A Fast and Robust Method for Moment Tensor and Depth Determination of Shallow Seismic Events in CTBT Related Studies

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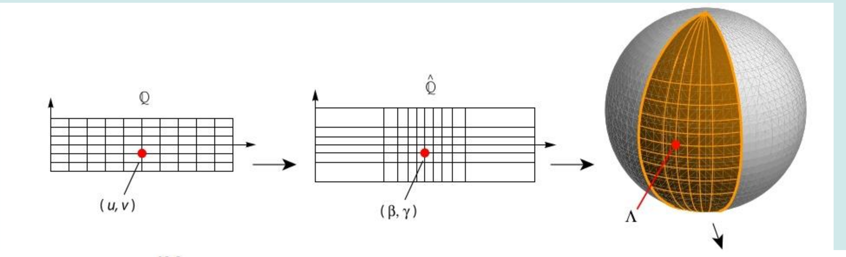
Abstract. International Data Center is required to conduct expert technical analysis and special studies to improve event parameters and assist State Parties in identifying the source of specific event according to the protocol to the Protocol to the Comprehensive Nuclear Test Ban Treaty. Determination of seismic event source mechanism and its depth is closely related to these tasks. It is typically done through a strategic linearized inversion of the waveforms for a complete or subset of source parameters, or similarly defined grid search through precomputed Greens Functions created for particular source models. In this presentation we demonstrate preliminary results obtained with the latter approach from an improved software design. In this development we tried to be compliant with different modes of CTBT monitoring regime and cover wide range of source-receiver distances (regional to teleseismic), resolve shallow source depths, provide full moment tensor solution based on body and surface waves recordings, be fast to satisfy both on-demand studies and automatic processing and properly incorporate observed waveforms and any uncertainties a priori as well as accurately estimate posteriori uncertainties. Posterior distributions of moment tensor parameters show narrow peaks where a significant number of reliable surface wave observations are available. For earthquake examples, fault orientation (strike, dip, and rake) posterior distributions also provide results consistent with published catalogues. Inclusion of observations on horizontal components will provide further constraints. In addition, the calculation of teleseismic P wave Green's Functions are improved through prior analysis to determine an appropriate attenuation parameter for each source-receiver path. Implemented HDF5 based Green's Functions pre-packaging allows much greater flexibility in utilizing different software packages and methods for computation. Along with traditional post processing analysis of waveform misfits through several objective functions and variance reduction, we follow a probabilistic approach to assess the robustness of moment tensor solution. In a course of this project full moment tensor and depth estimates are determined for DPRK events and shallow earthquakes using a new implementation of teleseismic P waves waveform fitting. A full grid search over the entire moment tensor space is used to appropriately sample all possible solutions. A recent method by Tape & Tape (2012) to discretize the complete moment tensor space from a geometric perspective is used. Probabilistic uncertainty estimates on the moment tensor parameters provide robustness to solution.

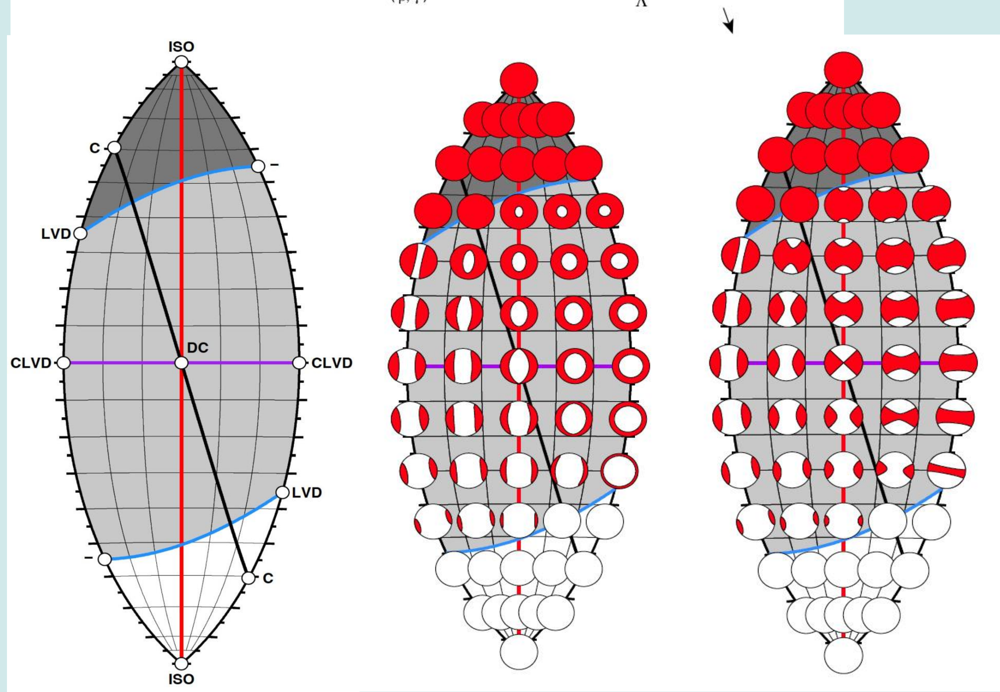
Conclusions. We continue development of methodological and technological frameworks of the Special Studies (SS) and Expert Technical Analysis (ETA) to be established at the International Data Center. A PARMT first version is developed, which is a second generation of the IDC prototype software for shallow seismic event depth determination and source parameters characterization. To better determine seismic source, source properties are estimated 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. Greens Functions are calculated using libraries modified from Computer Programs in Seismology for use in parallel processing. The software solves for the moment tensor for most types of sources (ISO, DC, CLVD) and source-receiver distances, as well as for body and surface waves observed. Uncertainties are addressed in a probabilistic framework by using an objective function that corresponds to summation of log-likelihood functions to consider the distribution of the set of possible solutions that places constraints on source depth and moment tensor source type. This approach allows for assessment not only of the final solution but the contribution of each observation as well. As requested by SS and ETA data from IMS network as well as non-IMS data can be used in processing. An approach for using a pre-calculated synthetic waveforms allowing for even faster solution is implemented. In future studies we look to add polarity information to the teleseismic body waves via a prior model with the understanding that even a single positive polarity would help to suppress the preferred implosive solution. Additionally, we look to further scrutinize the posterior model distribution and intend to marginalize magnitude and tensor orientations on the lune as generate a more complete statistical representation of the distribution of eigenvalues as a function of depth.

