SAND2022-16648C

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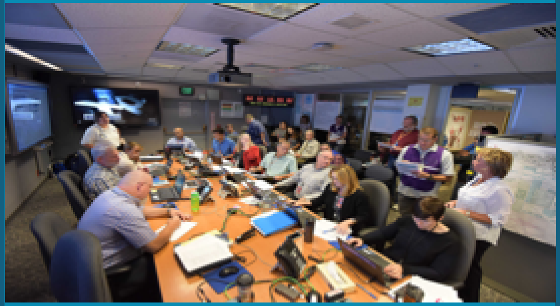
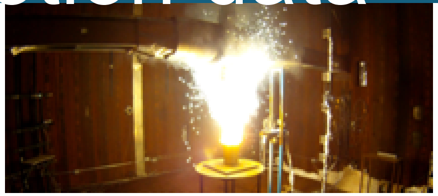
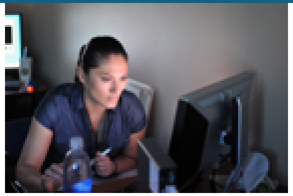
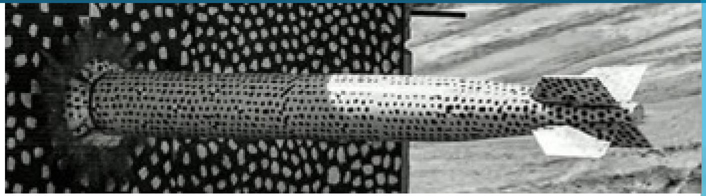
Estimating seismic source attributes using seismoacoustic models and acoustic, seismic, and rotational motion data









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Goal of our present work

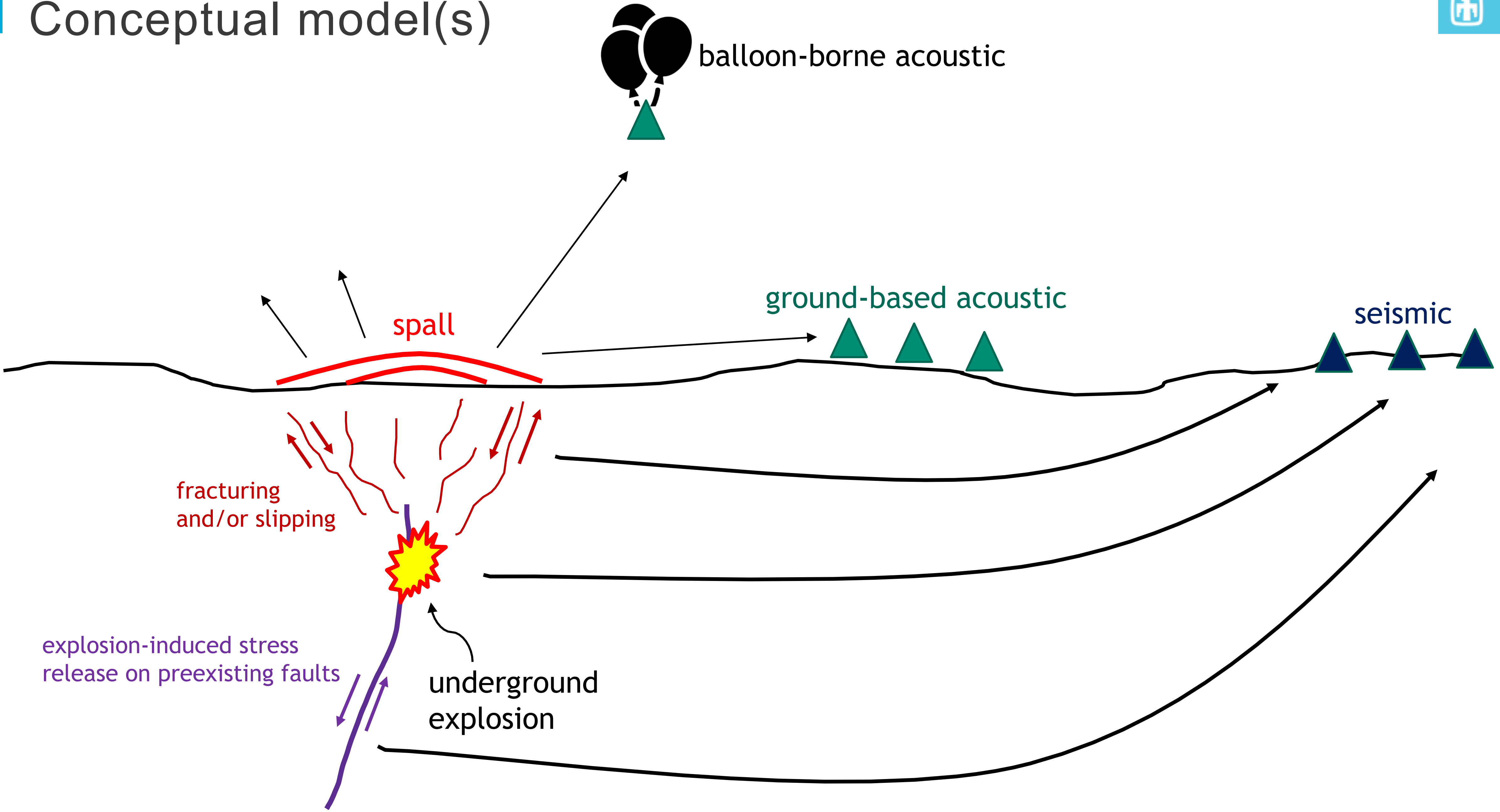
1) Estimate effective seismic source attributes of underground explosions

- Based on linear inversions
- Assume:
  - Time variable seismic source functions
  - Arbitrary numbers and locations of sources
- Jointly invert multiple datatypes

2) Questions we are asking

- Are elastic models strictly necessary?
- Do more data types increase accuracy or mitigate the effects of noise and/or model uncertainty?
- Can we resolve time-varying source mechanisms?

