Bayesian Inference for Signal-Based Seismic Monitoring

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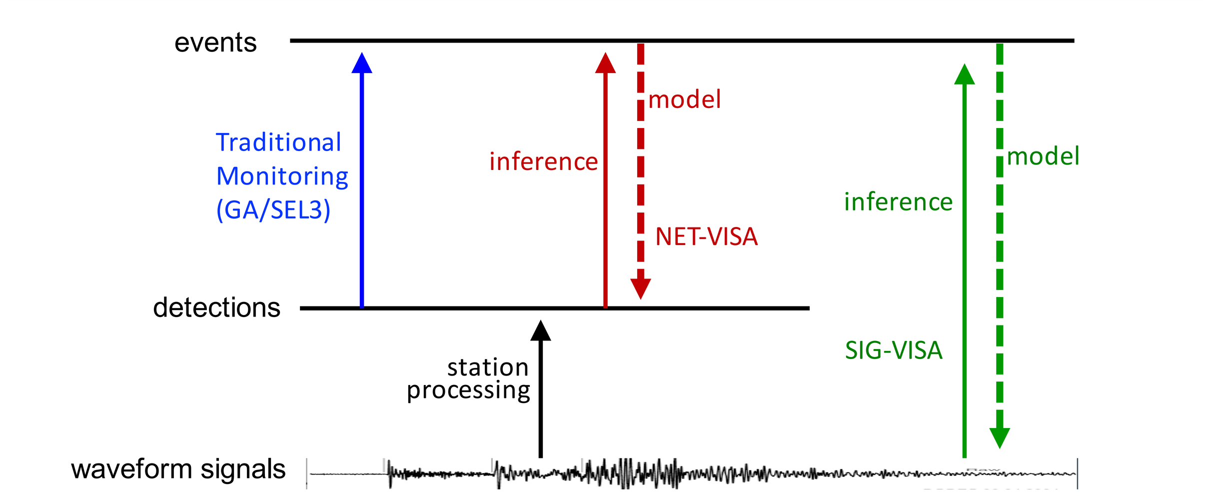
Overview

- Traditional monitoring systems relying on station processing **discard significant information** present in the original recorded signal.
- SIG-VISA (Signal-based Vertically Integrated Seismic Analysis) is a **system for global seismic monitoring** through Bayesian inference directly on observed signals, incorporating a rich representation of the physics underlying the signal generation process.
- Bayesian inference **correctly combines** statistical evidence from travel times and signal correlations, providing a unified approach to that encompasses promising recent techniques such as waveform matching and double differencing.
- We are making progress in scaling up the required computations to be **tractable for large-scale global monitoring**.

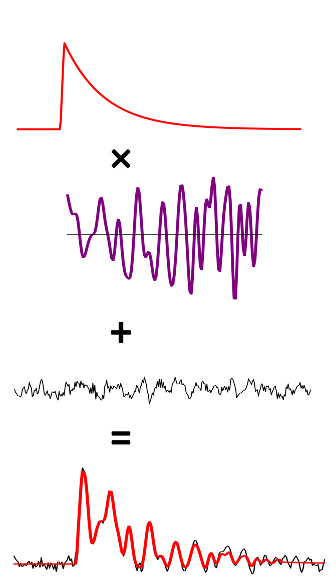
Signal-Based Monitoring



Bayesian monitoring with a generative model of seismic signals:
P_θ(world) describes prior probability for what *is* (*events*)
P_ϕ(signal | world) describes forward model (propagation, measurement, etc.)
Detection-based Bayesian monitoring:
P(world | *f* (signal)) ∝ P_ϕ(*f* (signal) | world) P_θ(world)
where *f* (signal) = set of all detections
Signal-based Bayesian monitoring:
P(world | signal) ∝ P_ϕ(signal | world) P_θ(world)

Generative Signal Model

The SIG-VISA signal model defines a probability distribution over observed signals, incorporating the event bulletin and a parameterized envelope template as *latent* variables that act through physical and statistical processes to generate the observed signals.



Envelope template: depends on event location, depth, magnitude, phase.

