Detection of Seismic Events with Model-Based Signal-Processing

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UCRL-PRES-226177

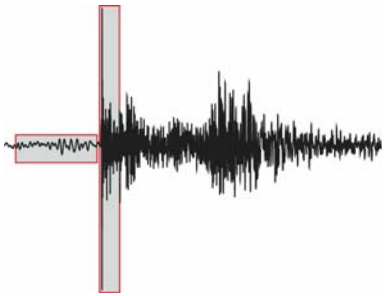
Acknowledgements

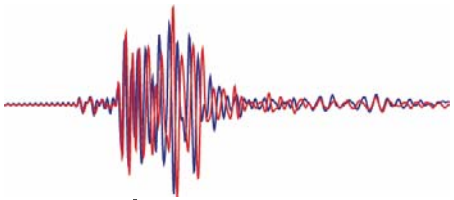
- Funded by LLNL Laboratory Science and Technology Office
  - Laboratory Directed Research and Development (LDRD) Program
  - Project 05-ERD-019, FY05-FY06
  - NAI/NHI Directorate

- Thanks to many others:
  - Tim Paik (summer student, developed subspace codes w/ D. Harris)
  - Sean Ford, Michael Thorne, Steve Myers, Steve Blair (E&ED)
  - JoAnne Levatin, Al Franz, Bob Matt, Kathleen McCandless (CAR)
  - Anders Petersson, Stefan Nilsson, Bjorn Sjogreen (CASC/WPP team)

Detectors for Seismology

- **Energy Detectors**
  - Incoherent Processing
  - e.g. short-term average/long-term average (STA/LTA)
  - Broadly applicable, conventional and widely used
  - However, these have high false-alarm rates when setting thresholds low to detect weak signals
  - *Don't know what you're detecting!*



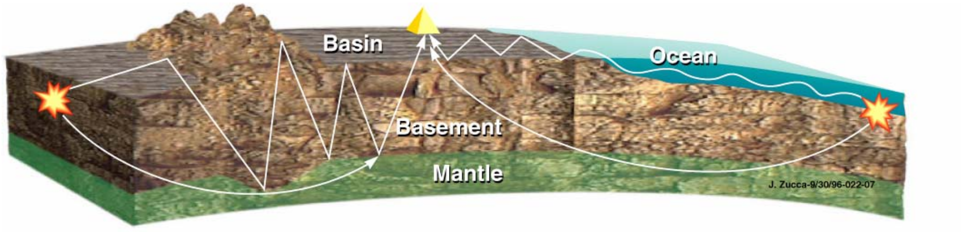


- **Correlation detector** (Match Filter)
  - Coherent Processing, uses temporal structure in the data to increase sensitivity
  - Is an optimal detector when one has perfect knowledge of the signal
  - Performance improved with multi-channel data
  - *Great for observing (~ exactly) repeated events!*
- Correlation detector computes running correlation coefficient between template signal and sliding window of continuous data
  - Detection declared when cc exceeds threshold value
    - Well-developed theory for trade-off between probability of detection at fixed false alarm rate under Gaussian stationary noise

The Challenges of Seismic Event Detection

- In seismic event detection signals are not perfectly known
  - Sources are very different
    - Location, depth, source mechanism, source-time function
  - Path-specific structure is unknown
    - Earth is heterogeneous on all length scales,
    - Causes scattering for high-frequencies

- These problems are compounded when trying to detect smaller events, e.g. nuclear explosion monitoring
  - Small events require proximity
  - Seismic background noise requires higher frequencies



Subspace Detectors for Seismology

- **Subspace detectors** span the gap between incoherent processing (e.g. STA/LTA) and correlation detection (match filter).

- Subspace detectors may match performance of correlation detectors when the desired signal is imperfectly known
  - Subspace defined by a set of linearly-independent basis signals
  - Subspace of dimension, $d \geq 1$, can be used to represent the variation of desired signals, i.e. "new signals"
  - Subspace detector projects each time window of continuous data onto the subspace template signals, computes correlation

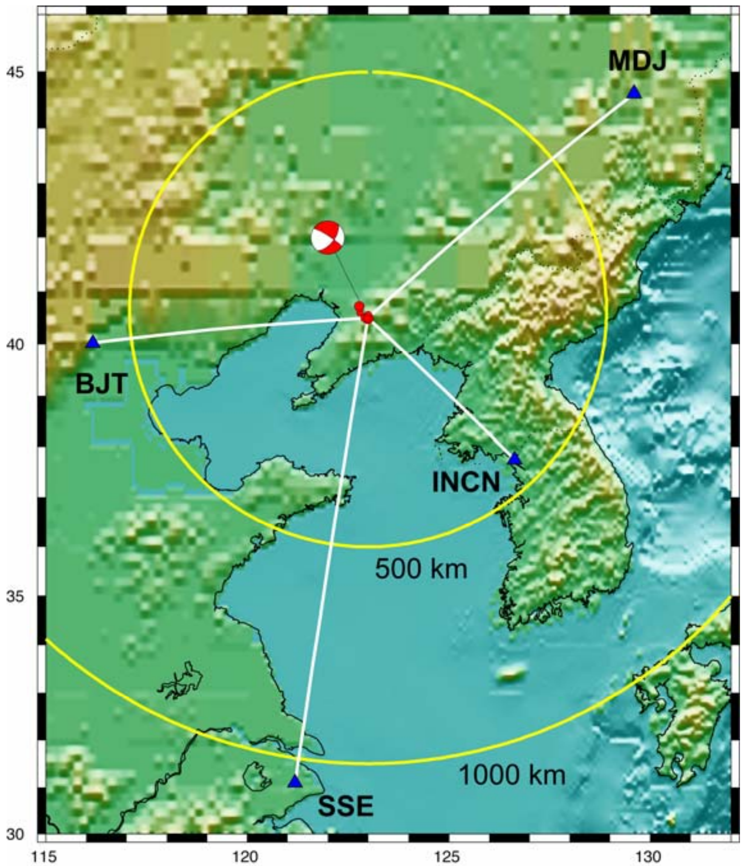
We're Proposing Model-Based Signal Processing for Seismic Monitoring

- Use subspace detection with model-based template signals
  - Does not rely on previous observations (waveform templates)
  - Possible to detect event(s) where no previous observations are available
  - Provides spot-light monitoring of a specific location and source
- Use stochastic geophysical (Earth) models
  - Addresses our ignorance of detailed Earth structure
  - Incorporates signal variability and uncertainty
- Template signals computed from simulations
  - Fully 3D calculations using HPC (expensive, low frequency)
  - 1D path-specific models (inexpensive, higher frequency)