Conceptual model(s)



Classical linear inversion: Moment Tensors

pseudo-Green's functions scaled by m_j

$$u_i(t) = \sum_{j=1}^{6} \widehat{G_{ij}}(t) m_j \longrightarrow \mathbf{u} = \mathbf{Gm}$$

solve for m

$$m_j = \begin{bmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \\ m_6 \end{bmatrix} \rightarrow M_{ij} \rightarrow \begin{bmatrix} m_{xx} & m_{xy} & m_{xz} \\ & m_{yy} & m_{yz} \\ & & m_{zz} \end{bmatrix}$$

six scalar values that describe magnitude and direction of force couples acting at a single point

"absorb" source function into the forward model by convolving it with the Green's function

$$\widehat{G_{ij}}(t) = \int_{-T}^{T} G_{ij}(t) s(t - \tau) d\tau$$

$s(t)$ is the source function; assumed, *a-priori*

Assumptions

- linear
- single point source
- source function identical for all components of the MT
- low frequency wavefield insensitive to Earth heterogeneities

→ works pretty good for low frequency teleseismic and/or global scale data ←

Relax assumptions:

1) Multiple sources such as explosion, fault release, spall, etc.

$$u = (\hat{G} m_{explosion}) + (\hat{G} m_{spall}) + \ ...$$

2) source functions can be independent and time variable

$$u = (G \otimes m_{ij}(\boldsymbol{x}_1, t_{ij})_{explosion}) + (G \otimes m_{ij}(\boldsymbol{x}_2, t_{ij})_{spall}) + \ ...$$

3) several wavefield types (seismic, acoustic, rotational, etc.)

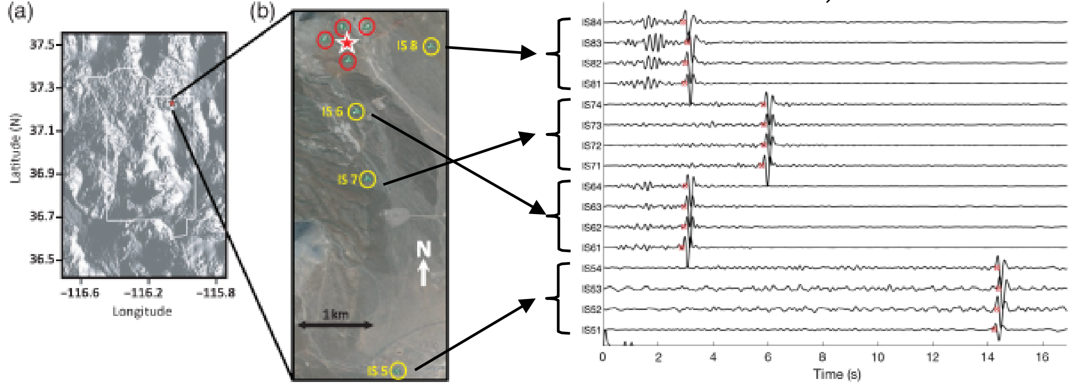
$$\begin{bmatrix} u_{seismic} \\ u_{acoustic} \\ \vdots \\ u_{rotational} \end{bmatrix} = \begin{bmatrix} (G_{seismic} \otimes m_{expl}) + (G_{seismic} \otimes m_{spall}) + (G_{seismic} \otimes m_{EQ}) + \cdots \\ (G_{seismic} \otimes m_{expl}) + (G_{seismic} \otimes m_{spall}) + \ ... \\ \vdots \\ (G_{rot} \otimes m_{expl}) + (G_{rot} \otimes m_{EQ}) + \cdots \end{bmatrix}$$

1) Multiple source types

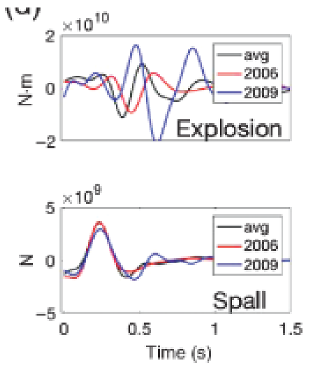
- Experiment: Source Physics Experiment Phase I
- Data: locally (<5km) recorded Infrasound produced by buried chemical explosion
- Source model: (buried) isotropic explosion and (surface) spall
- Estimate Green's functions using finite differences
    - constant wavespeed ACOUSTIC earth model
    - atmospheric model based on meteorological observations
    - wave propagation is fully ACOUSTIC
- Invert for source time functions

$$u_{infrasound} = (Gm_{explosion}) + (Gm_{spall})$$

IF data, SPE 6



estimated STFs (SPE 6)

