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A Joint Point-source Moment Tensor and a Single Force Inversion Within Hierarchical Bayesian Inference for Revealing the Source Mechanism of Underground Nuclear Explosions

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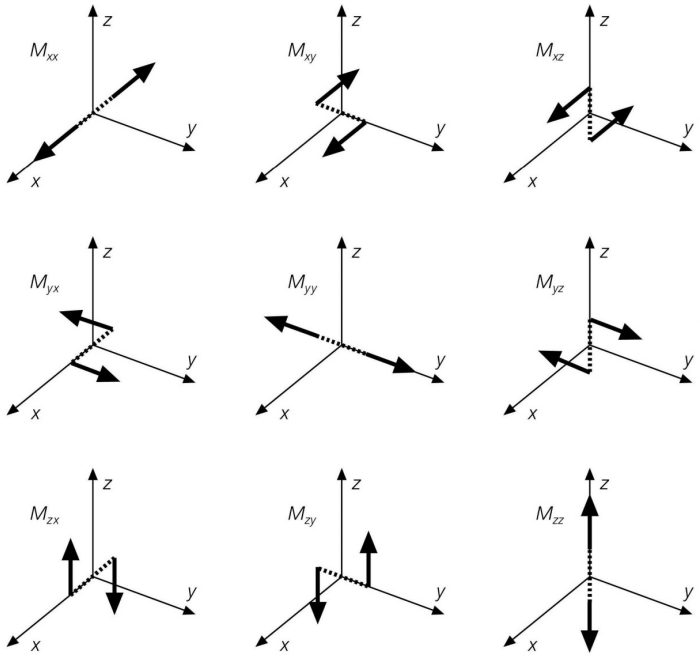
Two problems to solve in this study for seismic source inversion

1. A generalized source representation.

Combine Moment Tensor (MT) and Single Force (SF)

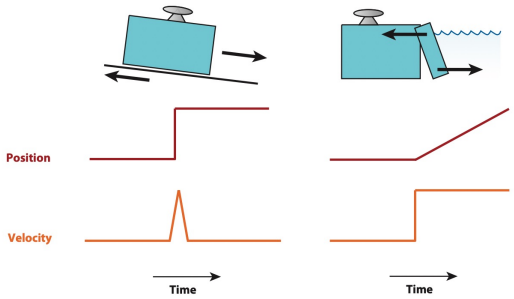
$$\mathbf{MT} = \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}$$

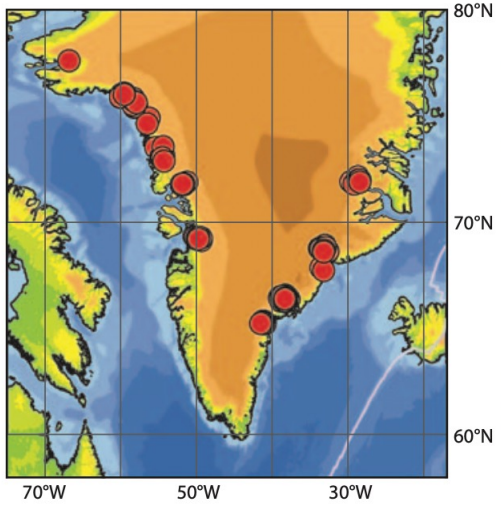


Aki & Richards, (2002)