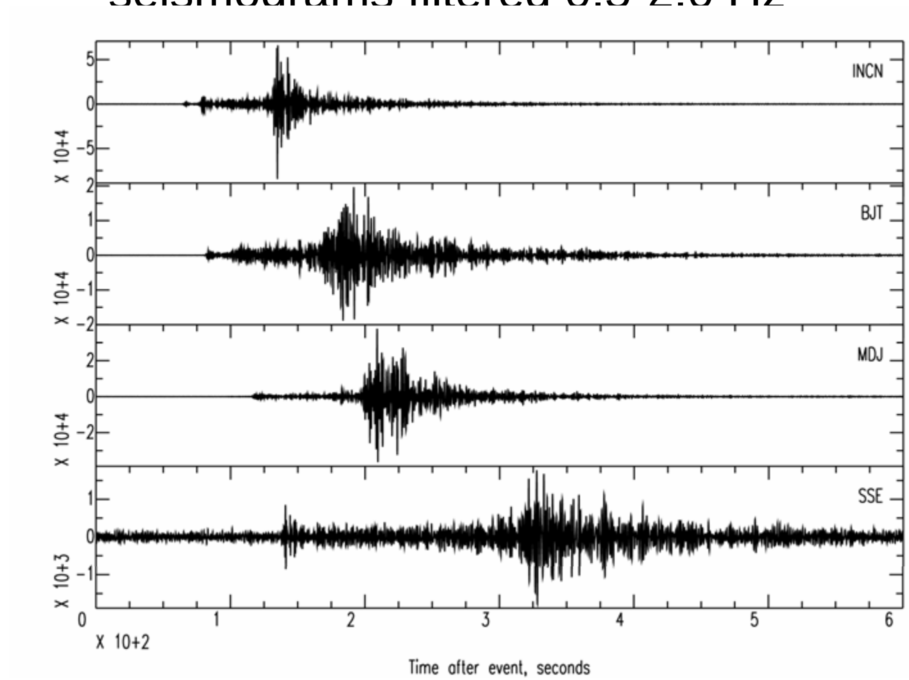
Target Earthquakes and Study Area

Jan 11, 2002 m_b 5.1 mainshock
Located near China-North Korea border

Several aftershocks m_b 3.1-4.4



Vertical component displacement
seismograms filtered 0.5-2.0 Hz



INCN
460 km

BJT
583 km

MDJ
709 km

SSE
1056 km

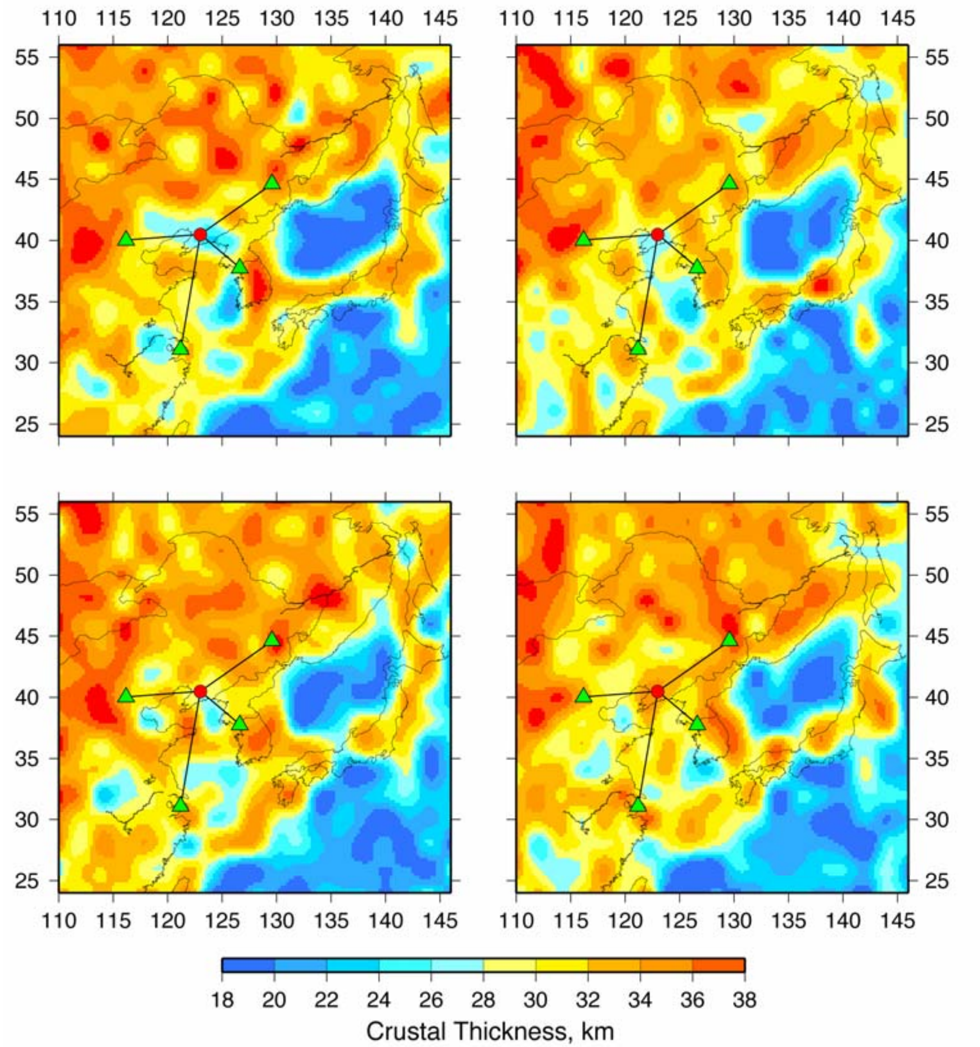
Stochastic Geophysical Models for the Korean Peninsula and Surrounding Region

Models estimated with the Markov Chain Monte Carlo (MCMC)
- uses Stochastic Engine
- computationally intensive
- reconciles multiple data sets

