Quantifying uncertainty in regional-scale seismic moment tensors

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INTRODUCTION AND MAIN RESULTS

- Understanding the uncertainty in moment tensor analyses is key to a proper interpretation of those results
- Earth model errors can cause biases in moment tensor results that basic statistical tests like the 95% confidence F-test used here will not identify, but a 1-D model based on a 3-D can help mitigate biases
- Errors are non-Gaussian; thus, standard F-test confidence intervals are inaccurate especially when realistic noise contaminates observations
- FW inversions provide more accurate, higher confidence results than amplitudes or FMs, but still can be biased by inaccurate earth models

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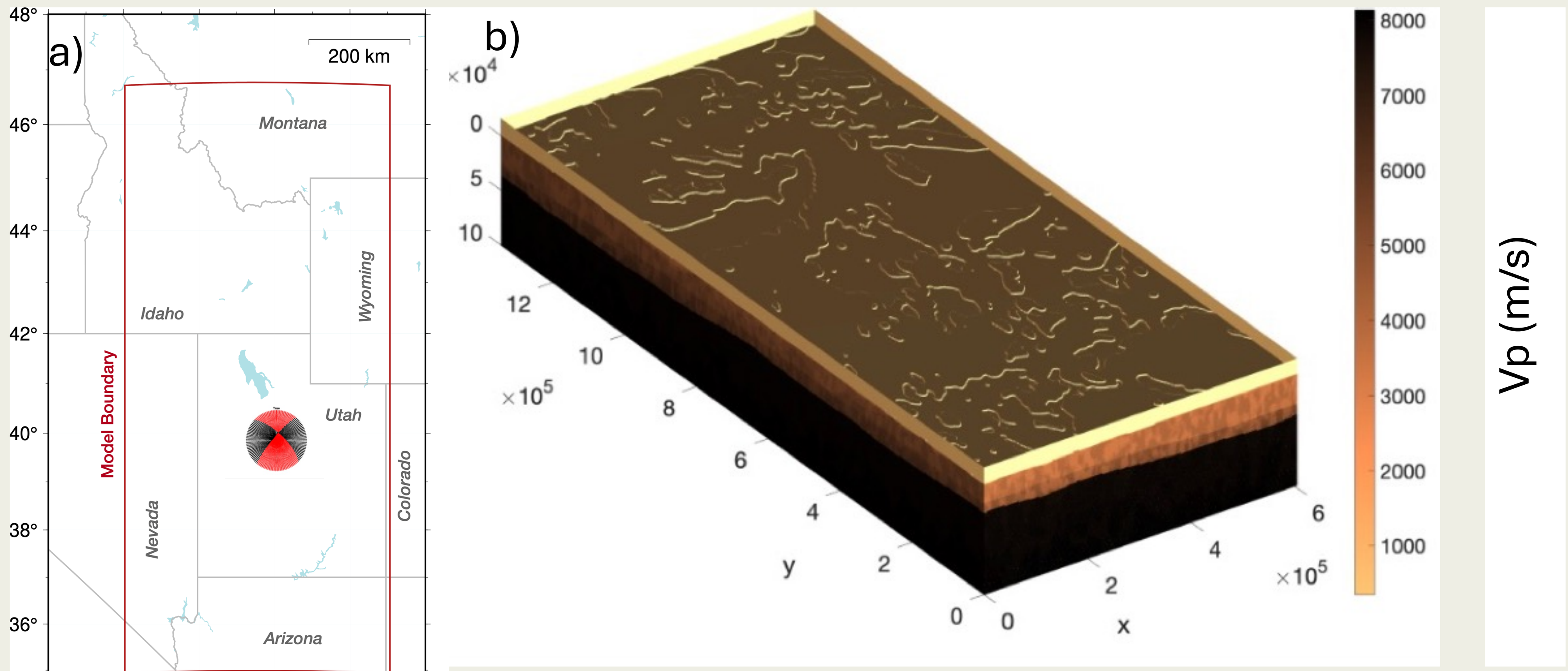
Introduction

One of the primary goals of nonproliferation research is seismic source characterization. Understanding the uncertainty in moment tensor analyses is key to a proper interpretation of seismic results. To evaluate the uncertainty and sensitivity of moment tensors to various factors, we perform a series of simulations and determine solutions over combinations of the factors shown below:

