

Disclaimer

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Abstract: Expert Technical Analysis (ETA) is a role that the IDC plays to provide higher-level research products on data from the IMS and other relevant data sources to improve the estimated values for standard event parameters and assist State Parties in identifying the source of specific events. As depth is an important event parameter, we focus on improving its estimation using modern advances in seismic modeling. The first part of our ETA work used cross-correlation between observed teleseismic and theoretical teleseismic seismograms to provide a depth estimate for varying t^* attenuation factors. To evaluate the importance of source mechanics on the depth recovery the Parallel Moment Tensor (parmt) software package was developed to fit body and surface wave recordings. This poster presents a summary of the cross-correlation driven and waveform-fitting depth estimation methodologies that are under active development and an application of the latest iteration of parmt to the September 09, 2016 DPRK nuclear test. The tools are intended to allow an expert to easily generate synthetic waveforms, compare the synthetics to the observed waveforms, drive the processing work-flow, and show results and uncertainties in a coherent fashion. These tools will enable IDC expert analysts to provide to member states impactful data products for events demanding ETA and special studies.

Conclusions and Future Work. We have presented a summary of the development of methodological and technological frameworks of the Special Studies and Expert Technical Analysis to be established at the International Data Centers. In particular, the first project iteration's event cross-correlation based attenuation and depth estimator was introduced. The second project iteration's waveform fitting methodology for assessing the moment tensor's effect on depth recovery was discussed. These previous developments have motivated the latest project iteration which looks to merge capabilities in a unified framework by way of a user interface while extending the expert analyst's ability to process data for use in the parmt software package. As we look to incorporate magnitudes, we have successfully demonstrated metadata compatibility between different data

sources by reprocessing previous examples using both IMS and GSN data. Additionally, we have extended parmt to estimate magnitudes and incorporate polarity data to better constrain the source eigenvalue distribution. This highly scalable parmt was applied to the DPRK September 09, 2016 nuclear test. The result favors a 1km depth, magnitude 4.9, explosive event. Potentially the most exciting development is the initial uncertainty quantification by way of marginal probability distribution functions. Because parmt performs parameter estimation instead of parameter inversion it enables us to holistically consider the relative importance of different datasets such as polarities, body waves, or surface waves and, surprisingly, demonstrate that useful information can be gleaned from under-determined parameter estimation problems. In the future we will

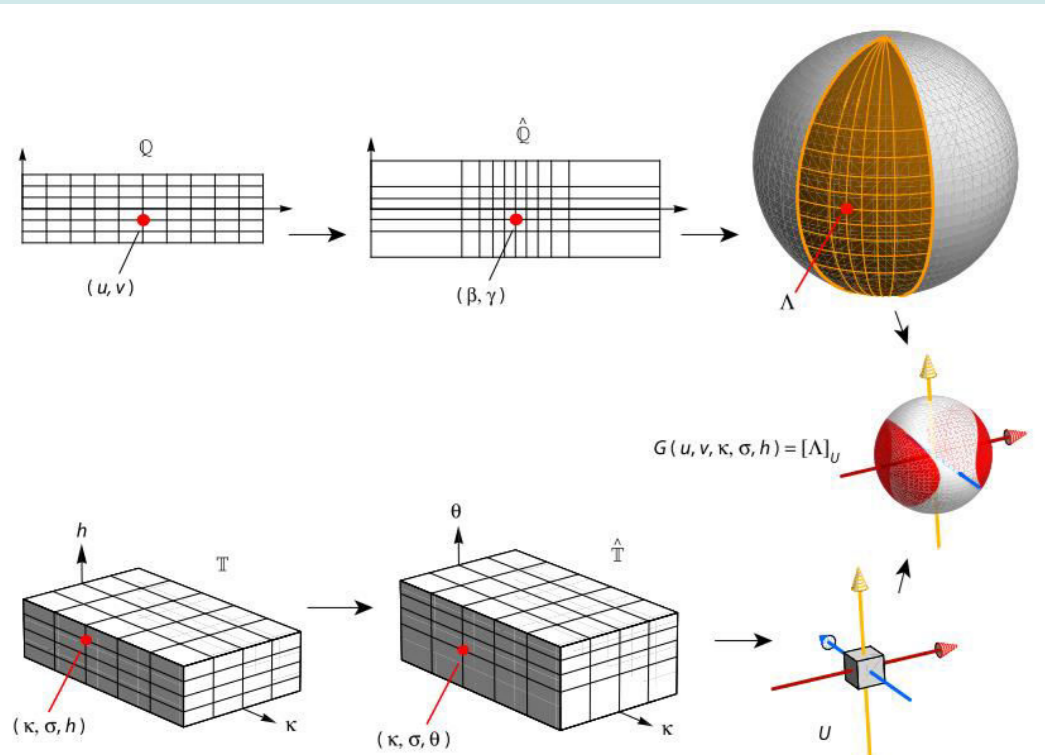
continue to integrate the cross-correlation driven depth and attenuation estimation and subsequent moment tensor estimation into a unified user interface framework with the understanding that effective data processing is essential to effective parameter estimation. Moreover, we will continue to pursue the open task of resolution analysis. While the mPDFs are in and of themselves tremendously useful, we expect that there exists many more interesting resolution related questions to be posed. To this end we believe it will be worthwhile to investigate the trade-off between model parameters such as depth and magnitude and further explore the utility of cumulative distribution functions for characterization of data products using a probabilistic formalism.