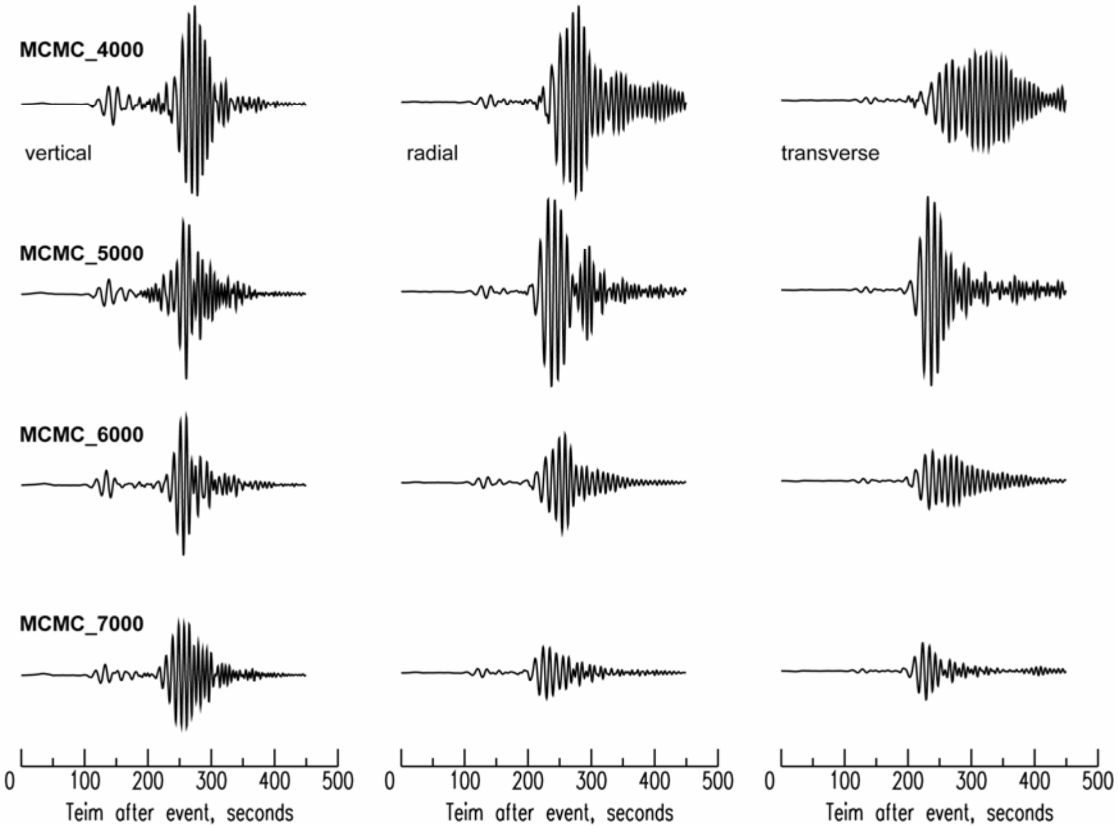
Results in suite of models
- provides improved uncertainties
- non-Gaussian statistics

Models derived from:
- surface wave dispersion
- travel times
- receiver functions
- gravity

Different MCMC Models



3D Synthetic Seismogram Calculations Run Using WPP Code on LC

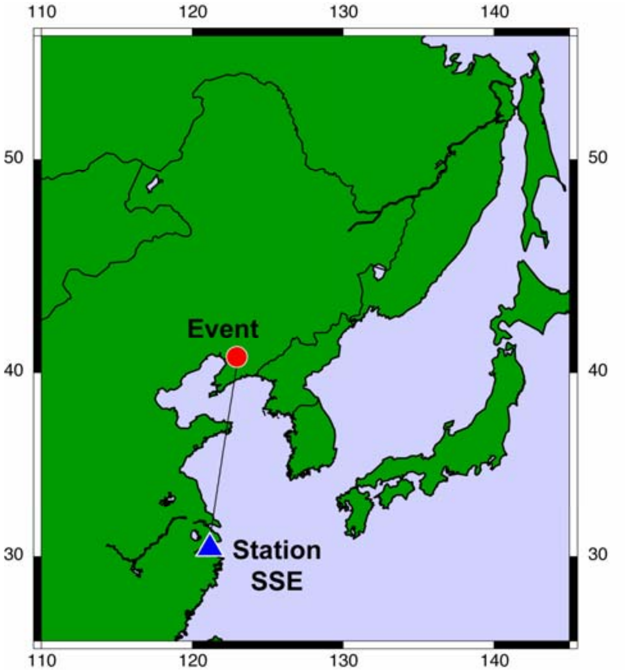


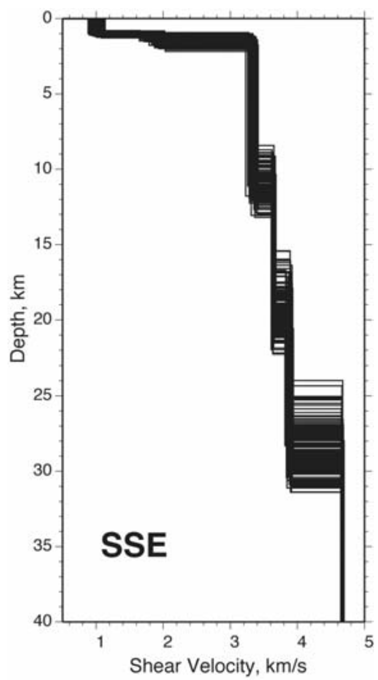
Synthetics computed with WPP code on MCR

Station BJT
Domain: 750 x 350 x 40 km
h = 250 m
over 0.67 billion points

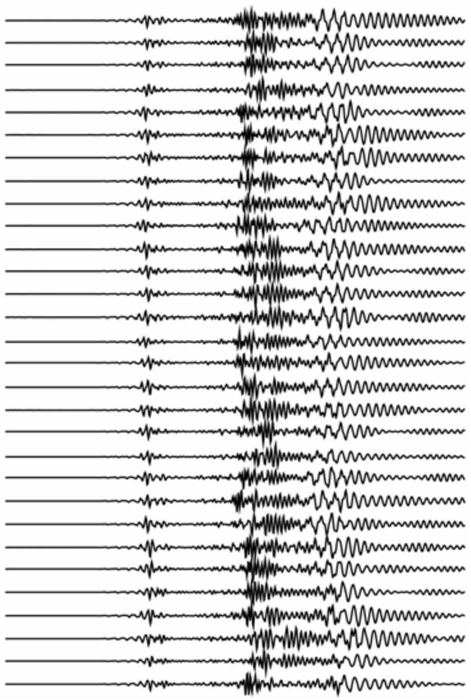
Signal variability generated by model heterogeneity.
Synthetics are valid 0.0-0.2 Hz.
However, these frequencies are difficult to observe for small (M<4.0) events.
Need to increase frequency and bandwidth!