Repeatable modulation: related to Green's function. Wavelet coefs depends on event location, depth, phase.

Background noise: autoregressive process at each station.

Observed envelope: sum of all arriving phases, plus background noise.

Unifying Monitoring as Bayesian Inversion

Existing monitoring and location techniques can be viewed as inverting individual aspects of the underlying physics.

Physical phenomenon	when inverted, yields	Modeled in SIG-VISA
Predictable travel times (1D)	Traditional pick-based monitoring	IASPEI 91 travel time model
Spatial continuity of waveforms	Waveform matching / cross-correlation methods for sub-threshold detections	Gaussian process (kriging) model of wavelet coefficients describing signal modulation
Spatial continuity of travel-time residuals	Double-differencing	Gaussian process model of travel-time residuals
Other predictable regularities (attenuation, coda decay rates, spectral content, etc.)	*Not exploited by existing techniques*	GP models of envelope shape parameters, Brune and Mueller-Murphy source models

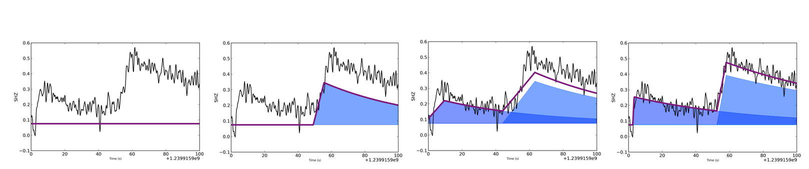
By combining all of these phenomena into a single forward model, inverted using Bayesian inference, SIG-VISA unifies and extends existing techniques within a single system, exploiting waveform correlations and historical data where available while gracefully reverting to travel-time-based inference for de novo events.

Inference

The generative signal model fully specifies the posterior distribution P(world | signal) from a mathematical standpoint. In practice, sampling from this distribution is computationally difficult. Designing tractable inference algorithms is an important and ongoing component of the project.

SIG-VISA uses the framework of Markov Chain Monte Carlo (MCMC) to sample from the posterior distribution over event hypotheses conditioned on observed signals. Move types include:

- **Template parameter moves** modify the shape parameters describing a envelope template.
- **Event attribute moves** modify the location, depth, time, and magnitude of an event hypothesis to better fit the templates associated with that event at stations across the network.
- **Template birth/death/split/merge moves** create and destroy shape templates to explain fluctuations the observed signals. New templates are proposed with probability proportional to the height of the observed envelope, minus envelopes from all current templates.

