Development of the microBayesloc Method

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MicroBayesloc is a cornerstone of LLNL’s SubTER effort

- LANL Stress Seedling
- Microseismic analysis
  - Open Fracture Imaging
- Pre-experiment modeling and monitoring design
- Geophysical inversion
- PNNL Muon Seedling
- LBL SURF Seedling
- NETL Big Data Seedling
- Oklahoma Big Data Set and Microseismic Analysis
- Inversion for fracture stress and conductivity
- SNL Fracture Seedling

LLNL analysis contributes to other efforts
MicroSeismic locations are used to assess the evolving state of stress.
Seismic locations are typically represented as point patterns.

- **Deep events** are located at greater depths.
- **Shallow events** are closer to the surface.
- Sensors are positioned at the top of the diagram.

The graph illustrates the distribution of events in a 3D space with coordinates X, Y, and Z (Elevation [z, km]).
MicroBasesloc produces validated uncertainty estimates

Point patterns work if seismicity trends are large compared to location uncertainty.
Bayesloc: Joint Probability Over Multiple-Event Parameters

- Event locations
- Travel times
- Measurement precision
- Phase labels

Statistical model

\[ p(o, x, T, W, \sigma, V, \tau | a, d, w) \]

- \( o \) = origin times
- \( x \) = locations
- \( T \) = phase travel times
- \( W \) = phase labels
- \( \int \) = measurement precisions (pick)
- \( V \) = measurement precisions (diff)
- \( \tau \) = travel time corrections
- \( a \) = arrival times (picks)
- \( d \) = differential arrival times
- \( w \) = input phase labels

Myers, Johannesson, and Hanley (2007, 2009)
Recast Probability of Inverse Problem Into a Set of Forward Problems, Bayes Theorem

Multiple-Event Conditional Probability

\[ p(o, x, T, W, \sigma, V, \tau \mid a, d, w) = \]

- \[ p(a \mid o, T, W, \sigma) \] \text{Arrivals times given a set of locations and measurement uncertainties}
- \[ p(d \mid o, T, W, V) \] \text{Differential times given a set of locations and measurement uncertainties}
- \[ p(T \mid o, F(x), W, \tau) \] \text{Travel times given a set of locations and travel time corrections}
- \[ p(W \mid w) \] \text{Phase labels given input phase labels}
- \[ p(x, o)p(\sigma)p(\tau) \] \text{Prior constraints}
- \[ /p(a)p(d) \] \text{Probability over all arrivals}
Simultaneous location and data analysis

Bayesian analysis: event location example (Bayesloc)

G. Johannesson
S. Myers
microBayesloc assesses components of error budget at Newberry

- S-wave uncertainty 3-times P-wave uncertainty and 40 times the sample rate
- Estimated time uncertainty (measurement + model + station corrections)
  - P waves: 0.05 sec
  - S waves: 0.16 sec

![Graph showing estimated summed error](image)

- Estimate of P: ~0.05 sec
- Estimate of S: ~0.16 sec
- Pick Model Station
  - ~0.02 (s) ~0.08 (s)
Adaptation of PageRank to assess microSeismic data

PageRank, as developed by Page et al. (1999) for webpages, is the probability that a “random surfer” will visit a particular web page.

We use PageRank to find the connectivity of seismic signals based on a correlation value.

\[ \bar{x} = A\bar{x} \]

\( x = \text{PageRank} \)
\( A = \text{transition probability matrix} \)

\[ a_{ij} = \begin{cases} \frac{p g_{ij}}{c_j} + \delta & \Rightarrow c_j \neq 0 \\ \frac{1}{n} & \Rightarrow c_j = 0 \end{cases} \]

\( g = 1 \) if cc exceeds a threshold
\( p = \text{probability that signals are linked} \)
\( \delta = \text{probability of a random link} \)

\[ c_j = \sum_i g_{ij} \quad \delta = \frac{(1 - p)}{n} \]
Adaptation of PageRank to assess microSeismic data
A closer look...

We reexamine waveforms that are determined to be linked
1) Rotate to principle components of particle motion

Station NB19 (near surface)

Bulletin pick

Average S-wave
Repick – Bulletin
Time
0.02 seconds
2) Re-assess windowing for phase-specific correlation analysis

Station NB19 (near surface)

Updated S-wave window

Initial windowing of S-waves for waveform correlation-based differential time measurement included probable surface wave
3) Relocate using microBayesloc

Old locations

New Locations

Elevation [z, km]

East [x, km]

North [y, km]
3) Relocate using microBayesloc

Old locations

New Locations
What’s next: Langevin-Hastings for improved MCMC sampling

MCMC sampling is inefficient, potentially inaccurate, when differential times are used.

We are adapting the Langevin-Hastings approach to efficiently sample high-dimensional, correlated parameter spaces.

\[
\frac{d}{dx_i} \log p(\theta|a, d) = \sum_{j,k} \left( A_{ijk} \cdot \mu'_{ijk} + \sum_{i_p \in Q_{ijk}^2} D_{i_p ijk} \cdot \mu'_{ijk} - \sum_{i_q \in Q_{ijk}^1} D_{ii_q jk} \cdot \mu'_{ijk} \right)
\]
Summary

- LLNL supports the SubTER effort with microSeismic analysis, geomechanical modeling, and basic research.

- The microBayesloc method is a cornerstone of LLNL’s microSeismic analysis
  - Formulation of the joint probability function for multiple-event location
  - Event location probability volumes are representative of true error
  - Improvements to microBayesloc
    - Use of 3D velocity models of seismic wave speed
    - Joint use of differential and absolute arrival time measurements
    - Improved analysis of differential arrival time data sets (PageRank)
    - Improved efficiency of the microBayesloc MCMC algorithm
Thank You!