Path-Averaged 1D Models Are Computationally Very Efficient





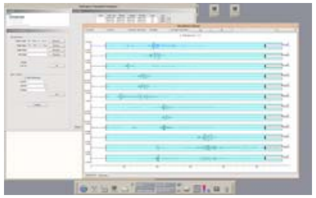
Model-Based Templates Filtered 0.1-0.5 Hz

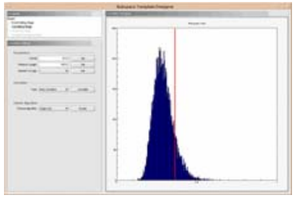


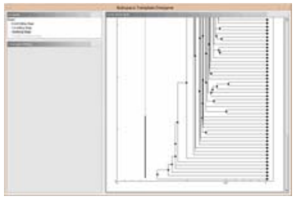
- 1D path-averaged structure extracted from 150 models
- 1D synthetic seismograms calculations are very efficient
- **Can compute to higher frequency (1.0 Hz)**

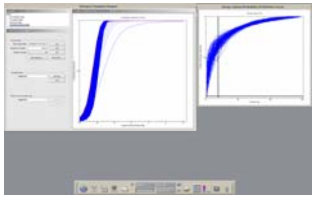
Subspace Detector Design and Processing

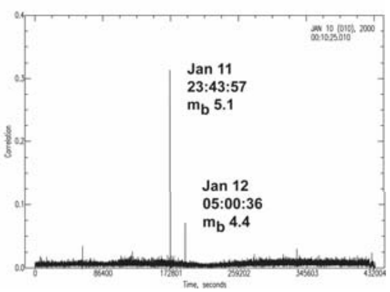
- Model-based signals are filtered and windowed
  - Formed into vectors in channel-sequential order
- Compute pair-wise waveform correlations
  - Define clusters with single-link algorithm
  - Define optimal alignment of signals
- Form the matrix of template basis signals
  - Decompose into eigenvectors & eigenvalues by SVD
  - Compute the energy capture
  - Determine the dimension of the subspace
    - Subset of orthonormal basis signals
- Process data stream with the subspace detector
  - Project data onto subspace signals
  - Compute detection statistic





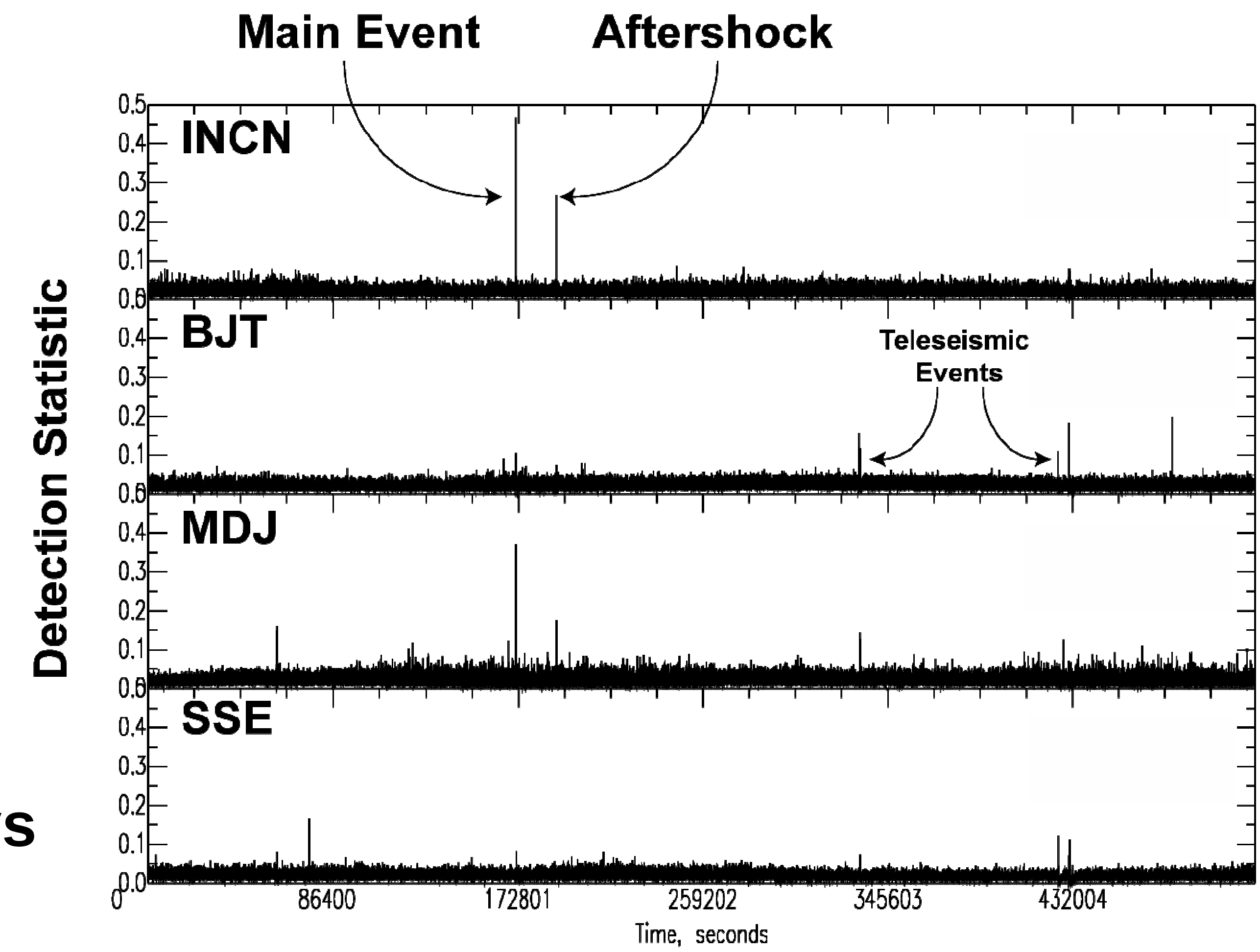






Performance For Single Stations

Subspace detector for each station detects main event and smaller aftershock **in some cases.**