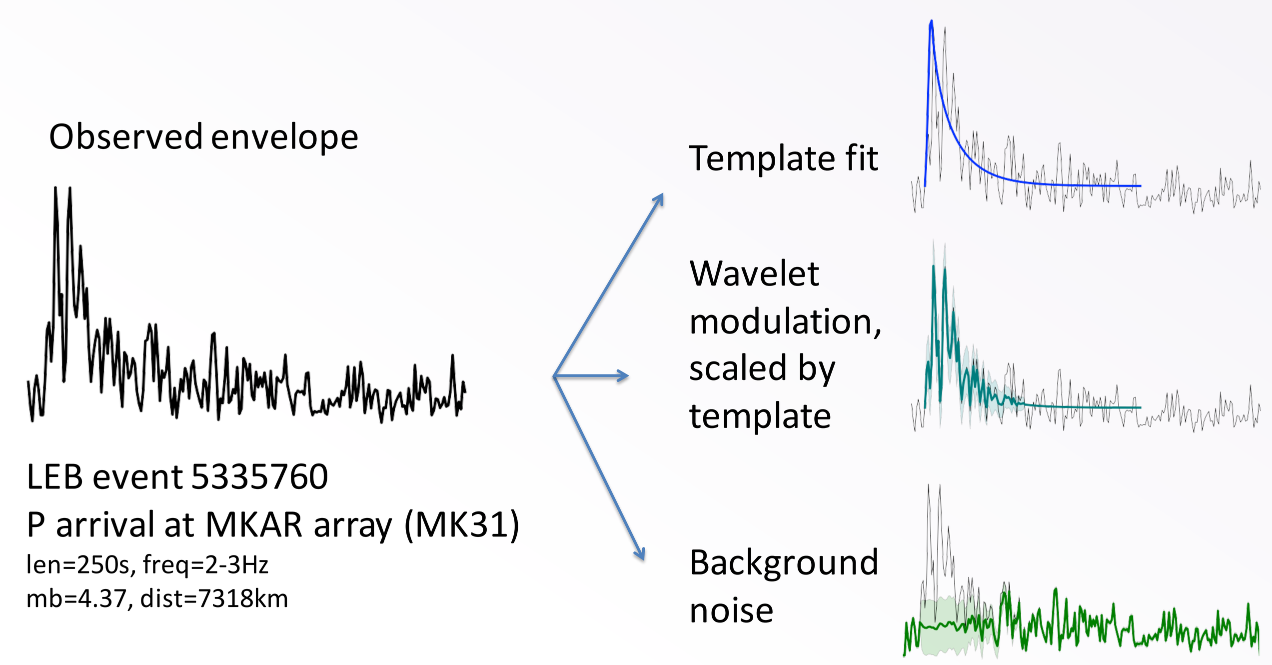


Example of template birth moves finding an explanation for an observed signal. The final frame shows the result after several additional template parameter moves.

- **Event birth/death moves** propose new hypothesized events to explain unassociated templates.
  - Event locations are proposed by Hough transform, using a 3D (lon, lat, time) accumulator array.
  - Weights of accumulator bins are sums of "votes" from all current unassociated templates; each template votes for all bins in its backprojected space-time cone.
  - Additional proposal mechanism based on historical waveform data (see *Bayesian cross-correlation*, right)

Signal Decomposition

Visualizing the internal representation of the model allows us to decompose an observed signal into a base shape, repeatable waveform structure, and non-repeatable background noise.

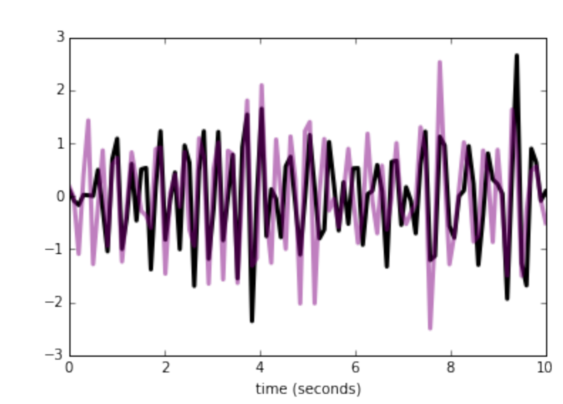


Bayesian Cross-Correlation

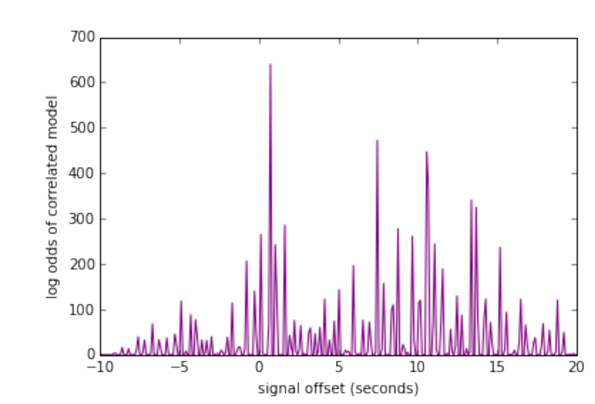
By explicitly modeling station background noise as an AR process, we derive a new, easily computed statistic that resembles cross-correlation but can be formally interpreted as a posterior probability.

$$\mathrm{xc}(\mathbf{a},\mathbf{b}) = \frac{\mathbf{a}^T\mathbf{b}}{\|\mathbf{a}\|\|\mathbf{b}\|} \qquad \log\frac{p(\mathbf{b}|\text{noise}+\mathbf{a})}{p(\mathbf{b}|\text{noise})} = \frac{(\mathbf{a}^T R^{-1}\mathbf{b})^2}{\mathbf{a}^T R^{-1}\mathbf{a}}$$