$$\mathbf{SF} = [F_x, F_y, F_z]$$

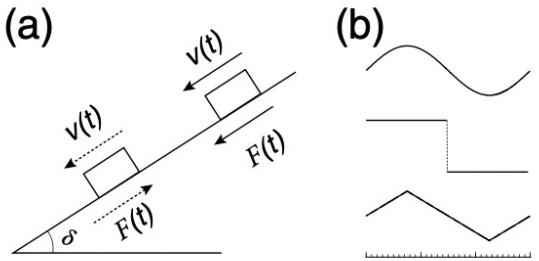
- Glacier Earthquakes



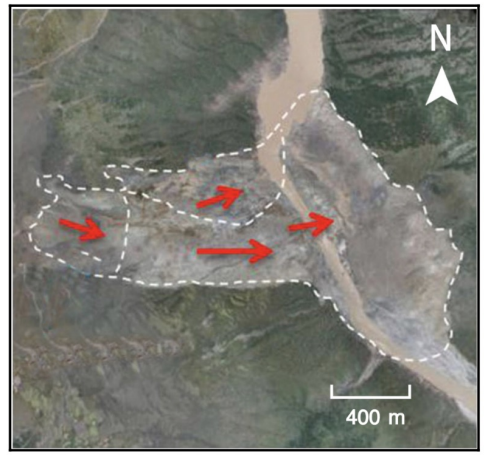


Nettles and Ekström, 2010

- Landslides



Typical force functions



Sheng et al., 2020

Two problems to solve in this study for seismic source inversion

2. Uncertainty estimate including:

a) Data noise.

Several noise models have been proposed, e.g.,

- Gaussian or an exponentially decaying noise model (e.g., Bodin et al., 2012; Duputel et al., 2012),
- Empirical noise model from data residuals (e.g., Dettmer et al., 2007) and from synthetic noise series (e.g., Gouveia & Scales, 1998; Piana Agostinetti & Malinverno, 2010; Sambridge, 1999)
- Two-attenuated cosine functions from pre-event ambient noise (Mustać & Tkalčić, 2016; Mustać et al., 2018)

We only consider the uncorrelated noise measured by a percent of RMS of ambient noise

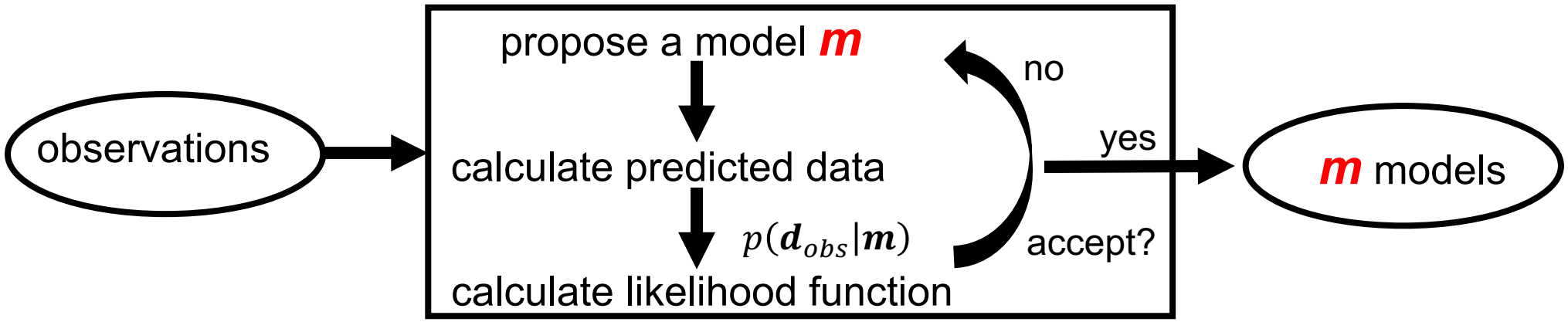
b) The structural error from the imperfect Earth's structure.

- e.g., Duputel et al., 2012; Hallo & Gallovič, 2016; Tarantola & Valette, 1982, Yagi & Fukahata, 2011
- Treating data noise and 1D structural errors jointly (e.g., Phạm & Tkalčić,, 2021; Vasyura-Bathke et al., 2021).

Use **time shifts** between observations and predictions to treat 2D structural error by an inversion manner as a transition from 1D structural error to 3D structural error.