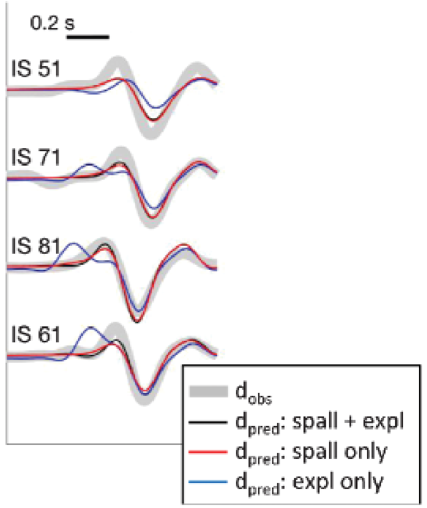


estimated isotropic source function

estimated spall source function

different colors correspond to different atmospheric models

fit to data (SPE 6)



different colors correspond to different source model assumptions

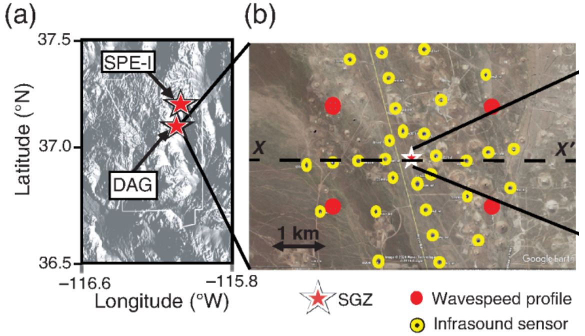
Results / conclusions
1) Spall source "well behaved", relatively insensitive to atmospheric model
2) Explosion source is a mess
3) Predicated data is almost totally controlled by spall term (suggests buried source term lives in the null space for this setup)
    - <u>Question</u>: is this because spall is the primary driver of the infrasound **OR** is it because our forward model doesn't do a good job predicting the elastic part of the wavefield?

Poppeliers, C., K.A. Anderson, L. Preston, 2019, *Bull. Seis. Soc. Am.*, **109(1)**, 463-475

1) Multiple source types, fully elastic model

- Experiment: Source Physics Experiment Dry Alluvium Geology (DAG)
- Data: locally (<3km) recorded Infrasound produced by buried chemical explosion
- Source model: (buried) explosion and (surface) spall
- Estimate Green's functions using finite differences
    - Coupled elastic/acoustic model
    - wave propagation is seismoacoustic
- Invert for source time functions (M_{ij} and F_z)

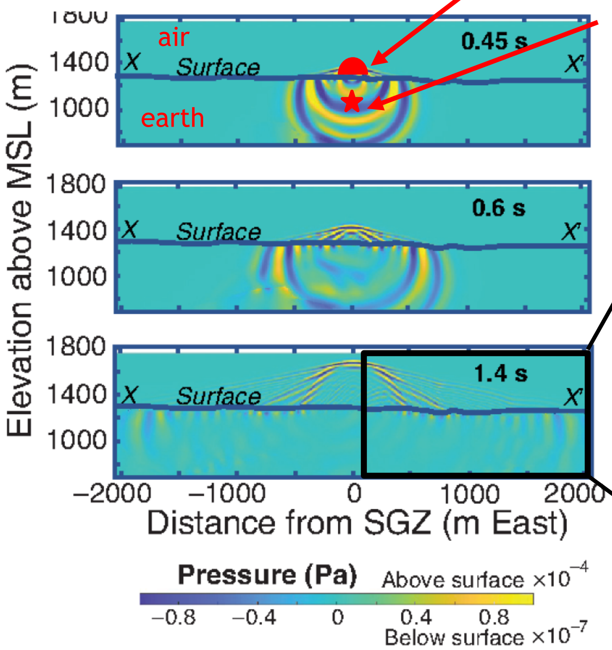
recorded infrasound produced by a buried (z=-52m) explosion: 10.4 metric tons (TNT equivalent)