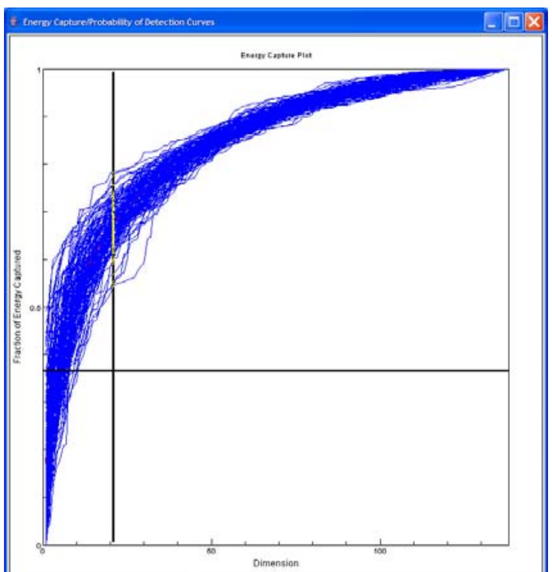
6 days

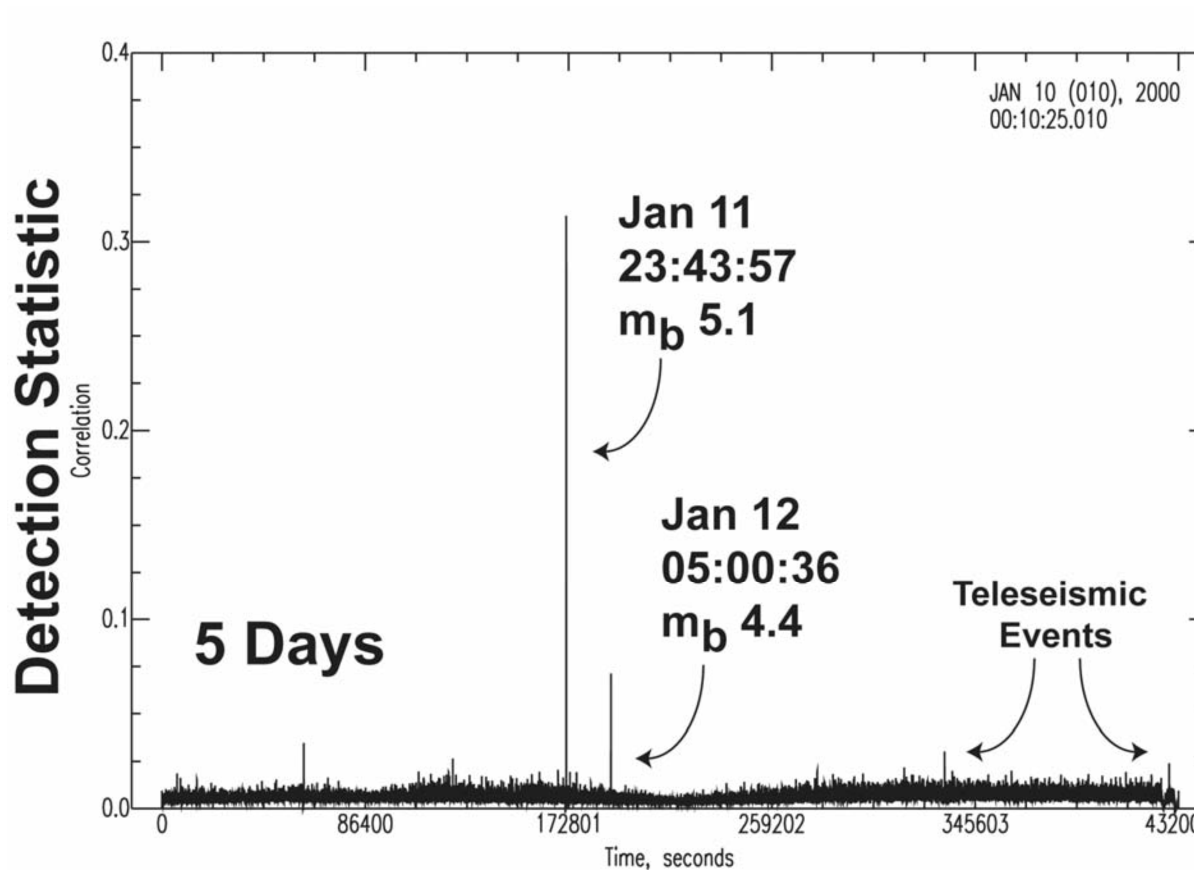
Results For Four Station Network

Subspace detector with 4 station network detects main event and smaller aftershock and lowers background.