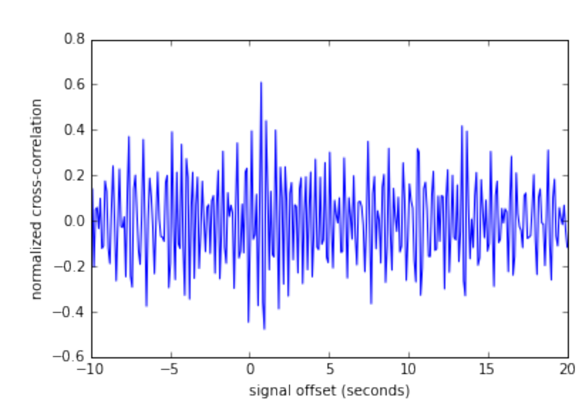
(for autoregressive noise process R)



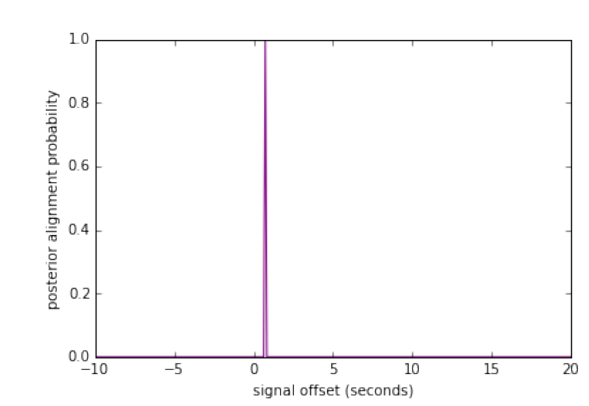
Correlated waveforms of doublet events



Log odds of candidate offsets under Bayesian cross-correlation



Normalized cross-correlation



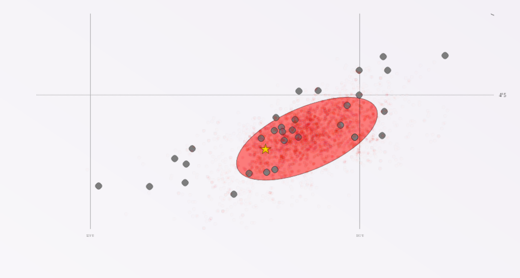
Bayesian alignment posterior

We use this statistic to compute proposal probabilities for historical events (see next pane), but it may have applications more generally as a drop-in replacement wherever normalized cross-correlation is used.

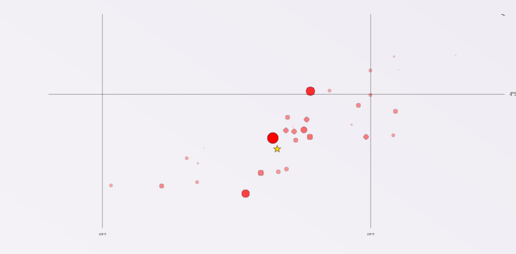
Locations from Waveform Correlation

Combining travel-time information with waveform correlations provides more precise location estimates.

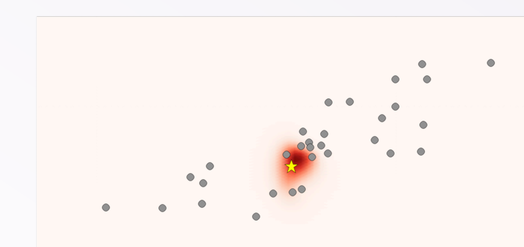
Locating held-out doublet (gold star) from aftershock sequence of Banda Sea event (mb 5.0, April 20 2009):



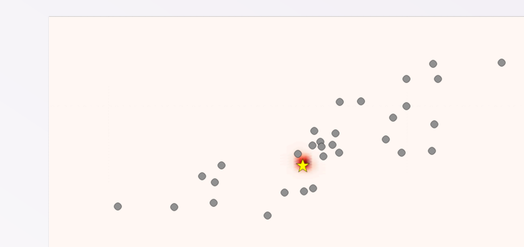
Posterior from travel-time-based model (12 3-component stations)