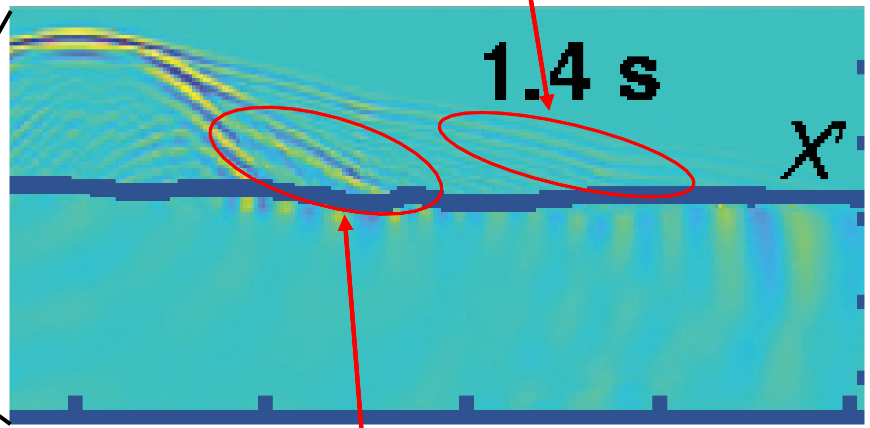
simulated seismoacoustic wavefield

spall source

explosion source



acoustic wavefield from seismic -to-acoustic coupling

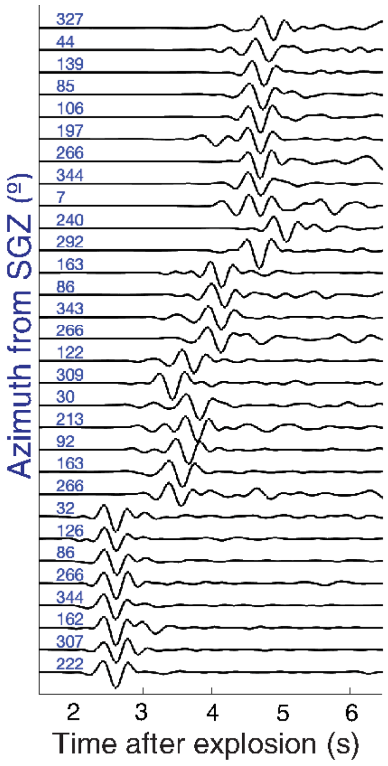


acoustic wavefield from spall

Berg, E., Poppeliers, C., 2022, BSSA 112(4), 2216-2230

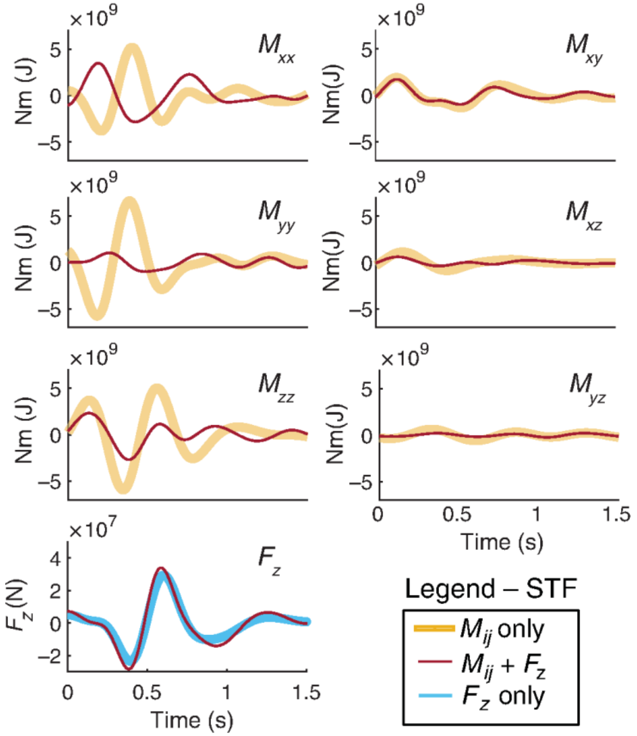
1) Multiple source types, fully elastic model

1-4 Hz acoustograms
(trace normalized)

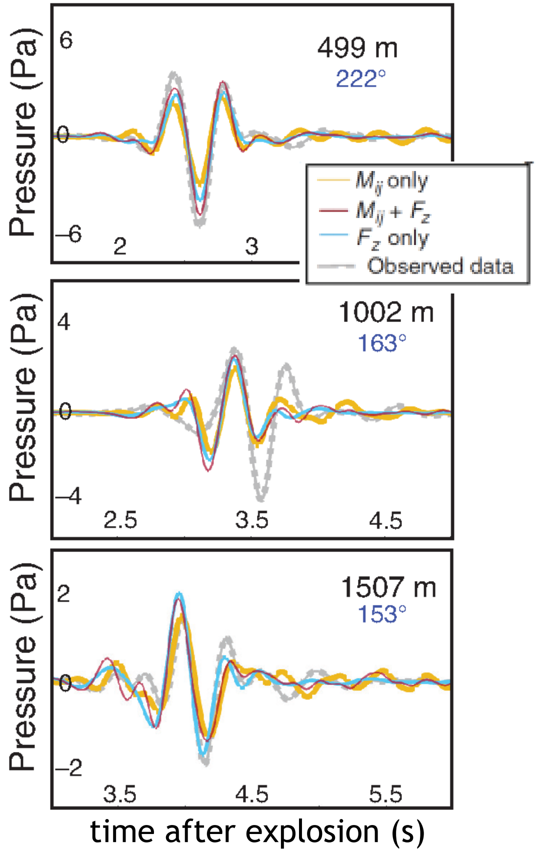


inverted the data using three source models

1) buried explosion only
2) spall (F_z) only
3) explosion + spall



observed and predicted data



Results:

1) Buried, full-tensor source is MUCH better resolved
2) explosion + spall model fits the data the best, but…
3) Spall-only model still describes most of the data, however…
4) Without spall source, the isotropic portions of M_{ij} attempt to compensate
   - ➢ M_{ij} looks very CLVD-like

Conclusion:

There is A LOT of value in using the full seismoacoustic model when inverting IF data produced by buried explosions

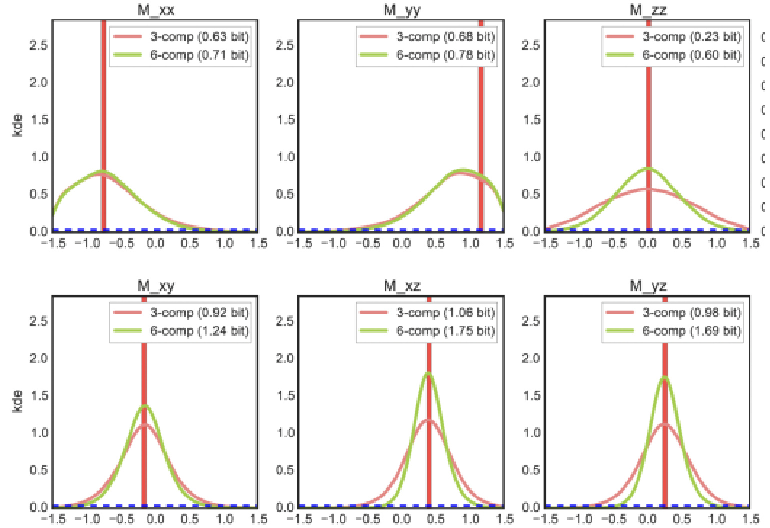
Berg, E., Poppeliers, C., 2022, BSSA 112(4), 2216-2230