dimension = 20

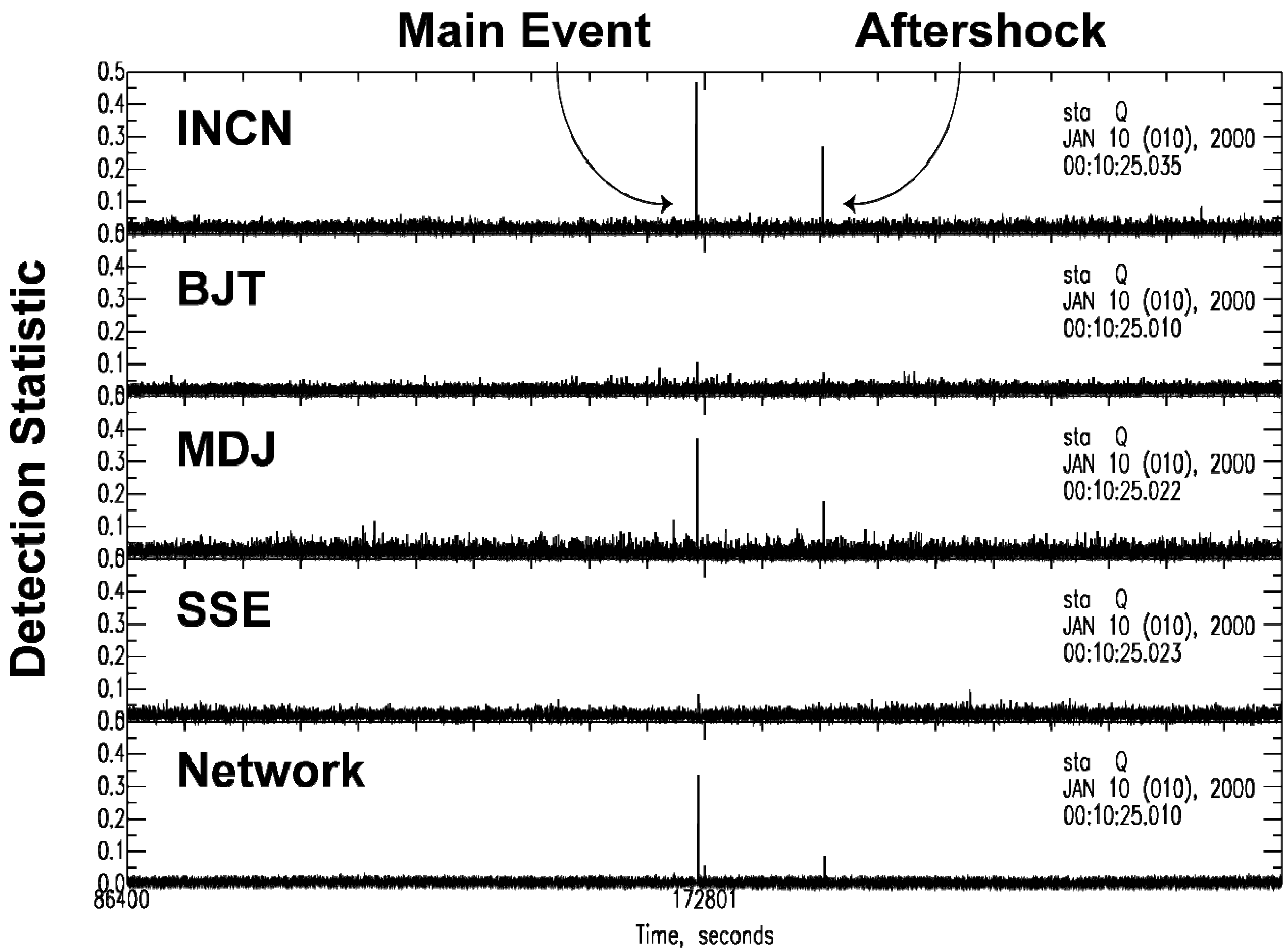
Energy Capture





Network vs. Single Station Performance

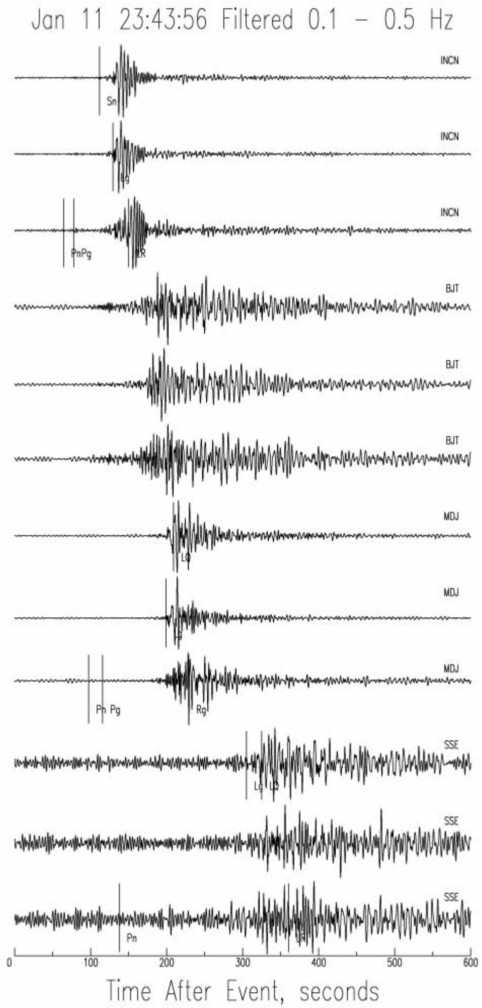
Network detection shows high correlation at the expected times, lowers background correlation values and reduces spurious correlations

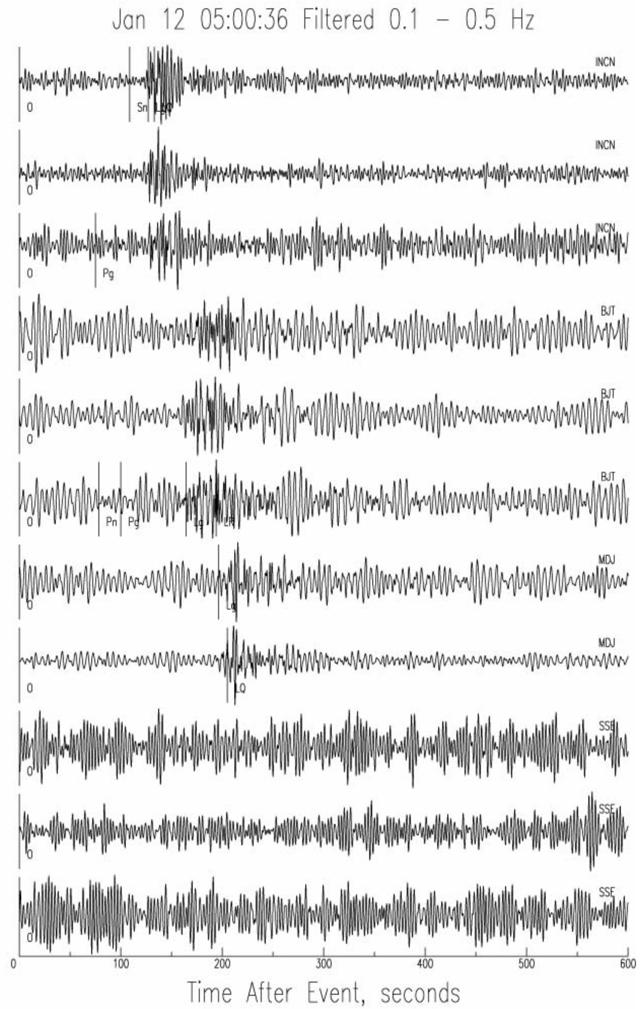


2 days

MBSP Detection Works With Low SNR

Main event, m_b 5.1 **Aftershock, m_b 4.4**





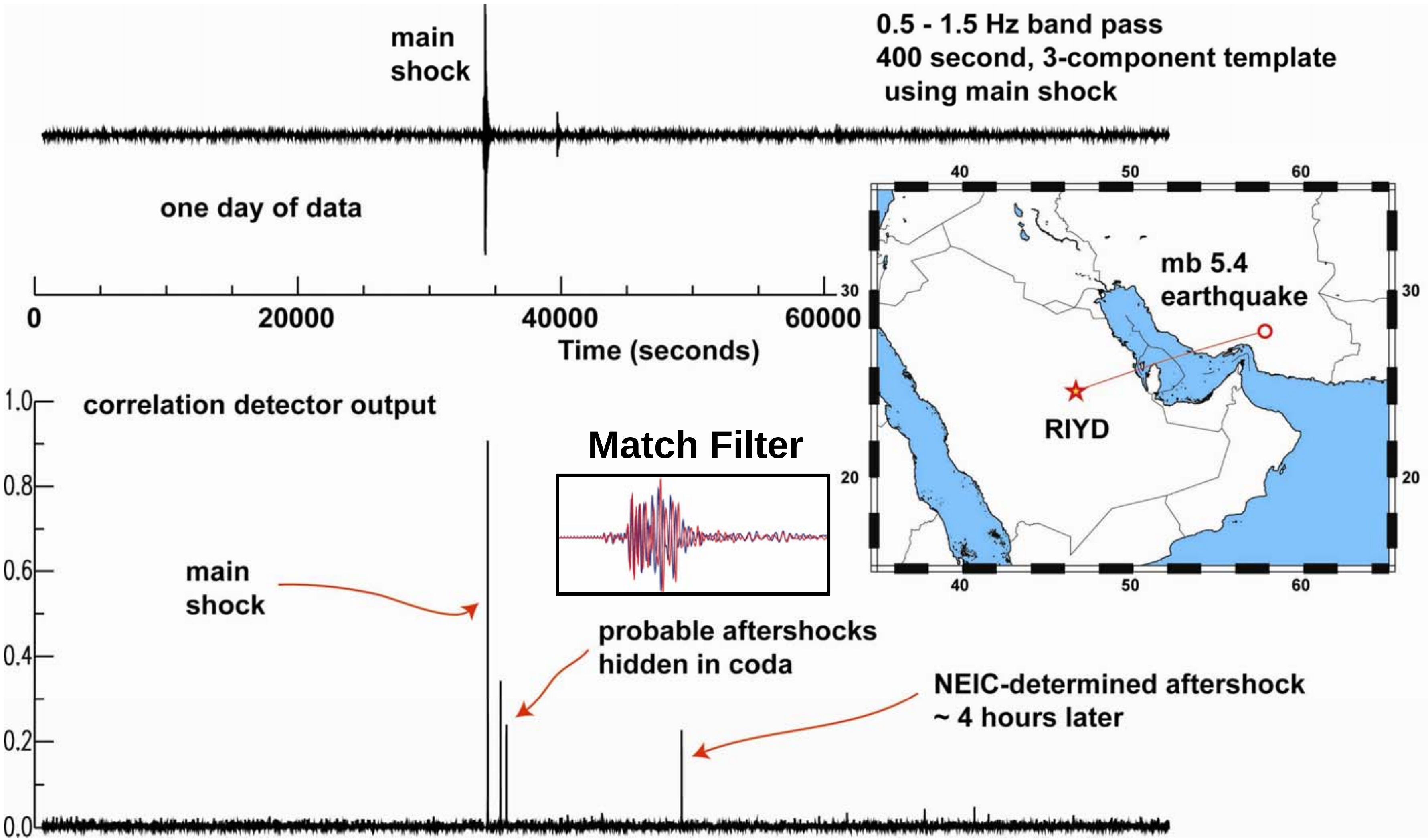
Much Lower SNR!