Method for Determining Moment Tensor Source Type

PARMT is a second generation of the IDC prototype software for shallow seismic event depth determination and source parameters characterization for Special Studies and Expert Technical Analysis. To better determine seismic source, source properties are also estimated 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. Greens Functions are calculated using libraries modified from Computer Programs in Seismology (Herrmann, 2002) for use in parallel processing. hudson96 program is used for teleseismic body waves synthetics and hspec96 is used for regional surface waves. This modification allows for millions of synthetic waveforms to be generated within minutes to fully explore the moment tensor search space. Several waveform similarity measures can be used, including time domain cross correlation and lagged p-Norm objective functions. For example, the lagged 1-Norm objective function calculates the L1 norm while shifting the observed trace up to a prespecified amount of time to simultaneously find the minimum misfit and best waveform alignment. Source location is kept fixed and we use teleseismic P waves windowed around an analyst picked first arrival on the vertical component and vertical component Rayleigh waves windowed around a calculated 3.5 km/s arrival time.



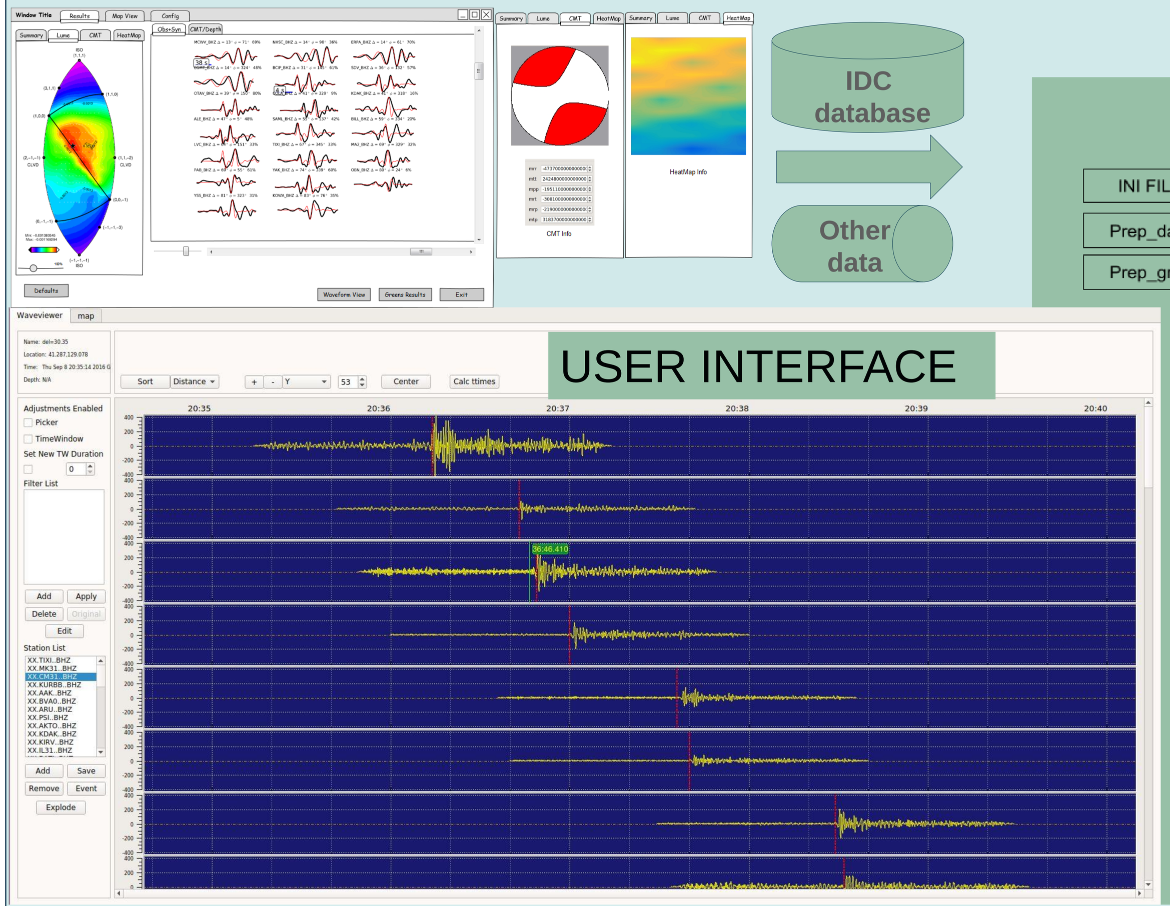
Left: Summary of the mapping from the uniform space in $(u, v, \kappa, \sigma, h)$ to the moment tensor. The (u, v) coordinates map to locations on the lune expressed in terms of co-latitude, β, and longitude, γ. Similarly, (κ, σ, h) are mapped to the fault orientation (κ, σ, θ). The fault orientation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