Introduction:

The XCORR project is an ongoing multi-year collaboration between the CTBTO and ISTI. The earliest software was designed to enable IDC analysts to estimate the event depth from teleseismic primary arrivals. This was achieved by cross-correlating observed primary arrival waveforms with synthetic waveforms. The synthetic waveforms were generated for explosive sources in 1D Earth reference models over a range of depths and t^* attenuation factors.

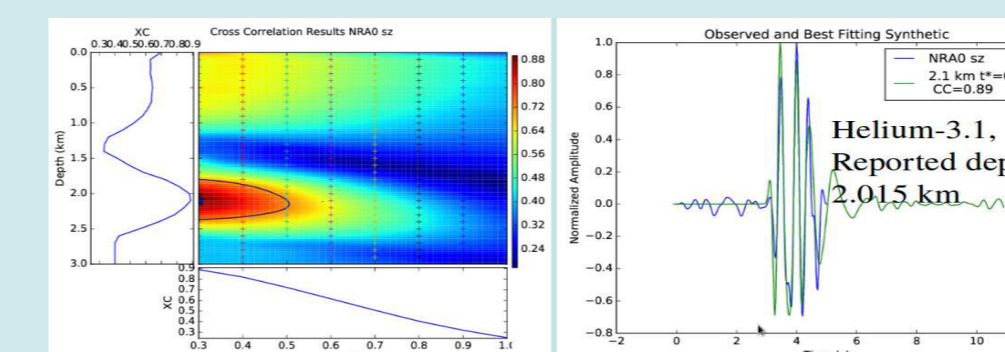
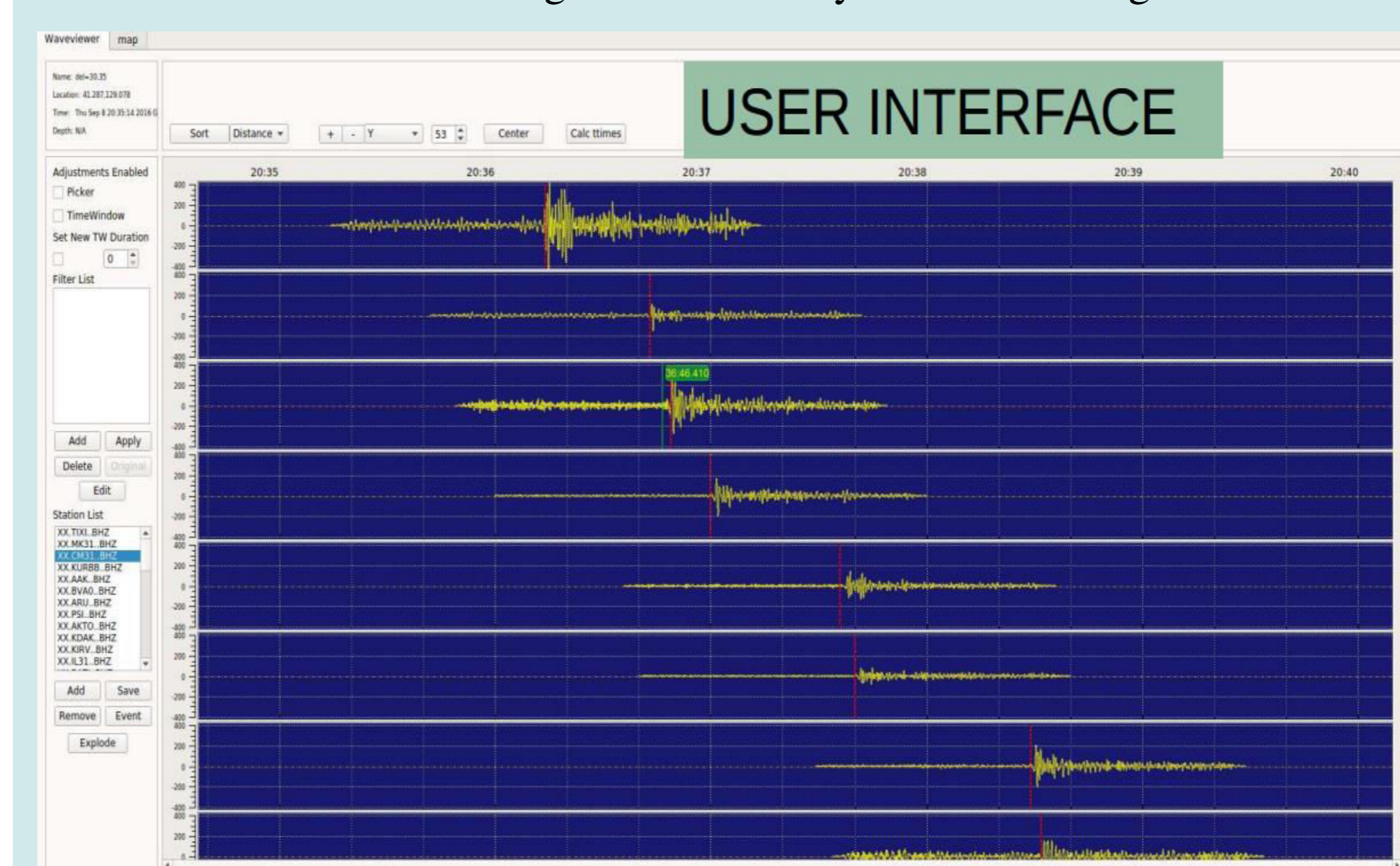
To further quantify the effect of the source mechanics on the depth estimation the second project iteration introduced a moment tensor search. Here, the moment tensor space is uniformly discretized and exhaustively searched. Each moment tensor in the grid-search then scales the preprocessed Green's functions for an observation and depth pair to generate a synthetic waveform. The synthetic waveform was then normalized and compared, in an L1 sense, with the preprocessed observed waveform at successive lag times. The best-fitting lag for the observation, depth, and moment tensor is tabulated and the search continues over moment tensors, depths, and observations. Ultimately, this procedure produced a best fitting depth and moment-tensor estimation for the entire dataset.

In the second phase it was discovered that batch-processing could be a mercurial task when observed waveforms of distinctly different quality were incorporated. Additionally, the internal rescaling in the grid-search prevented one from assessing the trade-off of event magnitude with depth. To remedy this, the third XCORR project iteration aims to increase the degree of user interactivity in data-processing, investigate how event magnitude co-varies with depth, better integrate IMS data into the work-flow, amalgamate new observations such as polarity information, and better incorporate the t^* attenuation estimation of the first project phase into the moment tensor-depth estimation work-flow.



Left: Description of the moment tensor grid-search space. The grid-search is discretized in the uniform (u,v) and (κ,σ,h) coordinates. (u,v) control the moment tensor eigenvalues while (κ,σ,h) control the orientation of the tensor. The (u,v) coordinates are then related to the more intuitive lune colatitude and longitude (β,γ). Similarly, h is related to the fault dip angle, θ. The fault strike and slip angles are denoted by (κ,σ), respectively. Not shown here is the grid-search in magnitude, which one can think about as the radius of the lune, and the grid-search in event depth. Figure taken from Tape and Tape (2015).

