Title
Sensor Array Processing for Seismic Source Localization (SYS 23)

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Introduction: Source Localization Using Seismic Signals Collected with a Sensor Array

Seismic DOA Estimation / Source Localization
- Seismic Event Detection Via Sample Covariance Matrix
- Utilized Previously Published DOA Estimation Scheme Developed for Long-Range Seismic Data
  - Polarization analysis applied to short-range data
- Novel Short-Range Techniques for Seismic DOA Estimation
  - Surface Wave Analysis utilizes the unique characteristics of short-range seismic signal
- Novel Extension to Kirtin’s method for near-field DOA estimation
  - Utilizes noise equalization estimates of the covariance matrix for DOA estimation
- $L_1$ and $L_2$ Norm Optimization Techniques for Seismic Source Localization from Estimated DOAs

Results
- Even Detection Results
  - Bearing Estimates Results
    - Covariance Matrix Analysis results
    - Surface Wave Analysis results
    - Modified Kirtin Method results
- Source Localization using DOA estimates using $L_1$ and $L_2$ criterion

Problem Description: Locate a Source Generating Seismic Signals with Seismic Sensor Arrays

Garner Valley, CA Seismic Experiments
- Episensor tri-axial/bi-axial accelerometer sensors
- Accelerometers have wide frequency/amplitude ranges, and wide dynamic range
- Outputs of accelerometers are fed to the low power, high resolution Quanterra Q330s recording systems
- 9 sensor (6 tri-axial and 3 bi-axial), 8 of them on the perimeter of a 100 feet square, and the last one in the center

Proposed Solution: Event Detection, DOA Estimation, and Source Localization Via DOA Estimates

Seismic Event Detection
- Form sample covariance matrix from data of window length N at each sensor
- The size of the eigenvalues of the sample covariance matrix is a good indication of the presence of an event of interest
- The simple eigen-decomposition procedure can be performed on sliding time windows through the data record to find significance events of interest
- The largest eigenvalue of the covariance matrix corresponds to the average energy of the strongest seismic mode polarized in the direction of the corresponding eigenvector
- Take the eigenvector associated with the largest eigenvalue to be the estimated DOA
- The estimated DOAs have a 180-degree ambiguity

DOA Estimation via Surface Wave Analysis
- All motions in the vertical direction are due to Rayleigh wave
- The other component of Rayleigh wave and the direction of motion of the Love wave are perpendicular to each other, and are both in the ground plane
- Rayleigh wave exhibits an elliptical motion in the plane made up by the vertical direction (z) and the direction of propagation (p)
- The velocity in the vertical direction (z) and the acceleration in the direction of propagation (p) are in phase and proportional to each other
- The projection of the integral of the vertical (z) acceleration onto the ground plane defines the direction of propagation
- The estimated DOAs have no ambiguity

DOA Estimation via Modified Kirtin’s Method
- Signal-part covariance matrix according to signal model
  - $R_{xx} = \sum_{j=1}^{N} R_{x} R_{x}^{T}$
  - Estimate the signal-part covariance matrix with noise equalization of signal in the frequency domain
- Seismic Source Localization with DOA Estimates
  - $L_1$ norm formulation: Minimize the sum of distances between an arbitrary point to the estimated DOA line
  - $L_2$ norm formulation: Minimize the sum of squares of distances from an arbitrary point to the estimated DOA line
  - Weighted with the product of uncertainty in the $m^2$ estimated DOA and the distance between the arbitrary point and sensor $m$

Seismic Sensor Array Processing for Seismic Source Localization


<table>
<thead>
<tr>
<th>Source Localization Results</th>
<th>True CMA L1</th>
<th>CMA L2</th>
<th>SWA L1</th>
<th>SWA L2</th>
<th>MKM L1</th>
<th>MKM L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>X coordinate</td>
<td>22.9</td>
<td>25.3</td>
<td>26.0</td>
<td>24.6</td>
<td>24.8</td>
<td>24.5</td>
</tr>
<tr>
<td>Y coordinate</td>
<td>7.6</td>
<td>8.7</td>
<td>9.7</td>
<td>8.1</td>
<td>8.4</td>
<td>7.3</td>
</tr>
<tr>
<td>Abs. Err.</td>
<td>2.6</td>
<td>3.7</td>
<td>1.8</td>
<td>2.1</td>
<td>1.7</td>
<td>2.0</td>
</tr>
</tbody>
</table>