Property	N	Values
Data type	3	P-wave 1st motions, P-, SV- and SH-amps, FW
Earth model (data)	3	3-D heterogenous, 1-D layered, 1-D ak135
Earth model (GFs)	1	1-D layered
Source Type	3	0/100%, 70/30%, 100/0% iso/DC
Noise level	3	SNR: Inf (no noise), min 2, min 5
Azimuthal Cov.	2	Full, 144° min azimuthal gap
# stations	4	5, 10, 14, 19



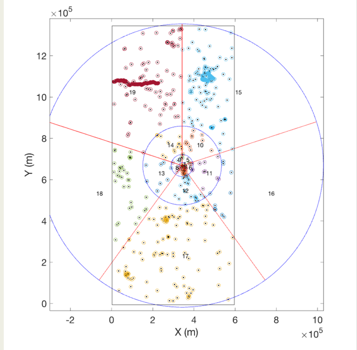


Figure 1: a) Map of study area with the double-couple (DC) source mechanism shown at the source location, b) 3-D stochastic earth model based on the Western US Geologic Framework Model, c) Station map color-coded based on distance and azimuth bins.

References

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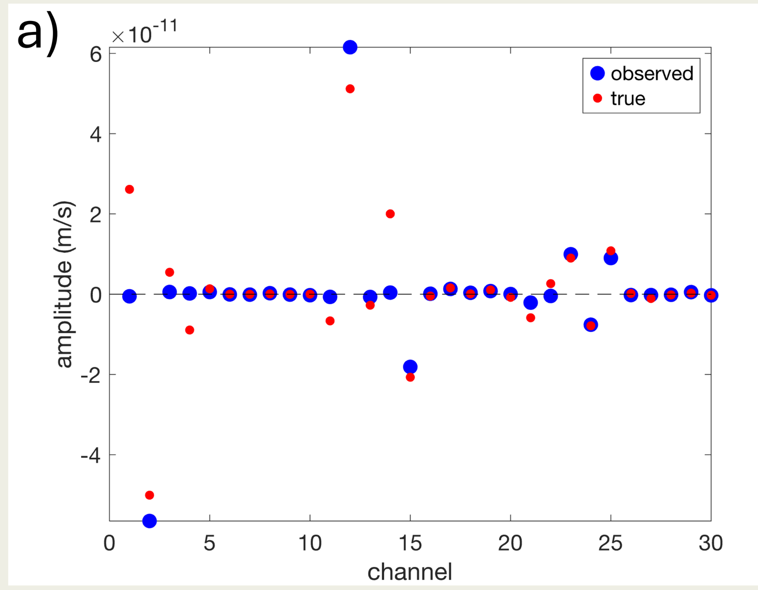
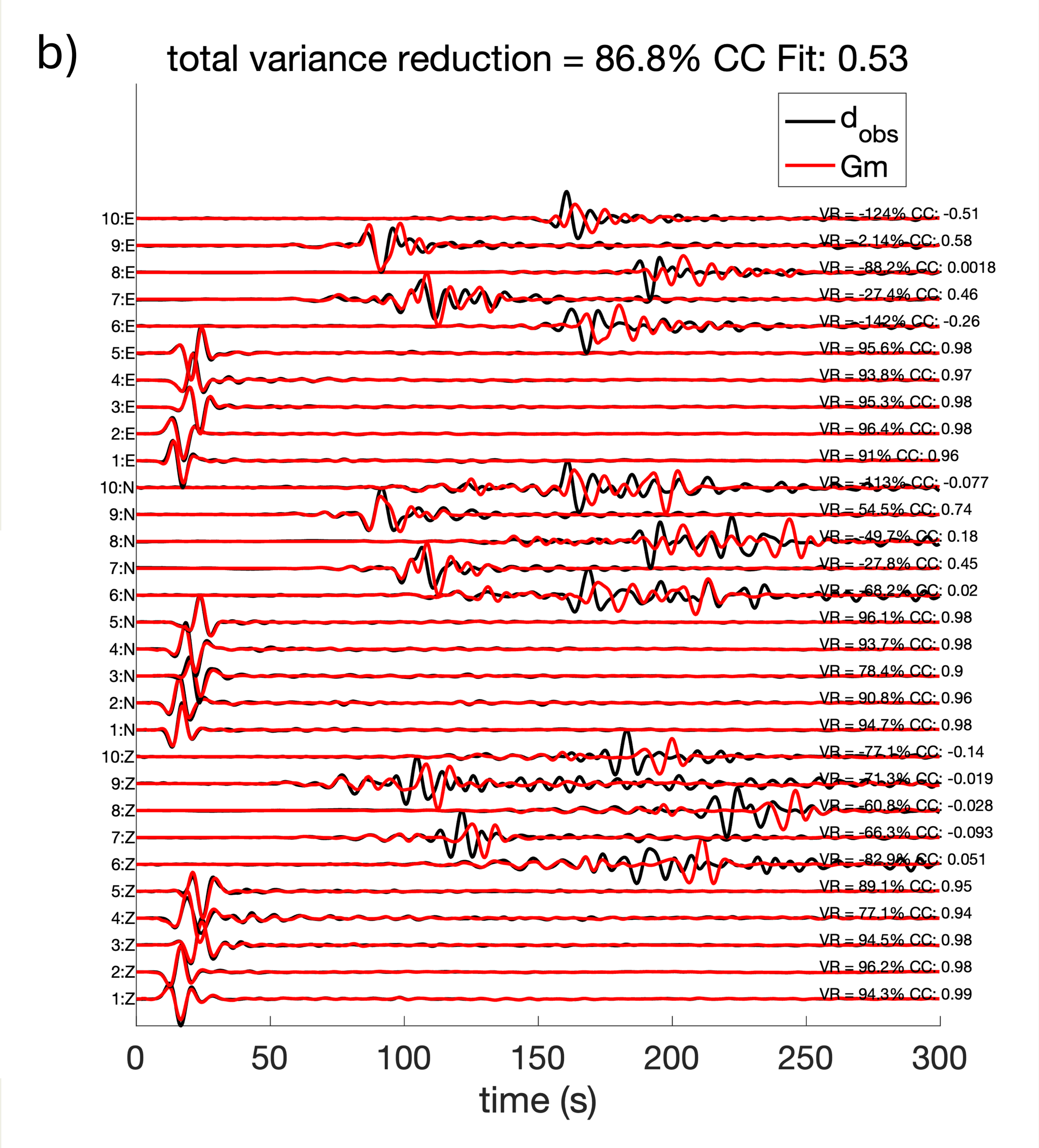
Method