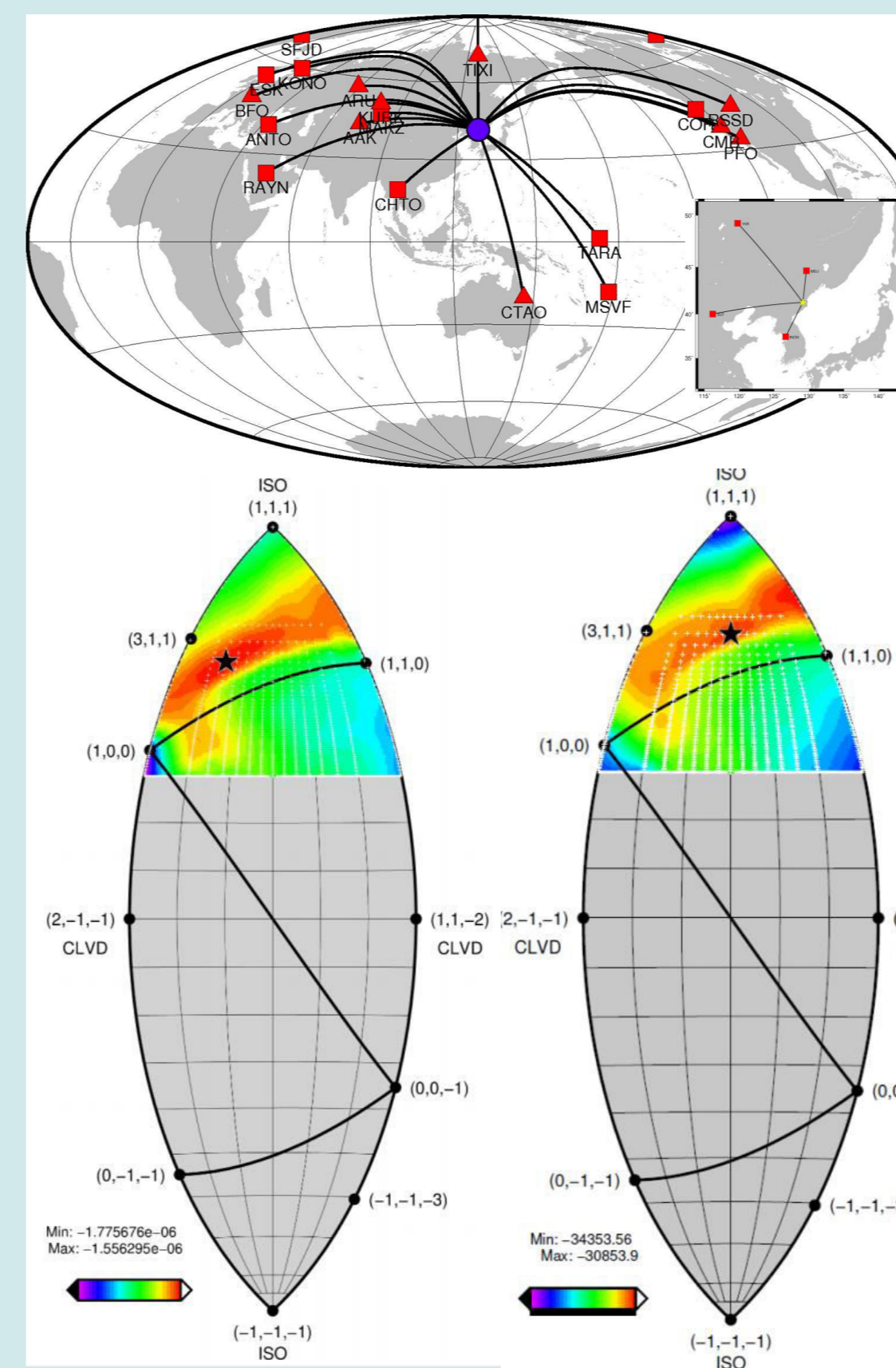
The goals of XCORR 3 present new challenges in software design. To meet this new set of requirements there has been considerable effort dedicated to deconstructing the monolithic design paradigm in previous iterations and emphasizing modularity, development of libraries, and performance. This strategy provides the opportunity to develop the essential fine-grained work-flows required for effective parameter recovery in high-dimensional model spaces while ensuring consistency between the command line utilities and user interface. It also enables us to effectively tackle the magnitude search which increases the algorithmic cost by an order of magnitude.