Join MT and SF Inversion Within Hierarchical Bayesian Inference

$$p(\boldsymbol{m}|\boldsymbol{d}_{obs}) \propto p(\boldsymbol{d}_{obs}|\boldsymbol{m})p(\boldsymbol{m})$$ (Bayes, 1763)



Noise level Time shift

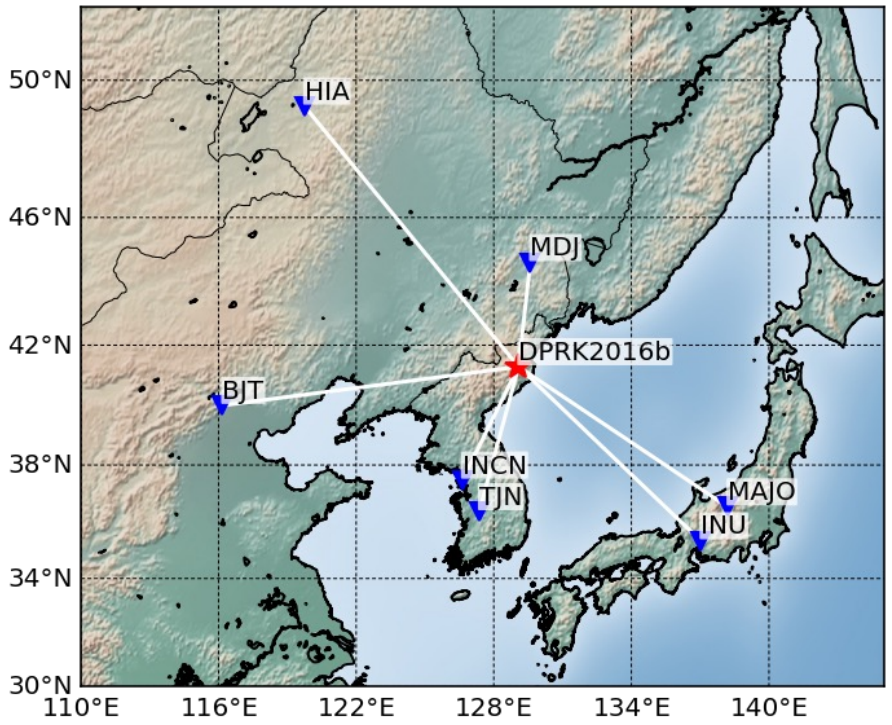
$$\boldsymbol{m} = [M_{xx}, M_{yy}, M_{zz}, M_{xy}, M_{xz}, M_{yz};\ F_x, F_y, F_z;\ k_1, \cdots k_n;\ t_1, \cdots t_n]$$

MT source SF source (n: number of station)

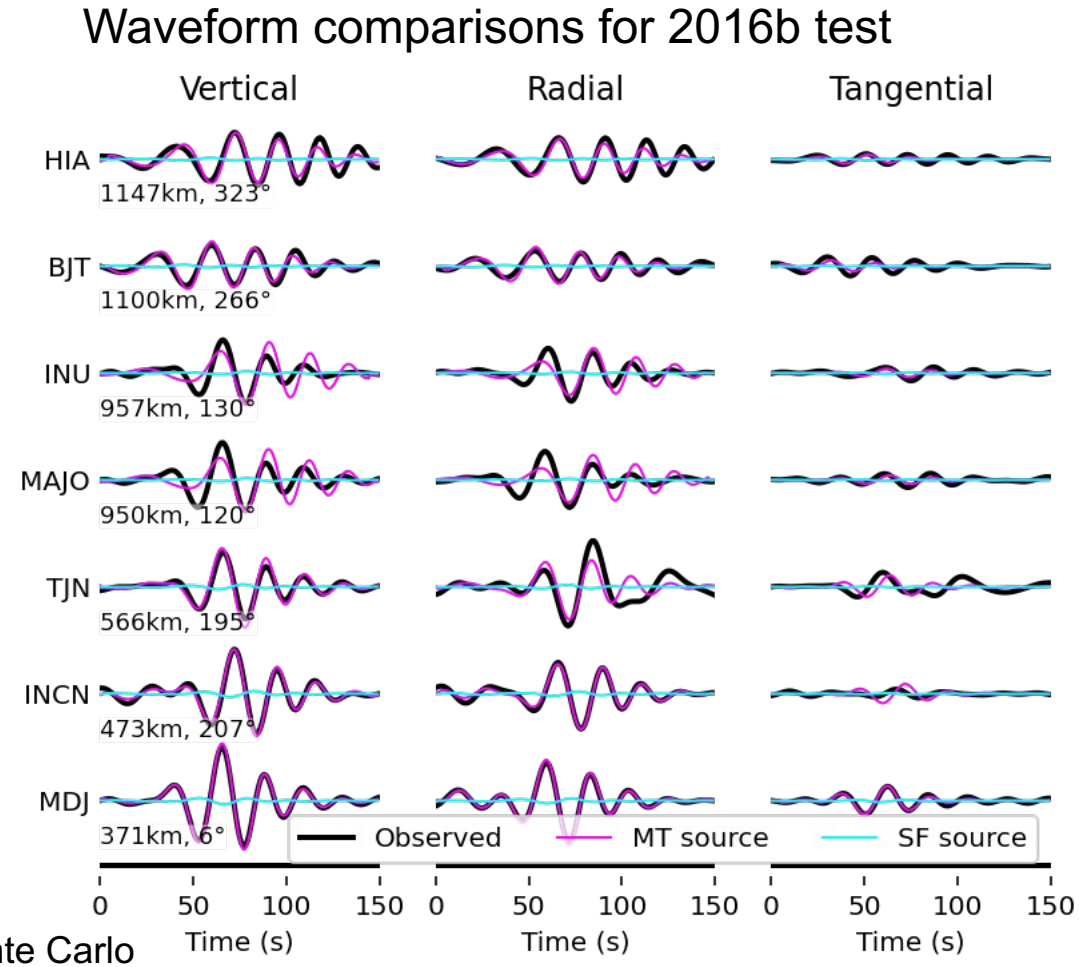
Our method considers both data noise (k_i) and 2D Earth's structural error (t_i).