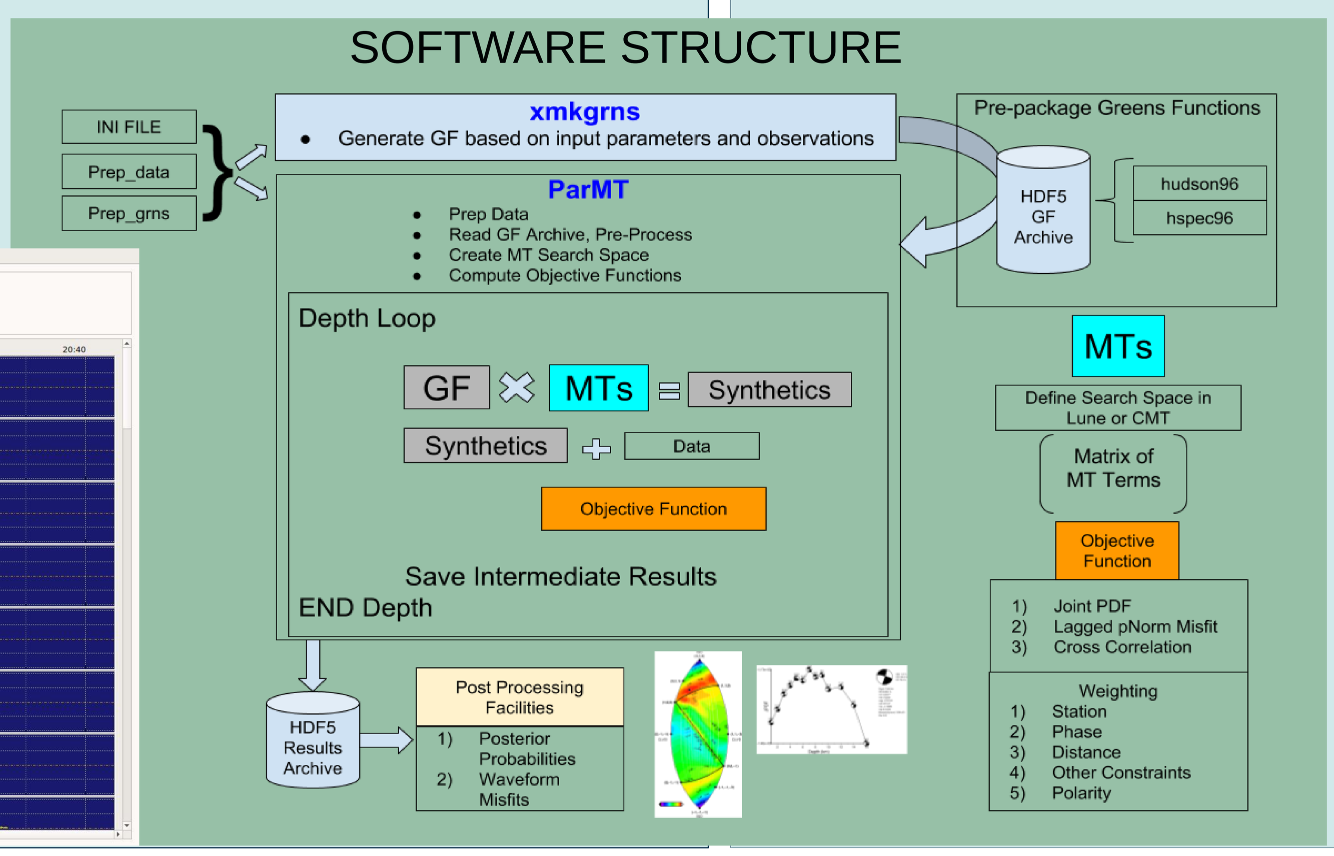


Fundamental lune of the unit sphere. We prefer the lune plot because it very naturally aligns with grid-search methodology later developed by Tape and Tape (2015) and we feel that the inherit symmetry in the density of moment tensors about the double couple (center of the lune) makes the lune plot very easy to interpret. Each node on the lune represents a moment tensor source type (beachball pattern). **Left**: The magenta equatorial arc is for deviatoric tensors, the red meridian is for sums of double couple and isotropic tensors, and the black arc is for crack + double couple tensors having Poisson ratio ν = 1/4. Above the upper blue arc all beachballs are only red, and below the lower blue arc all balls are only white [Tape and Tape, 2012a]. **Middle, Right**: The double couple is at the center. Note that in these two examples the orientation of the beachball changes.

Software development progress

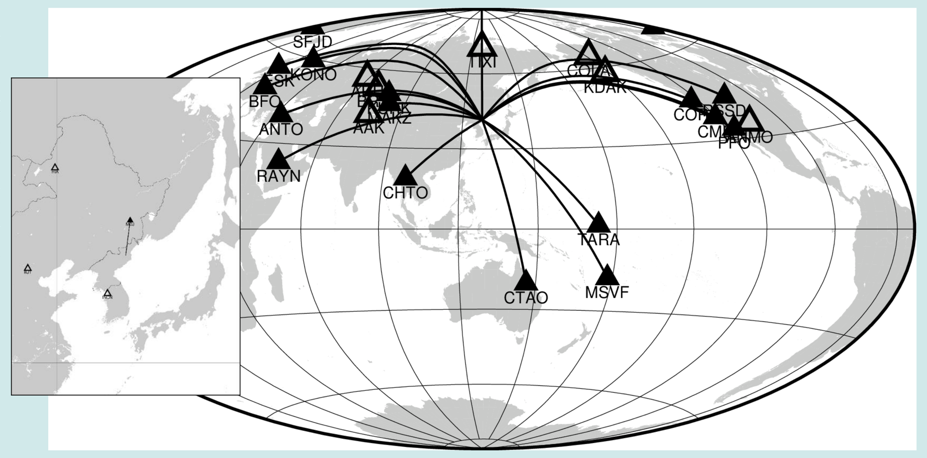
Recent software development mostly included moment tensor grid-search strategy improvement, including parallel computations, implementation of joint processing of IMS and non-IMS data, process automation and GUI development. Implementation of the grid-search is an important consideration because the computational work grows dramatically with the dimensionality of the model space growth. The distributed memory parallelism is realized with Message Passing Interface (MPI), the shared-memory parallelism is realized with OpenMP, and the vectorization is realized with OpenMP-4 preprocessor-based compiler hints. To encourage distribution of data we split the global MPI communicator into four levels. The highest level is a rarely used global communicator which allows all processors to talk to one-another. Below this is the observation communicator that allows for an asynchronous parallel loop on the summation. Below this is the location communicator that allows multiple source locations to be inspected simultaneously. Lowest in the hierarchy is the moment tensor communicator that allows chunks of moment tensor space to be inspected simultaneously. On the moment tensor communicator we can further parallelize the search in each chunk by way of a threaded OpenMP parallel for loop. Finally, at the lowest level, the waveform comparisons amount to operations on non-aliased arrays and are therefor appropriate for vectorization.