We generate synthetic "data" from three different Earth models: a 3-D heterogenous model based on the Geologic Framework Model of the Western US (Boyd, 2019) with stochastic perturbations added ("het"), a 1-D model based on that model ("layered"), and 1-D ak135 (Kennett et al., 1995) (Figure 1). In all cases, we use the layered model for Green's functions. From the Table, there are 72 cases per data Earth model for all 3 data types. The first-motion (FM) and amplitude data (amps) use a grid search method to find solutions with 10° bins in strike, dip, and rake and isotropic/DC ratios: -1.0, -0.7, -0.3, 0, 0.3, 0.7, 1.0. The full waveform (FW) data use a deterministic regularized inversion, solving d = G*m subject to model smoothness and minimization constraints, for all six unique components of the time-variable moment tensor (Figure 2). For each of the 216 cases for the amps and FMs, 100 realizations are performed, while for the FW cases, only 10 realizations are completed per case. Each realization randomly selects one station within each azimuth and distance bin (Figure 1c). These bins ensure that each case has a relatively even distribution of stations around the source. For the "az gap" cases, two of the five azimuth bins have no stations within them at any distance. Realistic noise is constructed using Karhunen-Loève expansion (e.g., Preston, 2018) of observed pre-event noise, scaled to match the signal-to-noise (SNR) for the case.

Figure 2: a) Example amplitude data from the het model ("observed") compared to that predicted from the layered earth model with the true source, b) FW inversion fit of the same case.