Several Wavefield types

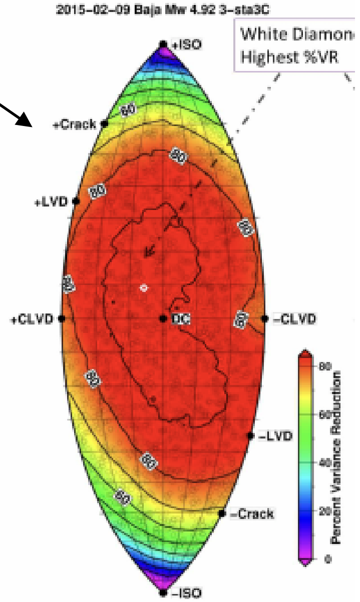
- translational seismograms + rotational motions

- Previous methods estimated
  - scalar MT components (e.g. “beachball”)
  - PDFs of MT components via Bayesian methods (e.g. Donner et al., 2016, 2020; Bernauer et al., 2014)
  - misfit of all source mechanisms (e.g. Ichinose et al., 2019)
- Previous work suggested that adding rotational motions helps to decrease uncertainty in scalar MTs (and hence seismic mechanism) <u>FOR LOW FREQUENCY TELESEISMIC DATA</u>

- We extend this idea to estimate time-variable source functions:
  - translation + rotational data
  - high frequency explosion source data
  - effects of model uncertainty



Donner, S., Bernauer, M., Igel, H., 2016, *Geophys. J. Int.*, **207**, 562-570



Ichinose, G.A., Ford, S.R., Mellors, R.J, 2019,AGU Fall 2019 Meeting, S032

Several Wavefield (data) types

inverse method

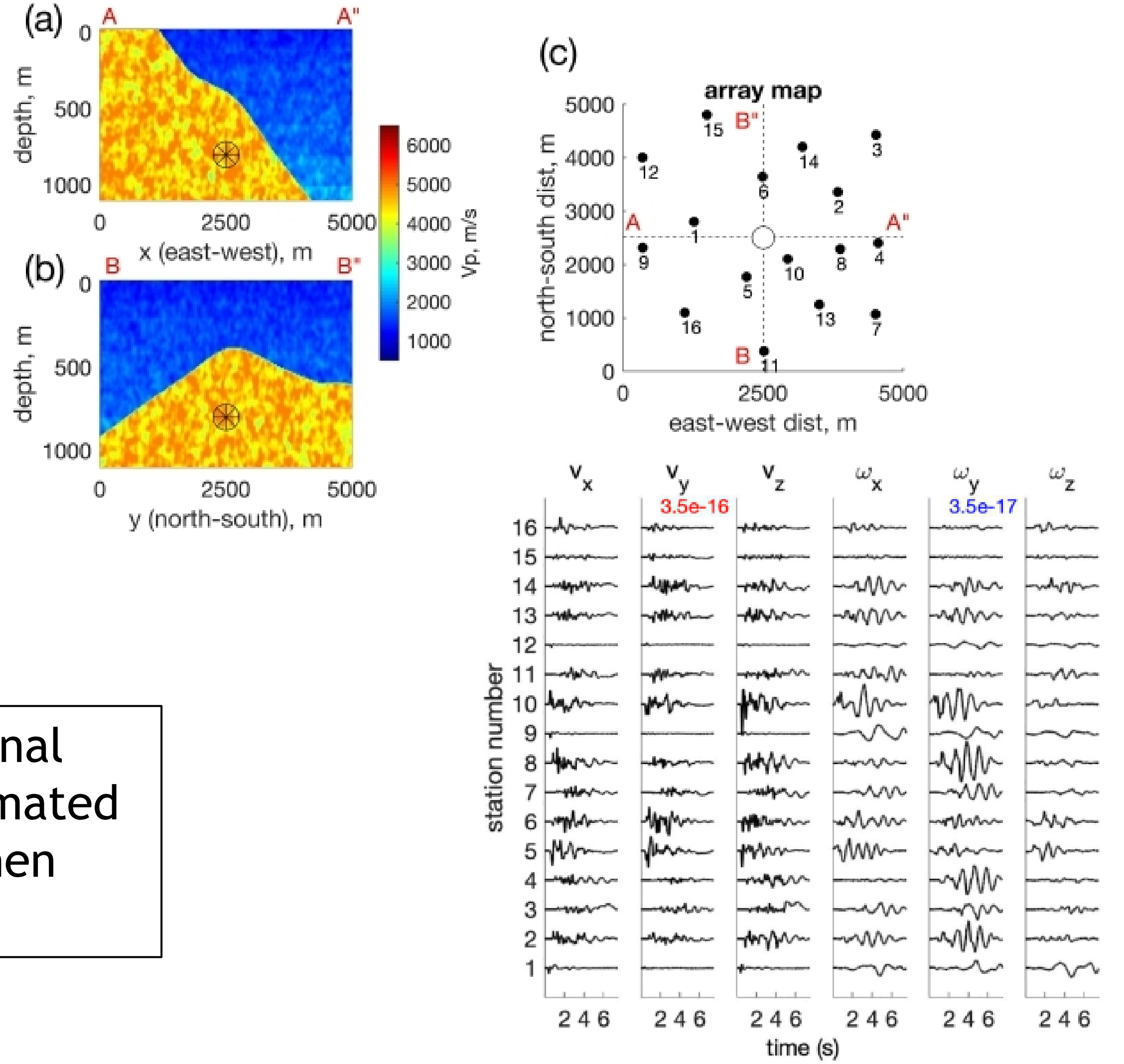
$$\begin{bmatrix} | \\ \mathbf{U} \\ | \\ | \\ \Omega \\ | \end{bmatrix} = \begin{bmatrix} | \\ -\mathbf{G}^{\{U\}}- \\ | \\ | \\ -\mathbf{G}^{\{\Omega\}}- \\ | \end{bmatrix} \mathbf{M}$$