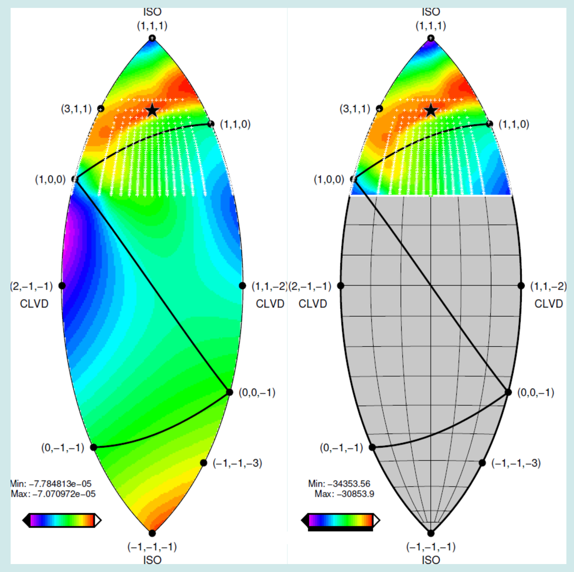




Moment tensor and depth estimation of the 2016-09-09 DPRK explosion: Preliminary Results.

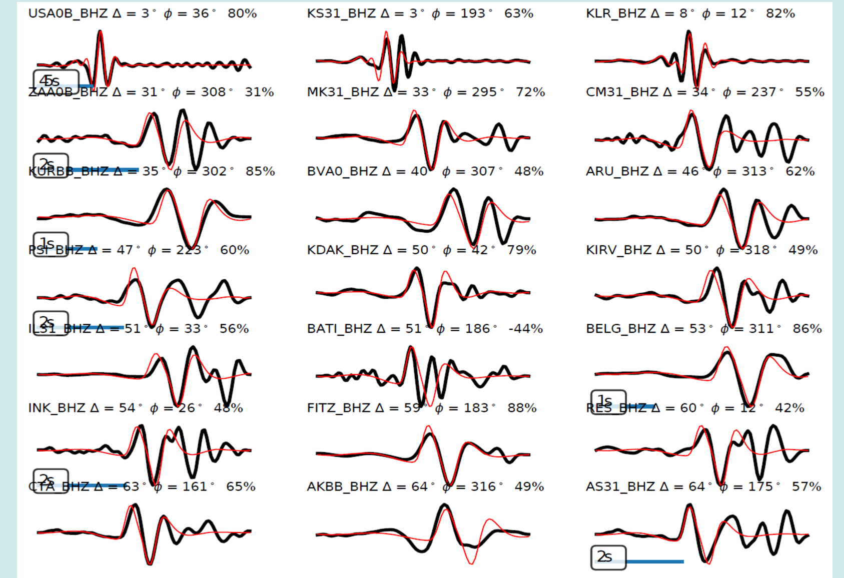
We show preliminary results from the DPRK2016-09-09 event using a lagged 1-Norm objective function. Teleseismic P waves windowed -2.0/+3.0 seconds around an analyst picked first arrival filtered 0.6 - 4.5 Hz. Regional Rayleigh waves on the vertical component are selected in a 180 second window filtered 10-50 s period. Instrument responses are removed from observed signals prior to processing. Teleseismic 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.



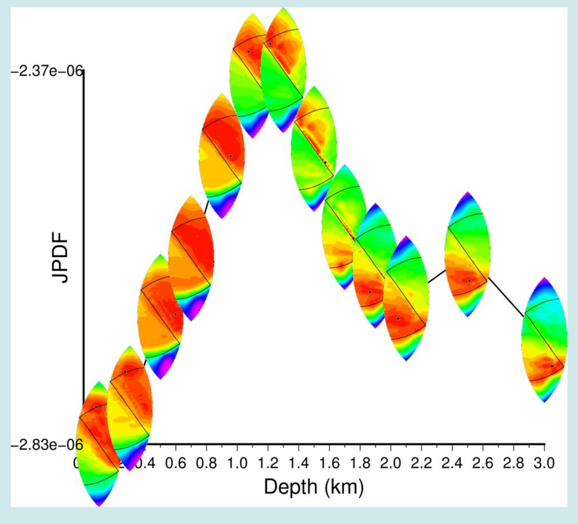


Left. Lune diagram at 1.3 km depth. Search region encompasses entire lune, white plus (+) symbols shown grid node locations sampled. Black star shows optimal solution. Note there are no grid nodes between the optimal solution and top of lune (pure isotropic). Color shows joint PDF contoured into 30 equal intervals.