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Results

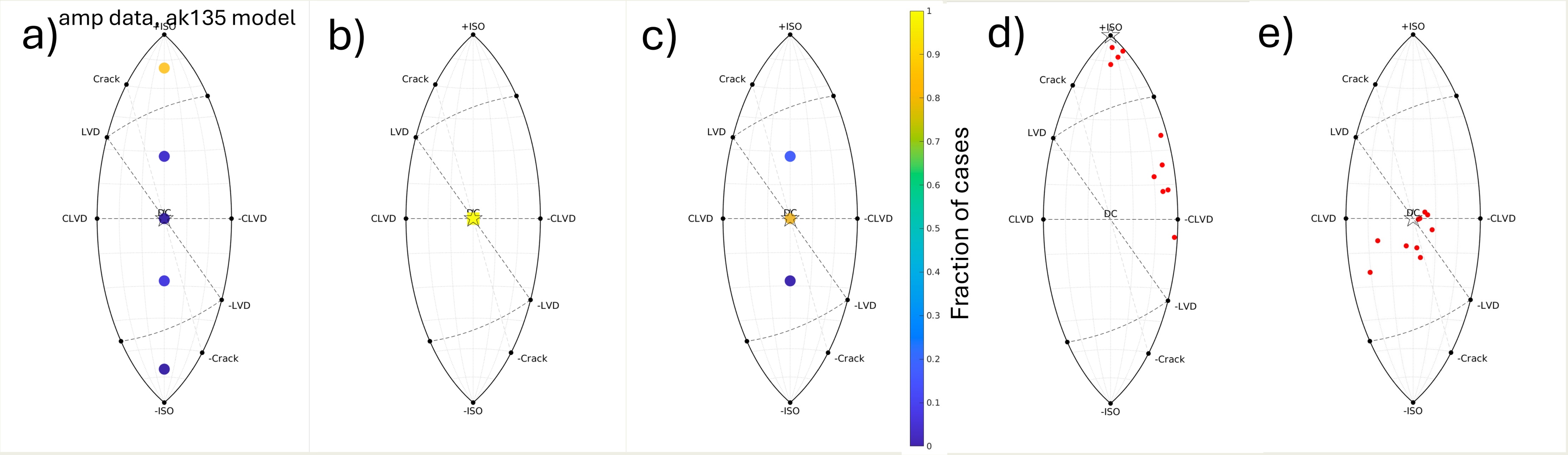
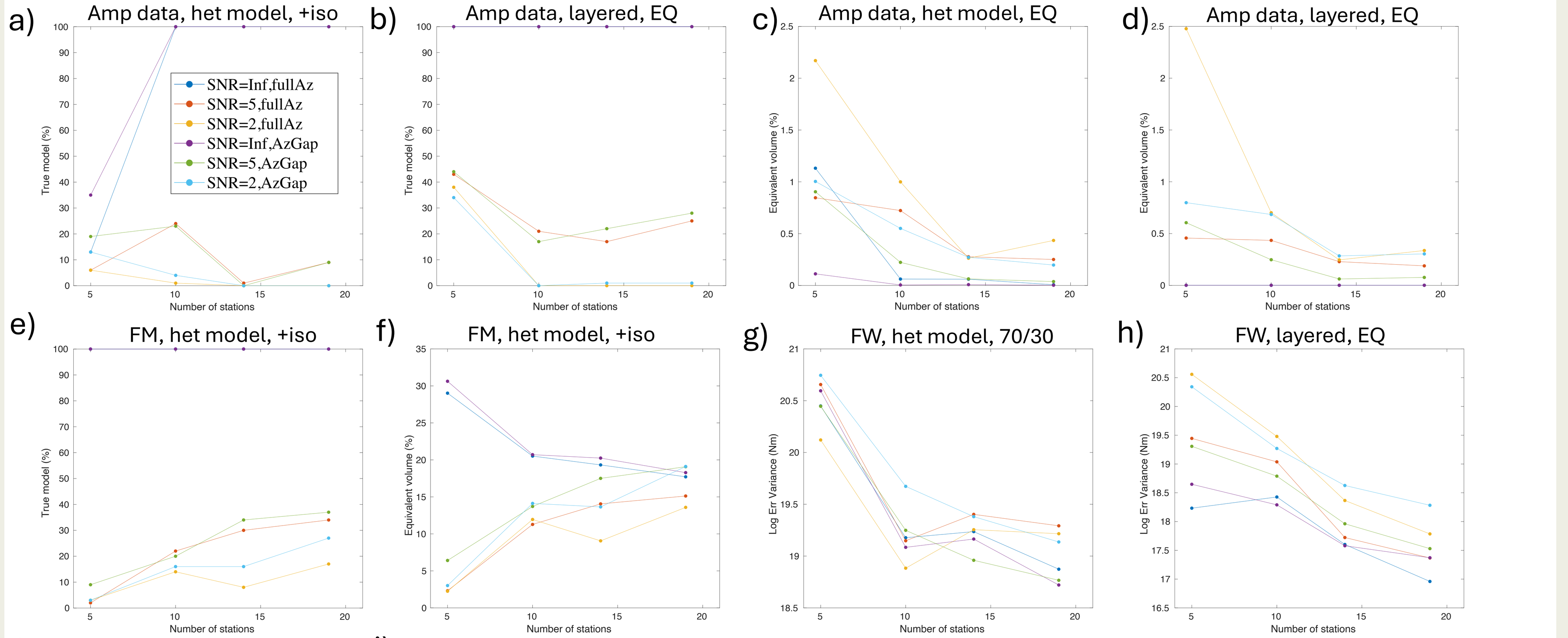


