Characterizing Isotropic Source Component of DPRK Nuclear Tests by Affine-invariant Bayesian Samplers with Uncertainty Estimate for Data Noise and Theory Error

BACKGROUND

There are two challenges in seismic moment tensor (MT) inversion for shallow events, e.g., underground nuclear explosions. Firstly, an intrinsic ISO-CLVD tradeoff impedes resolving shallow explosive sources due to the high similarity of long-period waveforms at regional distances. Even though this tradeoff can be mitigated by extra constraints, there is still an urgent need for advanced inversion algorithms to explore the solution space thoroughly. Secondly, a rigorous uncertainty estimate for both data noise and theory error is required to constrain the source better. The theory error primarily due to imperfect knowledge of Earth's structure is important but proven difficult to treat.

METHODS

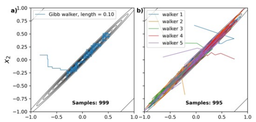
In Bayesian framework,

$$p(\boldsymbol{m}|\boldsymbol{d}_{obs}) \propto \frac{1}{\sqrt{(2\pi)^N |\boldsymbol{C}_D|}} exp\left(-\frac{1}{2}(g(\mathbf{m})-\boldsymbol{d}_{obs})^T \boldsymbol{C}_D^{-1}(g(\mathbf{m})-\boldsymbol{d}_{obs})\right)$$

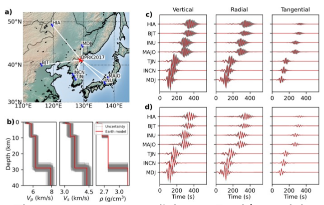
and $\boldsymbol{C}_D = \boldsymbol{C}_d + \boldsymbol{C}_t(\boldsymbol{m}^p)$

$\boldsymbol{C}_d$ is a data noise covariance matrix and $\boldsymbol{C}_t(\boldsymbol{m}^p)$ is a theory error covariance matrix due to inaccurate Earth model used in the forward problem to predict waveforms.

- The affine-invariant ensemble samplers (Goodman & Weare, 2010) are used to explore the parameter space especially the ISO-CLVD tradeoff thoroughly and effectively.



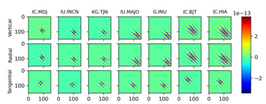
- Station-specific time shifts (TS) between observations and predictions are inverted for as unknowns to approximate the theory error, because time shifts dominate the theory error in long-period waveform.



a) Map of DPRK2017 explosion location and 7 seismic stations. (b) The MDJ2 model (Ford et al., 2009) and its perturbed models with 5% uncertainty. (c) The waveforms (20-50s) from perturbed 1D Earth structures in (b) for a given MT source. (d) The re-aligned waveforms in (c)

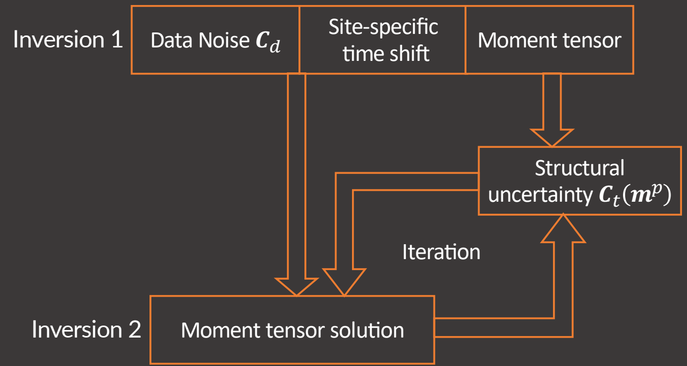
The waveforms from different Earth's models match well (VR=95.8%) with each other after re-aligning by grid search for the time shift at each station.