Summary

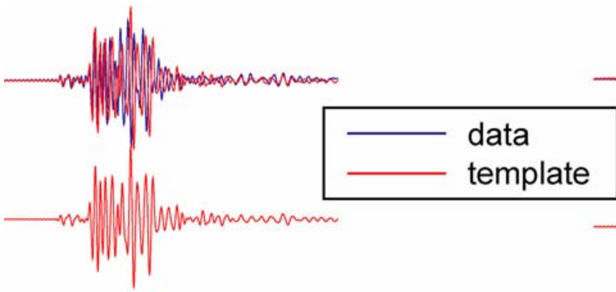
- Model-Based Signal Processing is feasible for detecting seismic events
- MBSP with a network improves detection performance over single stations
  - Improves correlation for target events
  - Lowers correlation values for events not of interest
  - Can apply to network of any size
- Use of model-based templates can improve detection capability where no previous seismic events have been recorded.
  - Offers coverage of aseismic regions (few or no events)
  - May provide detection capability for previously unobserved events
- Correlation methods provide other information because signals are strongly dependent on location and source type.
  - Location, path-dependent propagation
  - Identification by depth and source mechanism
- Future Work
  - Increase frequency content to detect smaller events
  - Investigate event identification power

EXTRA SLIDES

Correlation Detection Uses the Entire Waveform



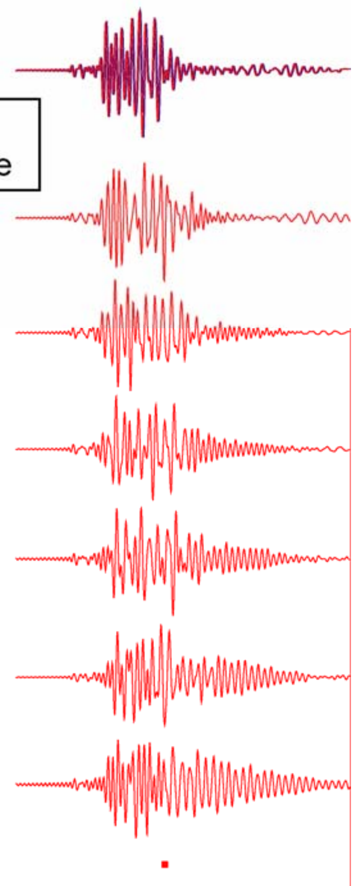
Coherent Processing Takes Advantage of Signal Correlation & Lowers Thresholds



MATCH FILTER

One-Dimensional Correlation Detector exploits correlation between event and a *single template*

Able to detect re-occurrence of an event.



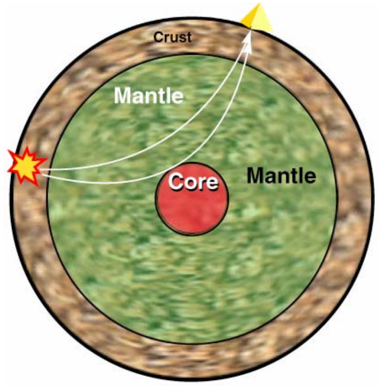
SUBSPACE DETECTOR

Multi-Dimensional Correlation Detector expresses event as an optimal linear combination of *several templates*.

Uses variability in waveforms from "similar" events to find best correlation and detect event

Conventionally, correlation detection uses empirical (observed) waveform templates

Current and Emerging Monitoring Requires Lower Yield Thresholds

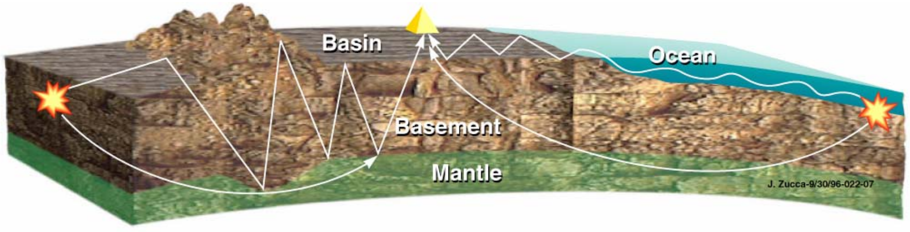


PAST
Teleseismic Monitoring

Long-range (>2000 km) large yield explosions at known test sites

CURRENT and FUTURE
Regional Monitoring (< 2000km)

Lower yield explosions at unknown, proliferating nuclear states.