Log probabilities of MCMC proposal distribution, using Bayesian correlation at MKAR



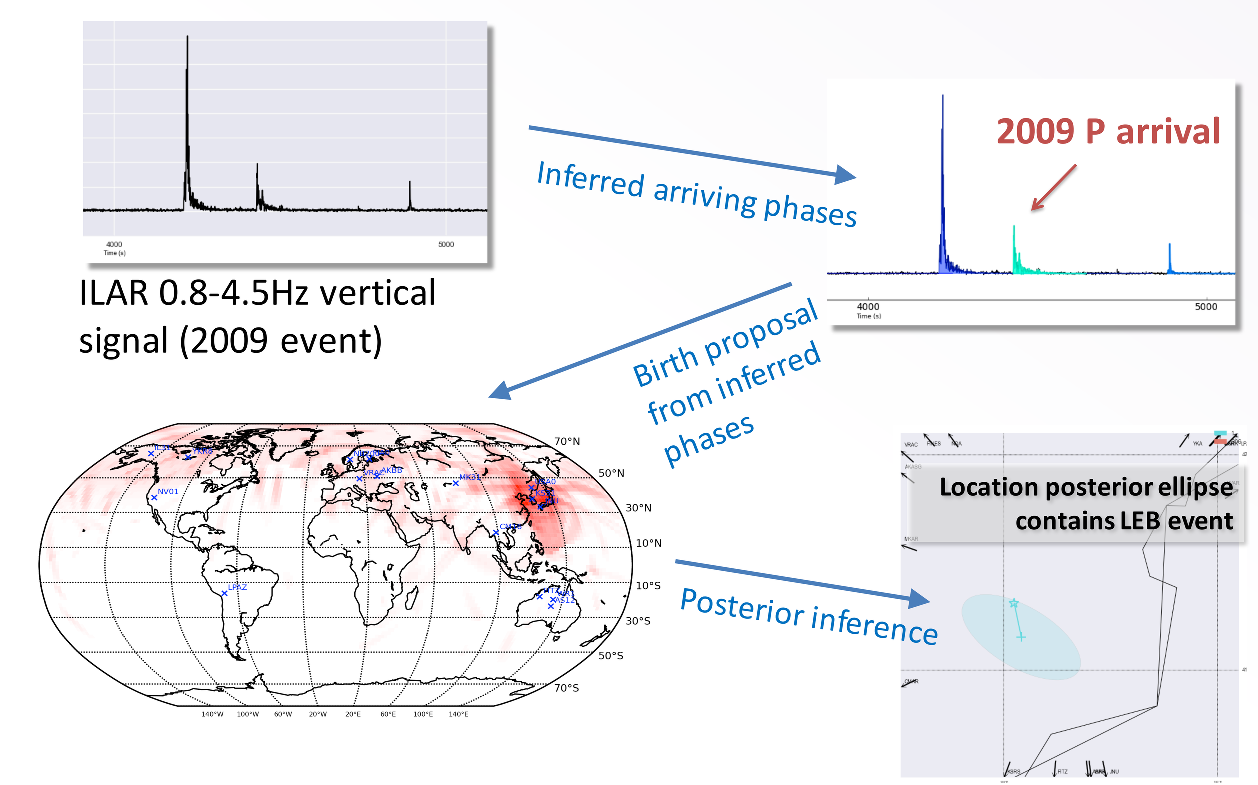
SIG-VISA posterior conditioned on waveform at MKAR



SIG-VISA posterior conditioned on waveforms from MKAR, CMAR, ASAR, FITZ

Detections of DPRK Events

Simplified SIGVISA model *detects and locates* all confirmed DPRK tests (2006, 2009, 2013), by automated processing on vertical channels at 15 three-component stations.



In progress: Bayesian analysis of purported 2010 DPRK test using waveform correlations from IMS and regional stations.

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