Applications for DPRK explosions 2009-2017

❑Single force does not play significant role in these explosive sources



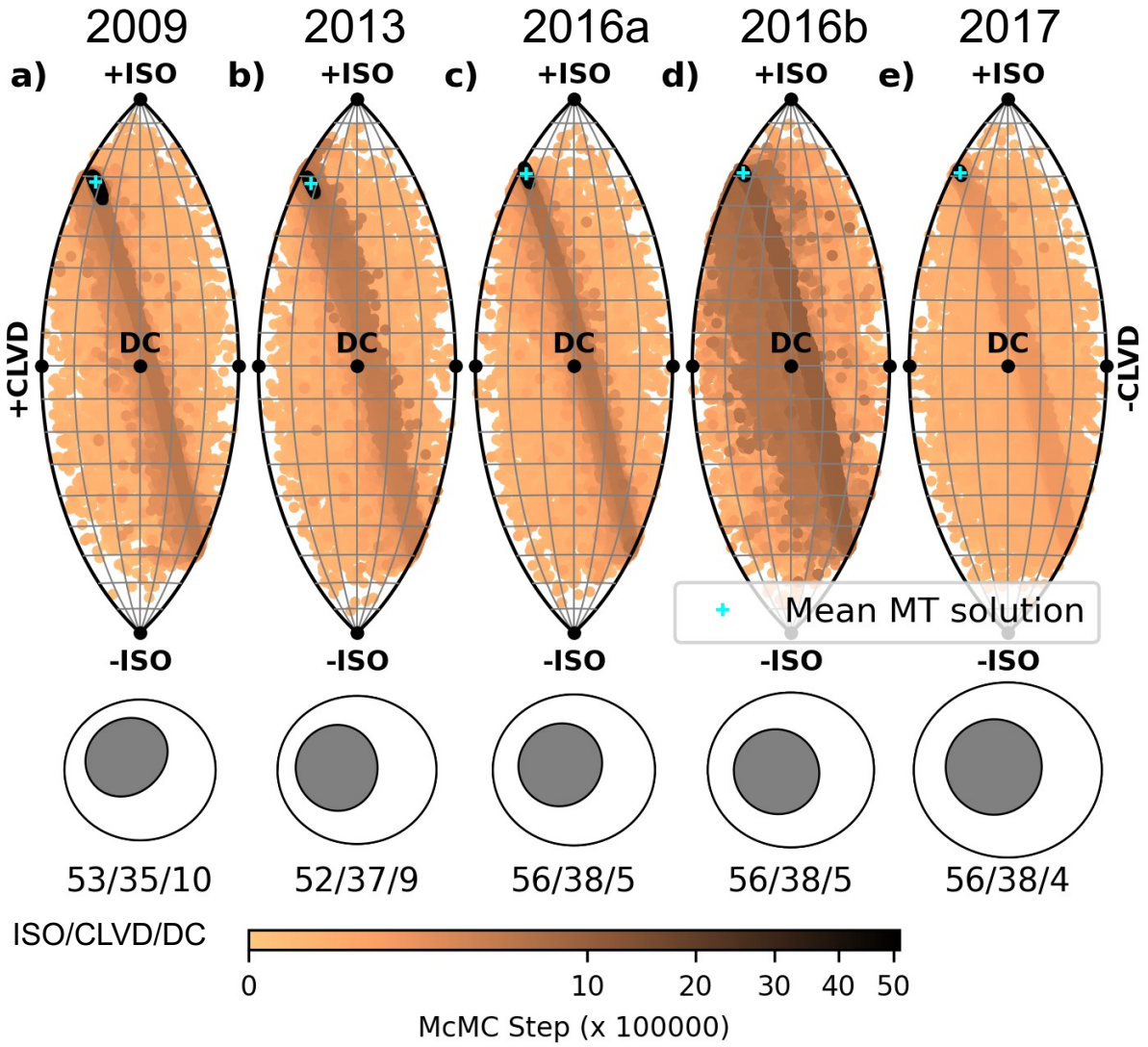
- **Depth=0.5 km, 20-50 s period band**
- MDJ2 velocity model (Ford et al., 2009)
- **emcee** for Bayesian inversion