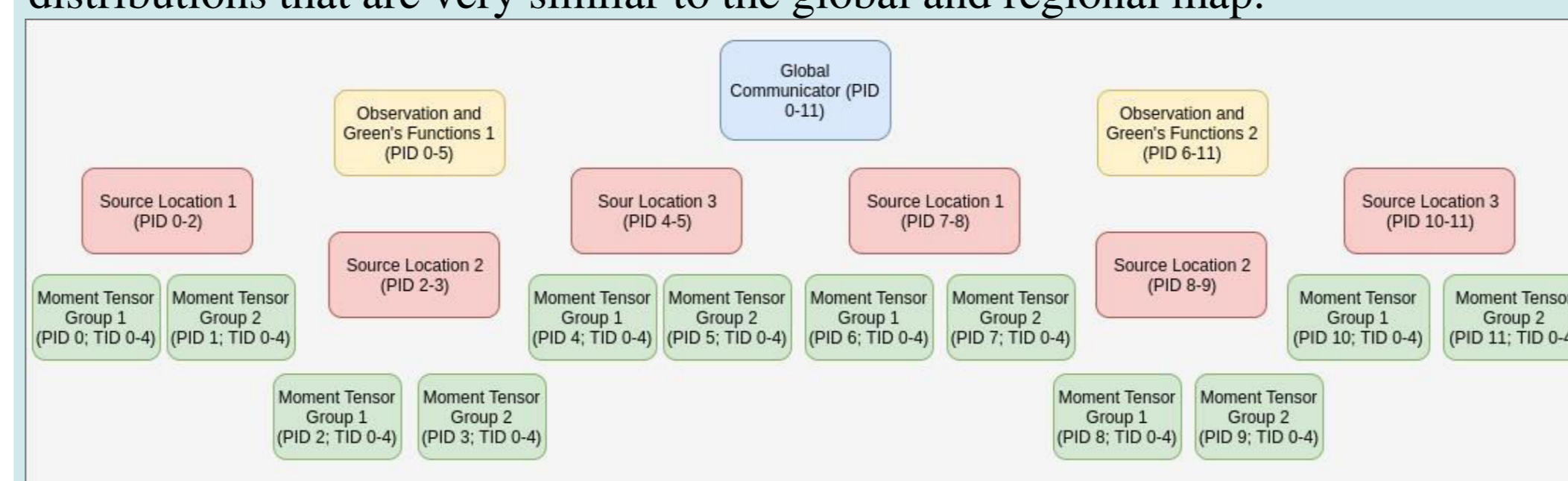
Left: A screen-shot of the graphical user interface (GUI). The GUI links to all libraries used by the command line utilities to ensure consistency of results. The GUI is implemented in C++ and Qt (pronounced "cute"). Above: The GUI can also drive the t^* , depth estimation for selection of an appropriate attenuation factor; a prerequisite for the parmt hudson96 teleseismic Green's functions generation. Example given for the Soviet PNE Hellium, one of the explosions processed at previous stage of the project.

Incorporation of IMS Data:

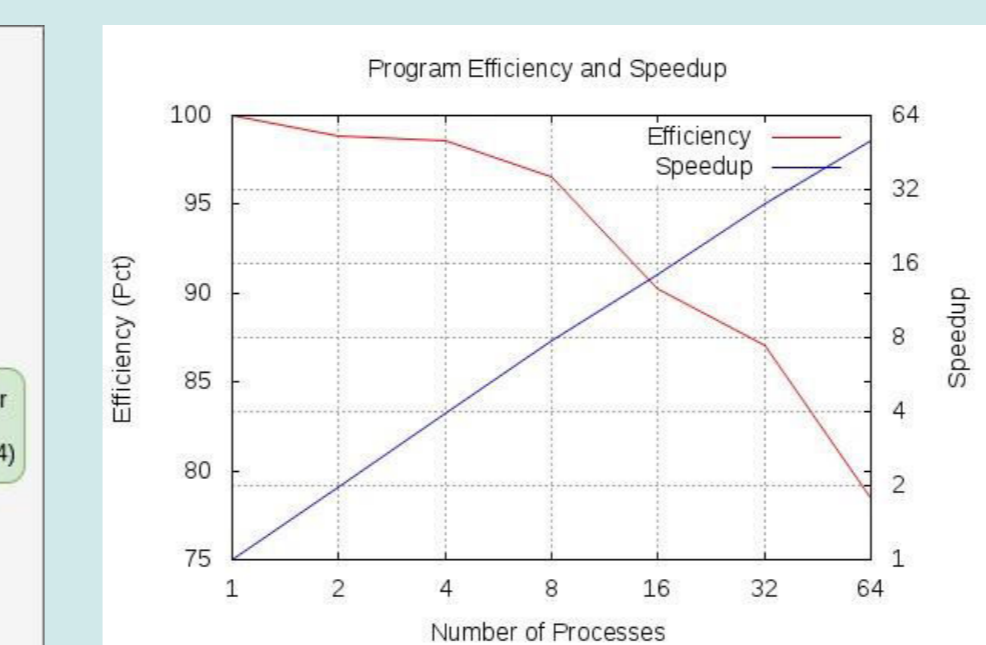
An inherent challenge in waveform fitting is understanding the relative units (e.g., displacement, velocity, acceleration) of any observation. Owing to different approaches for metadata management we elected to use only GSN data from IRIS in the previous project iteration. To bolster confidence in incorporating IMS data into the current work flow we have taken previous GSN data-only examples and not only added but, when possible, substituted IMS data, then repeated the analyses of the previous iteration with the joint IMS/GSN datasets. Also, as the third project looks to better quantify the event magnitude, we recently have demonstrated consistency in the instrument response amplitudes. We note that while only showing here the DPRK September 09, 2016 event that we have processed multiple DPRK events and PNEs with the cross-correlation and previous parmt code using both IMS and GSN data.