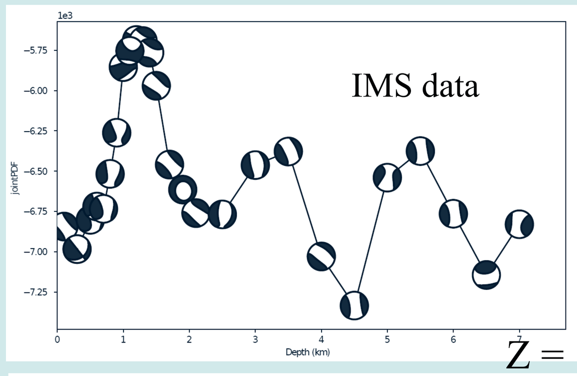
Right. Same for limited search to refine solution

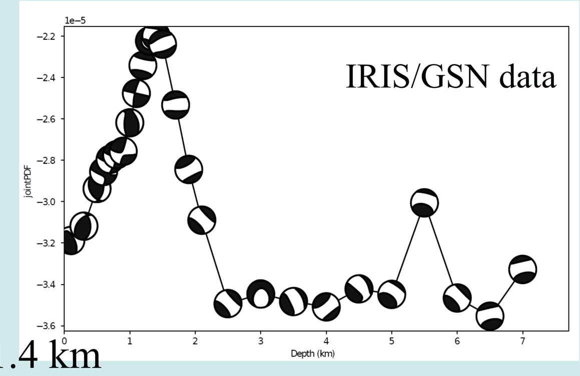


Observed (black) and theoretical (red) seismograms. Dataset incorporates records from the IMS primary and auxiliary stations.

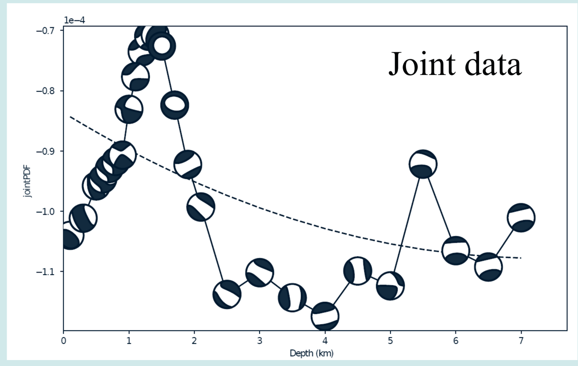


Lune diagrams shown for each depth indicating the optimal solution and distribution of joint PDF at each depth.