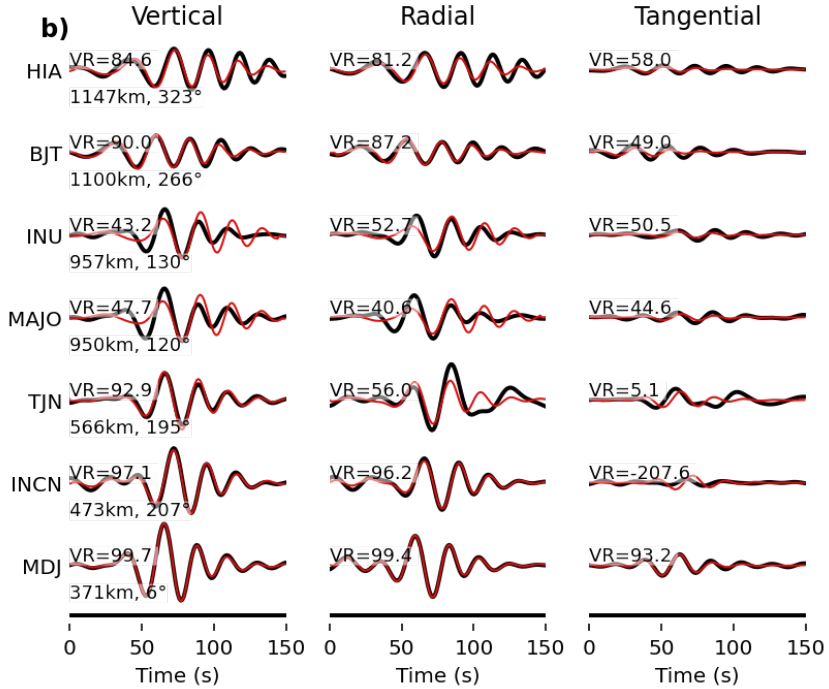
emcee — A pure-Python implementation of Affine Invariant Markov chain Monte Carlo (MCMC) Ensemble sampler. (Goodman & Weare, 2010; Foreman-Mackey et al., 2013)

MT inversions for DPRK explosions 2009-2017

❑ Similar source process of 5 explosions.



