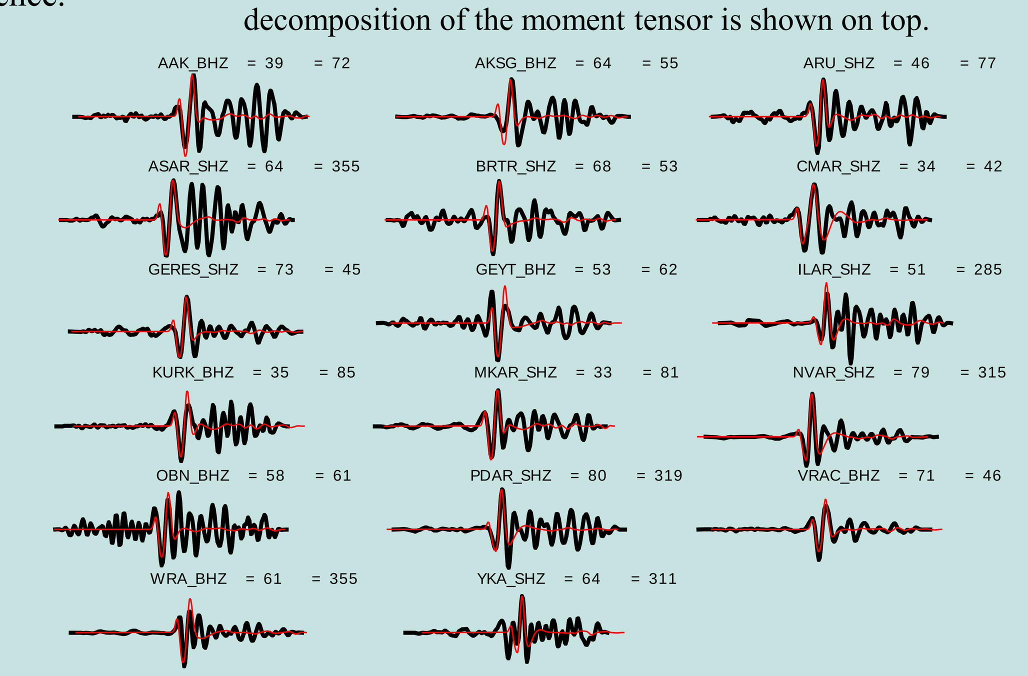


Source depths were searched 0.2 km to 3.0 km depth in 0.2 km increments. The weighted L1 Norm misfit is shown with optimal moment tensor solution at each depth. The decomposition of the moment tensor is shown on top.

Example: 2011 Virginia M5.7 Earthquake



The 2011 M5.7 Virginia earthquake was chosen as a test event for our method. Using cross correlation as the objective function, a maximum was reached at 5.5 km depth. The Global CMT catalog moment tensor solution is shown in upper right. See handout for more details.



Above: Observed (black line) and synthetic (red line) waveforms for stations used in depth and moment tensor estimation. Station code, channel, epicentral distance (degrees), and station-to-event azimuth shown above each trace. Synthetic waveforms shown for depth of 1.4 km and moment tensor shown in figure above.

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