(Right) Is an example of the reprocessed September 09, 2016 DPRK event using the original GSN dataset (left) and the joint IMS/GSN dataset (right). The lunes are plotted by taking the objective function corresponding to the best tensor orientation for a given latitude/longitude. Both events are functionally the same and highly consistent with an explosive event. The difference in scale is related to differences to the quantity of input waveforms as well as subtle differences in data processing that are endemic of different underlying signals processing packages. Both examples use station distributions that are very similar to the global and regional map.



(Above) On the left is an example depiction of hybrid MPI/OpenMP parallelism in parmt that exploits 12 cores with 4 threads per core. At the top level the 12 cores on the global communicator are broken into 2 observation groups of 6 processors apiece, each observation group then has 3 source groups, each source group has 2 processors per moment tensor block, and each moment tensor block is processed with 4 threads. On the right is a demonstration of parmt's speedup (similar to strong scaling) and efficiency (similar to weak scaling).



DPRK September 09, 2016 Example:

In this example we use parmt to estimate the magnitude, eigenvalue distribution, tensor orientation, and depth of the DPRK September 09, 2016 nuclear test. The estimation versus inversion methodology allows us to treat the polarity, body wave, and surface wave data each as independent estimators of the source properties. The most likely solution after synthesis of all three datasets is an explosive magnitude 4.9 event at a poorly resolved 1 km depth. We attribute the resolution of explosive nature of the event, characterized by the lune latitude, primarily to the polarity data but also see evidence for an explosive event in the body waves. We also find that the surface waves, despite constituting an under-determined inverse problem, contribute significantly to the magnitude resolution while, sensibly, adding nothing to the eigenvalue distribution, tensor orientation, and because of their long wavelengths, little to the event depth estimation.

The vertical component teleseismic primary body waves were bandpass filtered from 0.6-2.1 Hz then onset times, and when possible, polarities were manually estimated. The teleseismic data was then cut from -0.8s to +3.2s relative to the onset time. Green's functions were computed on-the-fly at all depths in the grid-search with a library-style version of hudson96. As parameters hudson96 took a constant t^* of 0.4, the ak135 global Earth model, a local receiver model from crust1.0, and the MDJ2 local source model. The Green's functions were then processed to match the data's bandwidth, response, and after alignment, signal duration. When possible the pick polarities were tabulated in the SAC headers thereby making the teleseismic body wave archive valid for both parmt and polarmt. The surface waves were bandpass filtered from 50s-10s then windowed -20s to +80s relative to assumed surface wave moveout velocity of 3.2 km/s. The fundamental fault Green's functions were precomputed up to 0.5 Hz using a parallel version of hspec96 which takes as input the candidate source depths in the grid search, regional station distances, and the MDJ2 velocity model. The precomputed fundamental fault Green's functions are then loaded from disk, processed in a manner analogous to the body waves, and written to an appropriate parmt archive. One distinction is that prior to cross-correlation based realignment the theoretical Green's functions surface wave moveout was taken as 3.1 km/s thereby indicating that the MDJ2 may be, on average, too slow.