- This method explore the whole Lune diagram of source type (Tape & Tape, 2012)
- MT solutions converge to the area of the highest probability



Waveform fit of 2016b test

MT inversions for DPRK explosions 2009-2017

❑ Consistency of time shifts and 2D structure

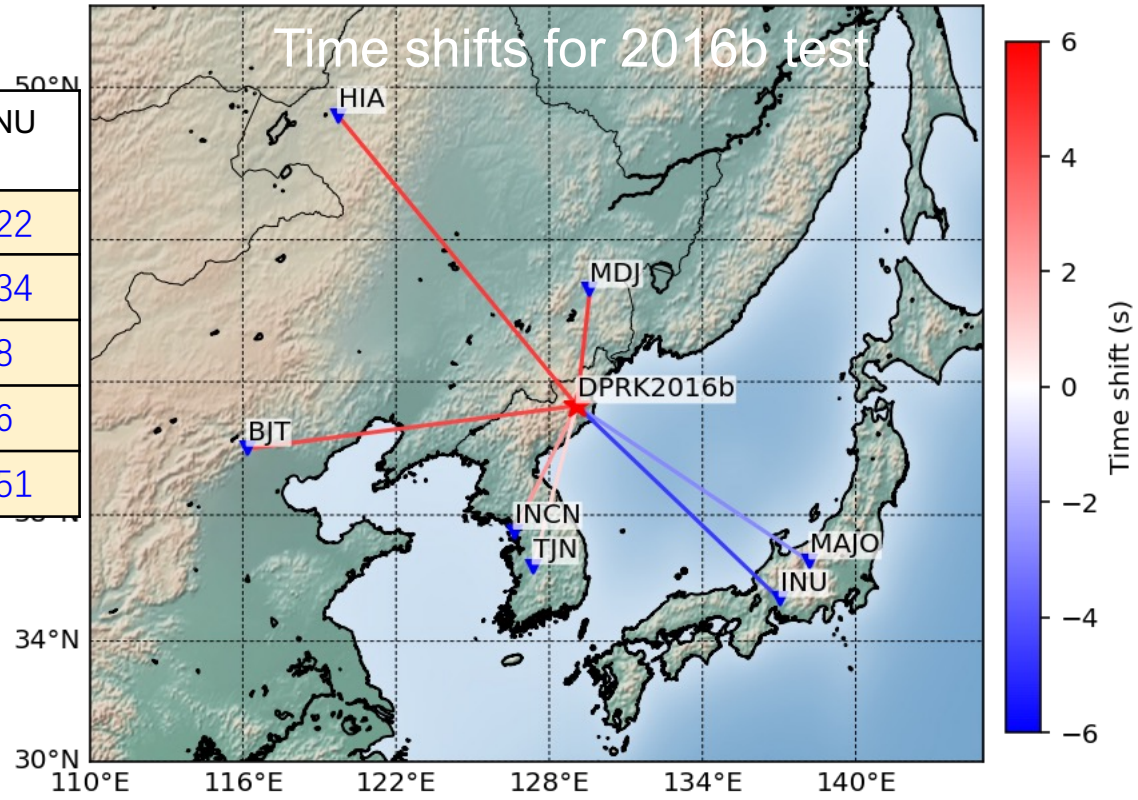
Recovered time shits for 2009-2017 explosions

Explosions	IC.MDJ	IC.BJT	IC.HIA	IU.INCN	KG.TJN	IU.MAJO	G.INU
2009	3.64	4.52	3.03	2.95		-2.7	-4.22
2013	4.06	3.55	3.3	2.41	2.05	-2.54	-4.34
201601	4.09	4.4	4.35	2.43	1.54	-2.9	-4.8
201609	4.72	4.4	4.68	2.39	0.96	-2.73	-4.6
2017	3.64	3.69	3.92	1.49	0.64	-3.61	-5.51

Definition of time shift:

Positive: the MDJ2 velocity is faster

Negative: the MDJ2 velocity is slower



❑ Noise parameters weight stations' contributions differently.

Result in a higher ISO component, which is important in explosion analysis.

Summary

- We developed a Bayesian source inversion for joint moment tensor and single force source.
- This method considers both uncorrelated data noise and Earth's 2D structural error. The 2D structural error is treated as the time shifts between observations and predictions by an inversion manner.
- We are conducting applications on real data e.g., Earthquakes, DPRK nuclear tests, and volcano eruptions, etc. More investigations for the preliminary results are still ongoing.

Thank you!