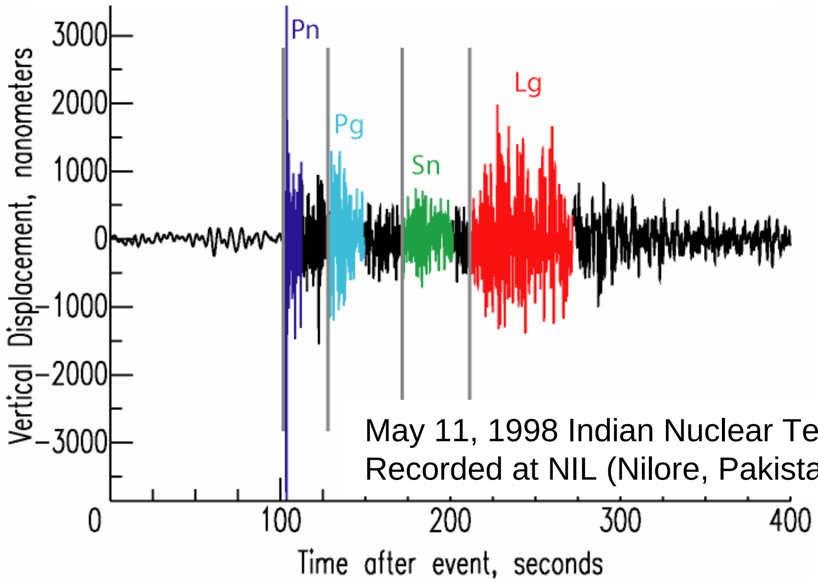


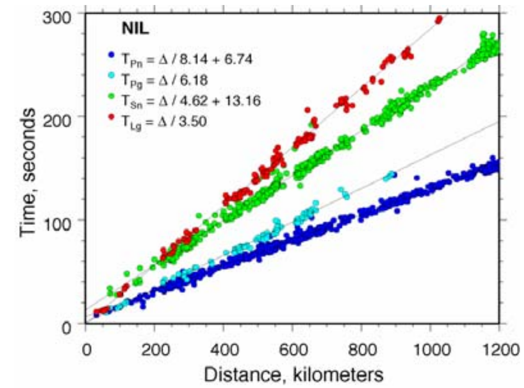
Current and Future Requirements:
- Lower detection, location and identification thresholds & improve confidence
- Monitor broad regions of interest
- Predictions of signals where no previous observations exist

Challenges of Regional Monitoring:
- Impact of crustal heterogeneity
- Requires region-specific calibration
- Low-frequencies poorly excited
- Need to use higher frequencies

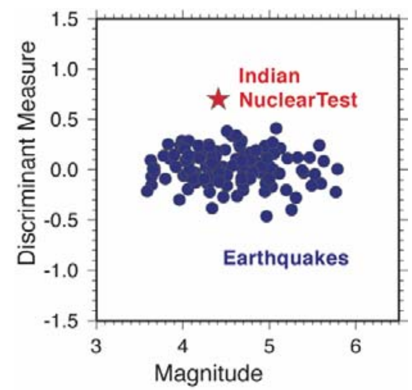
Current Practice Relies on Incoherent Processing

Detection by identifying increase of energy over background - **requires signal-to-noise ratio (SNR) > 2:1**





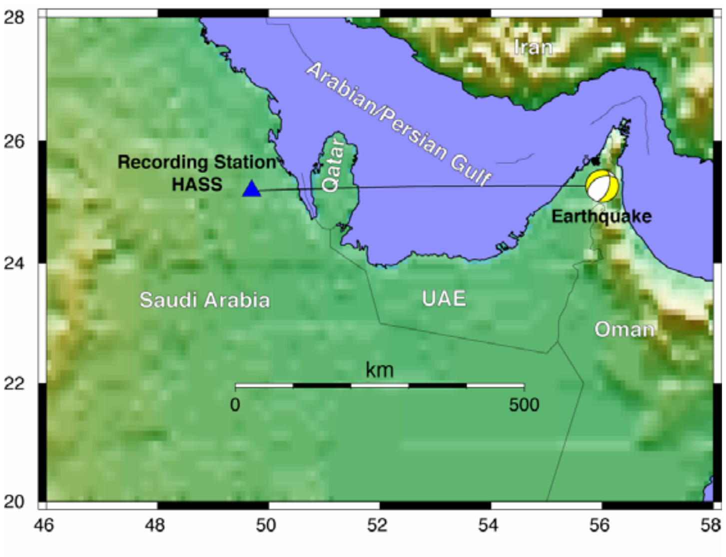
Arrival times are used to estimate velocity profile and locate events

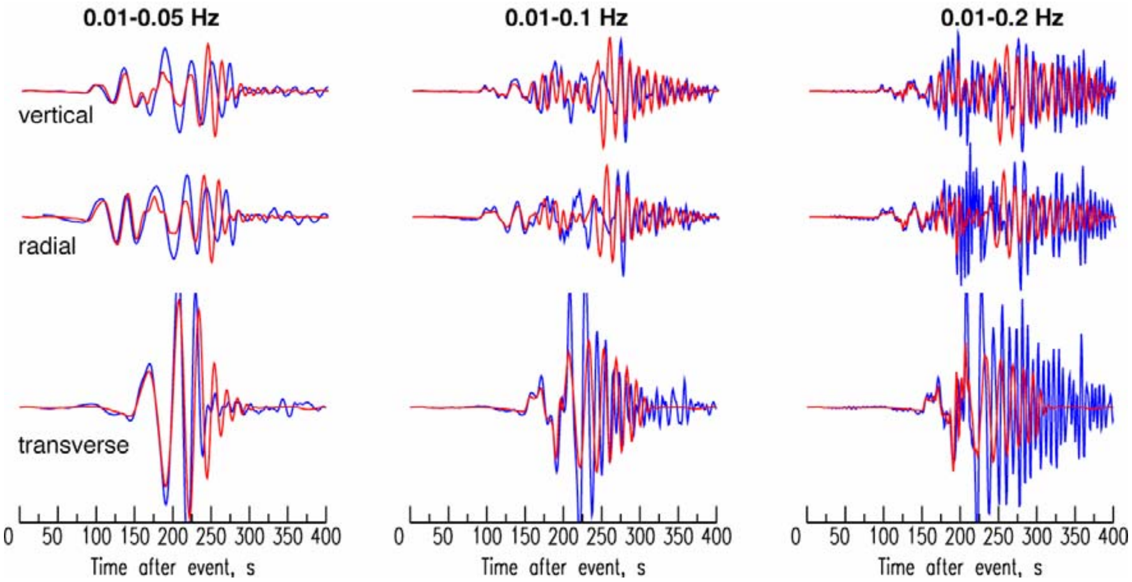


Amplitudes used to form discriminants to identify explosions and earthquakes

We Can Model Low-Frequency Seismic Waves, However Higher-Frequencies Are A Challenge

A regional earthquake





Observed seismograms (blue) and a 1D model (red)

3D models can improve fits, however, for frequencies above about 0.1 Hz we need to specify heterogeneity on scale-lengths of 100 km and smaller.