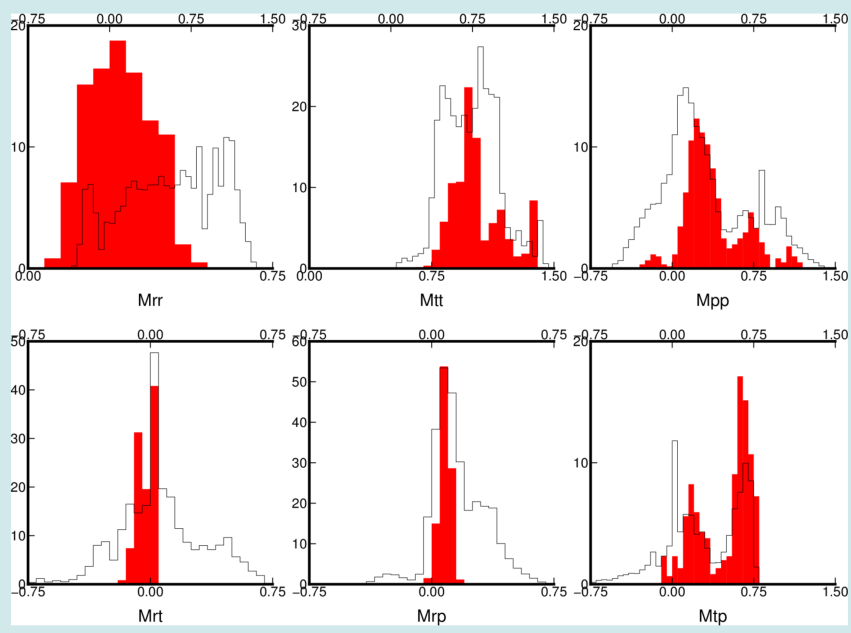




Z = 1.4 km

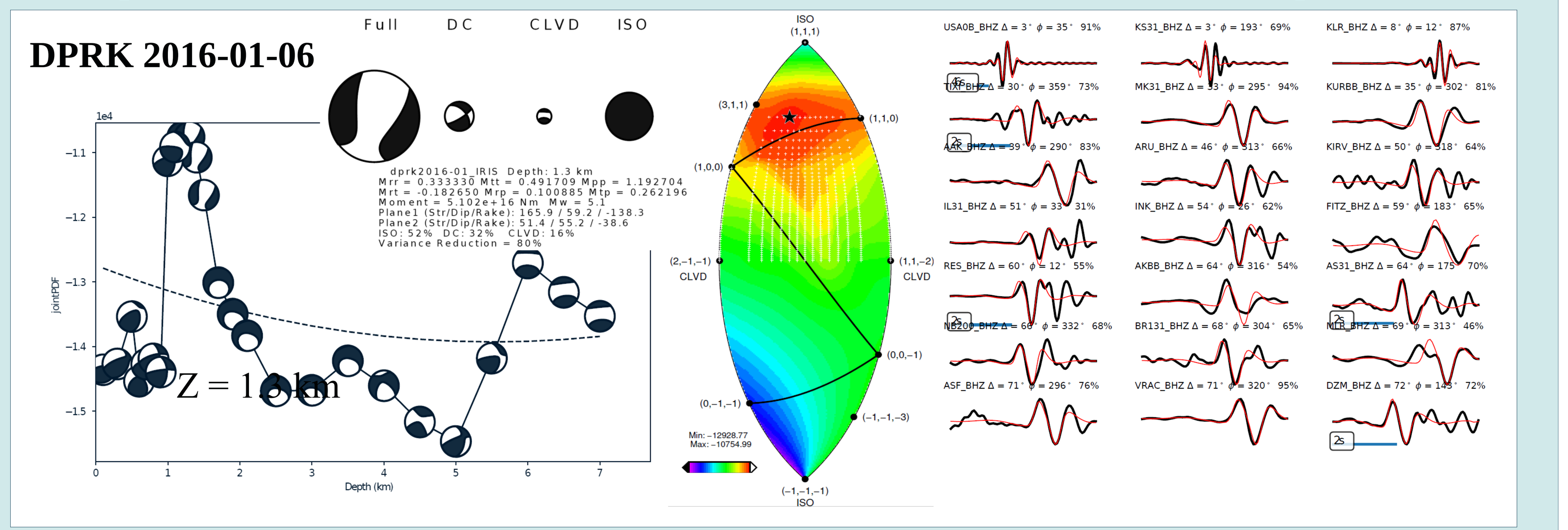


Results from grid search over depth and moment tensor source type. Optimal solution shown as beachball at the sum of the joint PDF for each depth. Plots are for solutions based on IMS-only data, IRIS/GSN only data, and for joint processing of IMS and IRIS data. The depth does not change for different data sets, while moment tensor does.



Distributions of moment tensor components. Black outline shows distribution across all points on lune (upper axis). Red bars show distribution of moment tensor components within upper 5% of jPDF values.

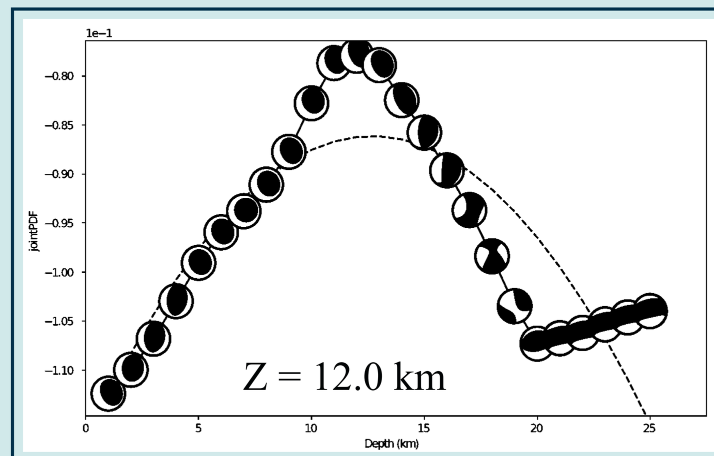
Depth determination and moment tensor estimation for the DPRK event of September 2016



The results show depth and moment tensor solutions after refined grid search over the upper portion of the lune, similar to results shown in panel to left. Left Figure: Results from grid search over depth and moment tensor source type. Optimal solution shown as beachball at the sum of the joint PDF for each depth with percent isotropic indicated above. Middle: Distribution of joint PDF in region of grid search for best depth indicated. Right: Observed (black) and synthetic (red) waveforms for optimal moment tensor at the best depth.