- translational seismic data → $\mathbf{U}$
- rotational seismic data → Ω
- translational Green's functions → $\mathbf{G}^{\{U\}}$
- rotational Green's functions → $\mathbf{G}^{\{\Omega\}}$
- source functions to estimate → $\mathbf{M}$

can normalize/nondimensionalize and/or weight different data types

<u>Hypothesis we test</u>: The addition of rotational motions reduces the uncertainty in the estimated source functions for high-frequency data when the earth model is uncertain.

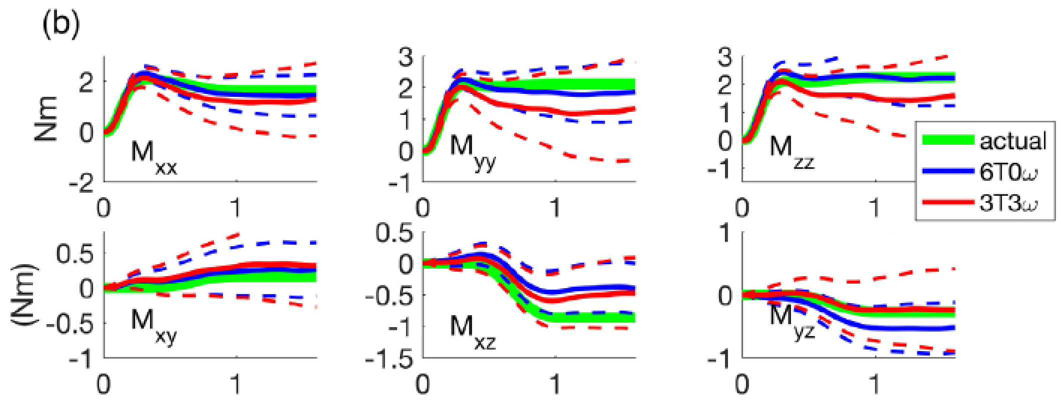
Test with numerical experiments,
Effects of model uncertainty using Monte Carlo



Poppeliers, C., Preston, L., 2022, *Geophys. J. Int.*, **230**, 235-251

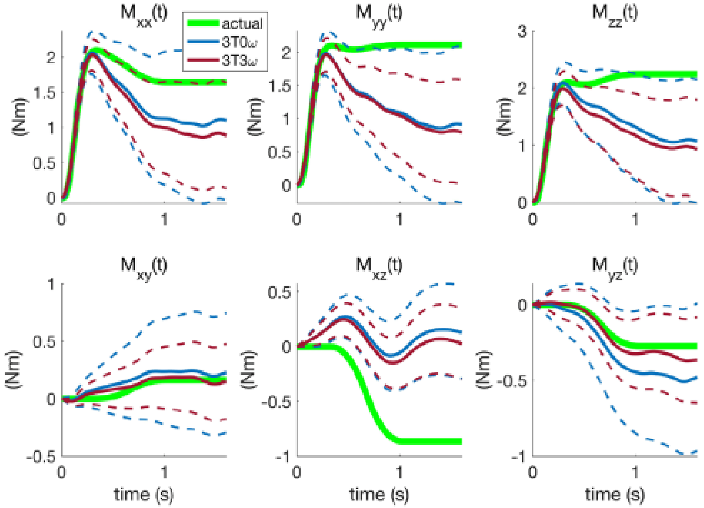
Results: mixed

1) For “many” stations/channels, adding rotational motions **IN**creased uncertainty of the results!

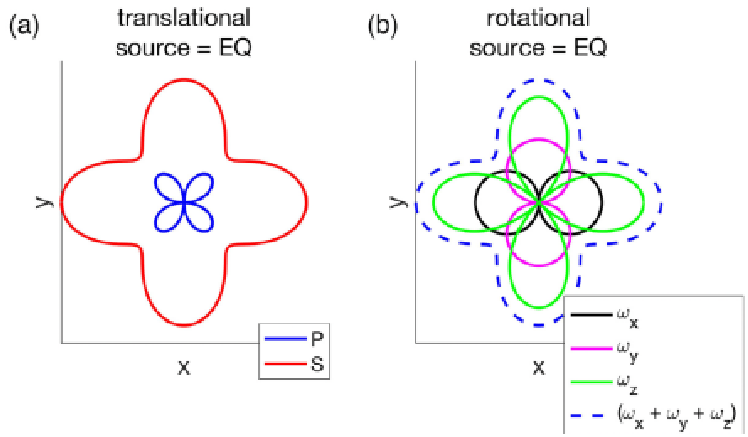


Why??

2) However…. given a small number of stations, adding rotational motions (at same location) decreases uncertainty. Likely due to simply having more channels of data to invert.



- Rotational motions are more sensitive to model heterogeneity, and thus uncertainty.
- Theoretical combined radiation pattern of all rotational motions (Aldridge, 2000) is virtually identical to that of translational shear waves.