Figure 3: Summary plots of source type on lune plots (Tape and Tape, 2012). a)-c) Grid search on source type with color indicating the fraction of statistically equivalent solutions with each DC/iso% (colorbar). Star indicates true source type. All three are amplitude data in az gap, no noise cases: a) ak135 b) layered, c) het. d)-e) Full waveform solution source types for all 10 realizations (red dots) for d) het, no az gap, SNR 2; e) az gap, no noise.



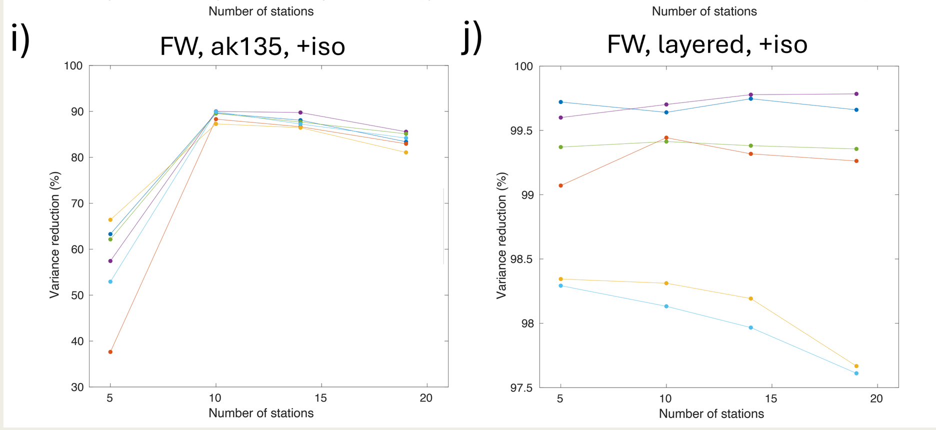


Figure 4: Statistics versus number of stations colored by case. a)-d) amp data; e) & f) FM, g)-j) FW. a), b), e) average % of realizations having the true model within F-test region. c), d) ,f) mean % of the 4D volume that is statistically equivalent to the best model. g) & h) log10 of the error variance. i) & j) % variance reduction.

Conclusions

- Earth model errors can cause biases in moment tensor results that basic statistical tests like the 95% confidence F-test used here will not identify, but a 1-D model based on a 3-D can help mitigate biases (Fig. 3a and 4)
- Noise further complicates and increases scatter in results (Fig. 3d & e)
- Errors are non-Gaussian; thus, standard F-test confidence intervals are inaccurate especially when realistic noise contaminates observations (Fig. 4)
- Five stations result in much different statistics than 10 or more especially with earth model errors
- Having >=10 stations only subtly improves accuracy, error variance, and confidence intervals and can actually worsen results in some cases
- FW inversions provide more accurate, higher confidence results than amplitudes or FMs, but still can be biased by inaccurate earth models