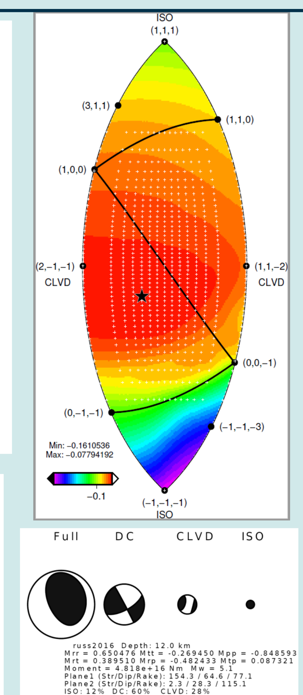
Shallow Earthquake Processing Examples

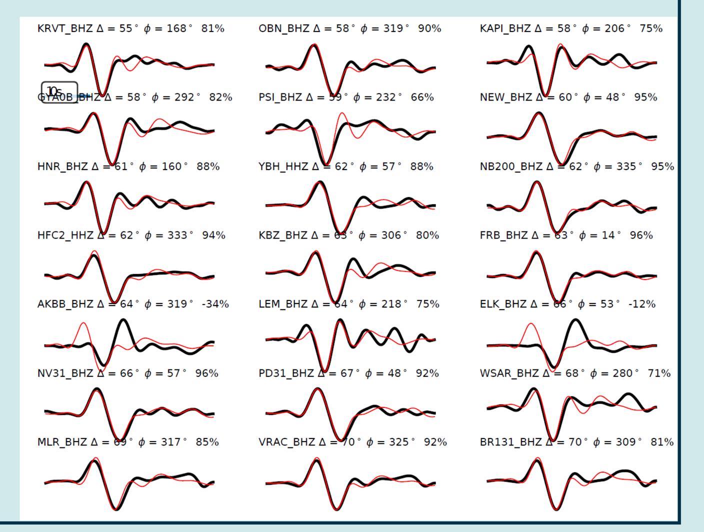
Example 1: 2016-08-14 Sakhalin, Russia, MW 5.8 Earthquake



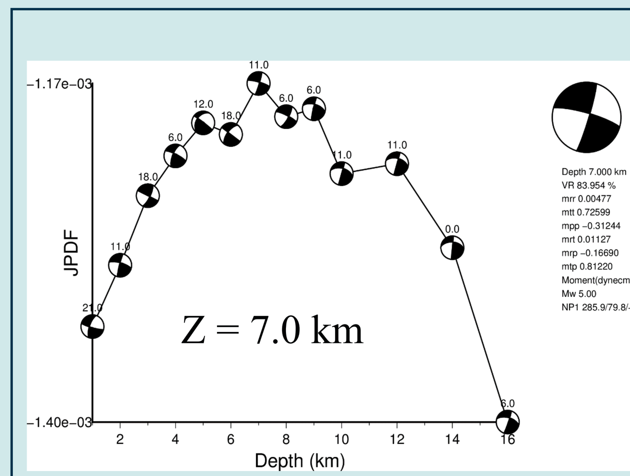
Date-Time (UTC):	2016-08-14 11:15:17
Location:	SAKHALIN, RUSSIA
Latitude, Longitude:	50.470 °, 142.300 °
Magnitude:	5.8 MW
Depth:	12.0 km
Author:	Global CMT Project
Catalog, Contributor:	GCMT, GCMT-Q

Depth determination for the shallow earthquake occurred in Sakhalin area, Eastern Russia (top). The results are consistent with the GCMT catalogue (left).

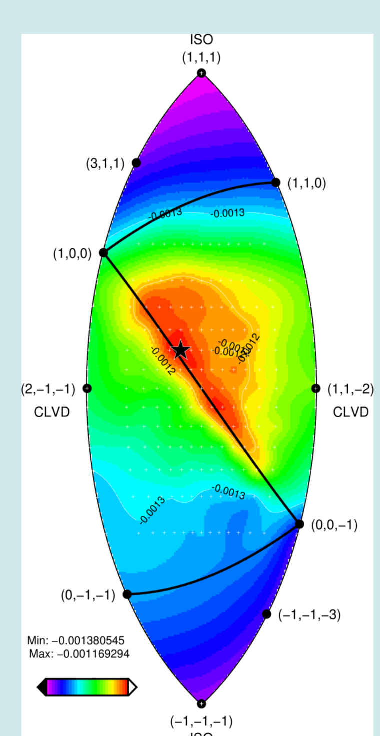




Example 2: 2016-09-03 Pawnee, OK, USA M5.8 Earthquake



The 2016 M5.8 Pawnee, Oklahoma, earthquake was chosen as a test event for our method. Using L1 norm as the objective function to determine the joint PDF, a maximum was reached at 7.0 km depth. At each point the double couple portion of the moment tensor is plotted as a beachball.



Lune diagram at 7.0 km depth showing best fit solution. Our result indicates at 70% double couple (DC) source with primary nodal plane:

NP1 strike/dip/rake = 286 / 80 / -5

This is consistent with moment tensor solutions from the USGS that have depths ranging from 2.0 – 11.5 km. The USGS preferred solution has nodal planes:

NP1 strike/dip/rake = 289 / 72 / 16

NP2 strike/dip/rake = 194 / 74 / 161

References

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Tape W. and Tape C, 2012. A geometric comparison of source-type plots for moment tensors, Geophysical Journal International, 190, 499-510.

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