- This is at odds with previous work based on rotational radiation patterns given by Cochard et al., (2006), eqn 30.4, which predicts the radiation patterns of these two datatypes to be different: → combining two data types should “fills in” holes in the radiation pattern.
- Who’s right??

Poppeliers, C., Preston, L., 2022, *Geophys. J. Int.*, **230**, 235-251

Time variable source mechanisms

Current techniques to estimate source mechanism assume that the source is a point in space and time. Too restrictive for low-yield, local scale data?

We've already developed methods to account for multiple sources and independence of source functions, so let's simply compute the mechanism as a function of time.

$$u_i(t) = \sum_{j=1}^{6} \widehat{G_{ij}}(t) m_j$$

$$\widehat{G_{ij}}(t) = \int_{-T}^{T} G_{ij}(t) s(t-\tau) d\tau$$

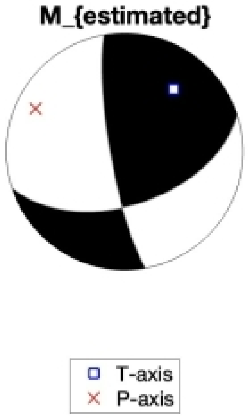
$s(t)$ is the source function; assumed, *a-priori*

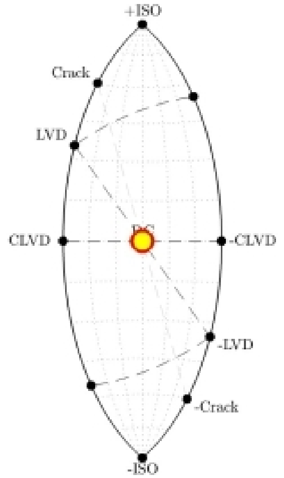
moment tensor

$$m_j \rightarrow M_{ij} = \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix} \longrightarrow \text{SVD} \longrightarrow [\lambda_1 \quad \lambda_2 \quad \lambda_3]$$

eigenvalues

use eigenvalues to calculate spherical coordinates on the fundamental wedge

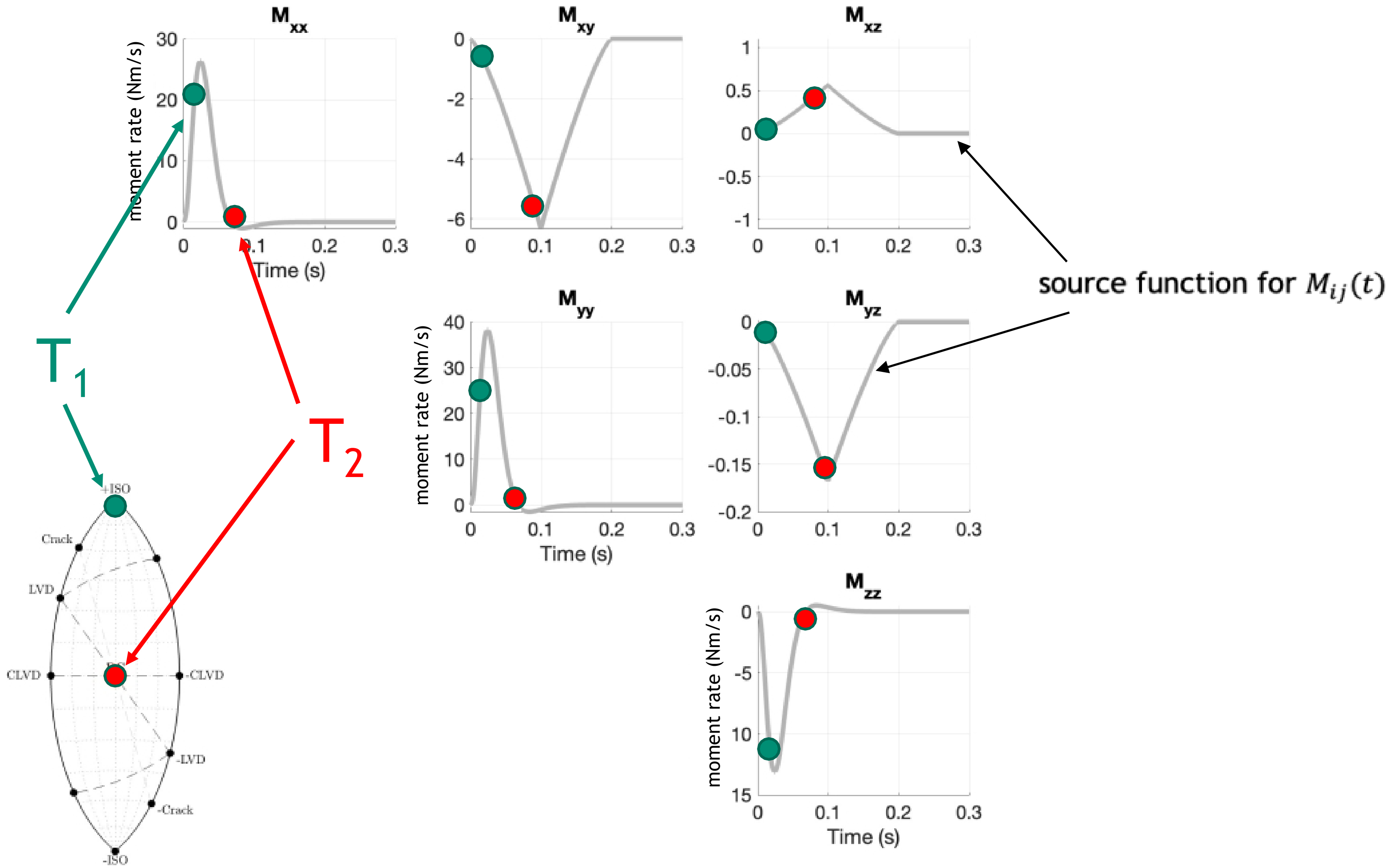




Time variable source mechanisms

Concept:

1) estimate time-variable source functions $M_{ij}(t)$,
2) extract amplitude at discrete time points (or windows) $M_{ij}(t = T_i)$,
3) Decompose $M_{ij}(t = T_i)$ to obtain eigenvalues,
4) plot on a lune



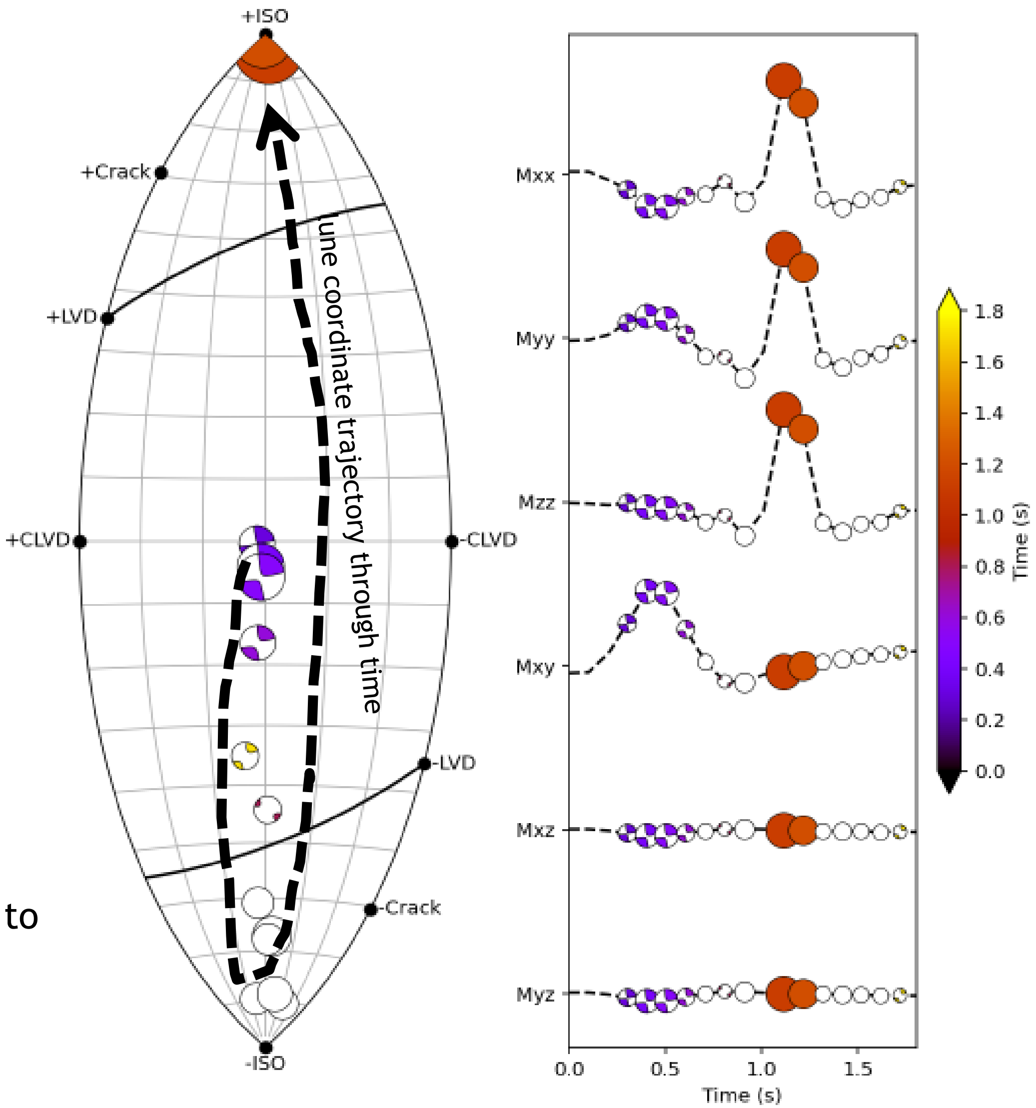
Time variable source mechanisms

Numerical test: Two sources, offset in time: double couple followed by isotropic.

In concept, we can combine time-variable source function estimates into traditional source mechanism estimates.

This is a work in progress!

- size of beachball corresponds to magnitude
- color corresponds to time



Concluding remarks

1) We've successfully developed and implemented a linear inversion method that estimates time-varying source functions for fully elastic Earth models and multiple source types

2) We can now combine multiple data types, such as translational seismic, acoustic, and rotational motions into a joint inversion for source functions

3) We've developed a method to estimate time-varying source mechanisms based on the inversion schemes in bullets 1 and 2

Questions we asked

Are elastic models strictly necessary?

→ no, but they give us more robust source estimates for buried explosions when using acoustic data

Do more data types increase accuracy or mitigate the effects of noise and/or model uncertainty?

- → No and Yes: for many stations and uncertain propagation models, adding rotational motions may increase uncertainty;
- → However, for a small number of stations, the additional rotational channels appears to decrease uncertainty

Can we resolve time-varying source mechanisms?

→ So far, it looks promising!