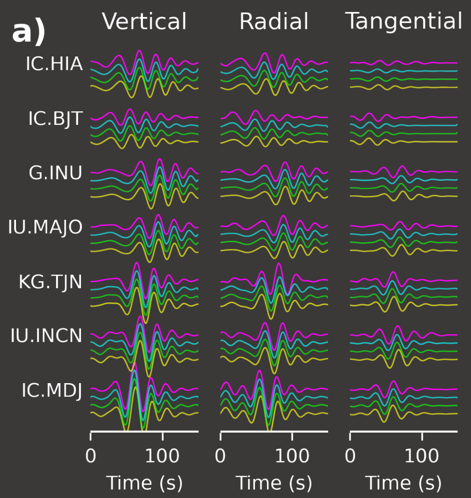
- Alternatively, the theory error can also be treated by covariance matrix $\boldsymbol{C}_t(\boldsymbol{m}^p)$ obtained from the ensemble of waveforms in (c). Phạm & Tkalčić (2021)

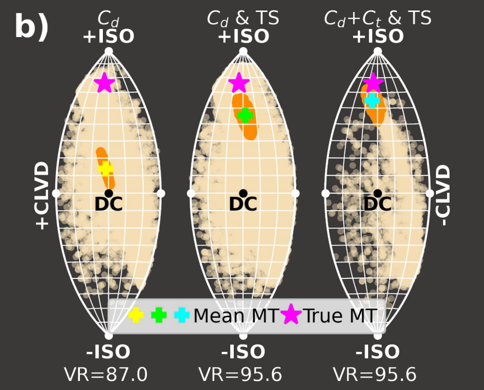


The data noise is assumed uncorrelated, i.e., diagonal $\boldsymbol{C}_d$

Quantifying **data noise** and **structural uncertainty** greatly improve the resolution of shallow seismic sources.







Synthetic results demonstrate the importance of source and data uncertainty quantification.

Note: (a) Waveform fit between observations (magenta) and three sets of predictions in yellow, green and cyan corresponding to three MT solutions denoted by pluses in (b); (b) Lune diagrams compare the source types of recovered solutions with only treating data noise (left), with treating data noise and theory error via time shifts (TS, middle) and via a covariance matrix (right). Wheat color dots denote MTs in the warm-up stages, while orange dots denote MTs in converging stage. Solutions with considering data noise and theory error are closer to the true MT.

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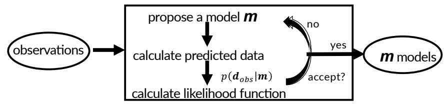
- Inversion1: Invert for data noise, station-specific time shifts, and MT parameters (Hu, Phạm & Tkalčić, in review)



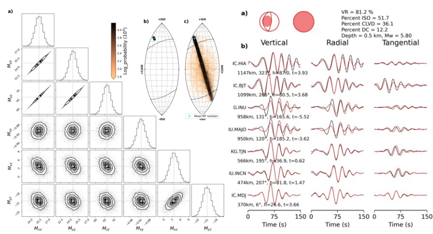
$$\boldsymbol{m} = [M_{xx}, M_{yy}, M_{zz}, M_{xy}, M_{xz}, M_{yz};\ k_1, \cdots k_n;\ \ t_1, \cdots t_n]$$

MT source — Noise level — Time shift (n: number of station)

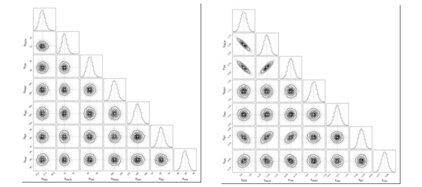
- Inversion2: Invert for MT with considering $\boldsymbol{C}_t(\boldsymbol{m}^p)$ by using MT from inversion 1 as a prior, and fix data noise and station-specific time shifts recovered in inversion 1. Update $\boldsymbol{C}_t(\boldsymbol{m}^p)$ with an iteration scheme.

RESULTS

- Inversion1: MT solution for DPRK2017 explosion at a source depth of 0.5 km with inverting for uncorrelated data noise and station-specific time shifts.

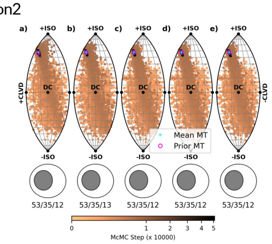


Posterior distribution of MT parameters — Waveform fit



Posterior distribution of noise parameters (left) and time shifts (right)

- Inversion2



Source types in each of 5 iteration

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