Sandia National Laboratories

REFINEMENT AND TESTING OF THE PROBABILISTIC EVENT DETECTION, ASSOCIATION, AND LOCATION ALGORITHM

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National Nuclear Security Administration

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PEDAL (Probabilistic Event Detection, Association, and Location)

Key to accurate event location is comparing the differences in observations at various monitoring stations, s, with expectations of those same observations given an event occurring at a particular source location ω. In addition, the relative patterns seen between stations are characteristic of signals coming from that source location. A set of observables readily available from IDC database tables (arrival time, T, horizontal slowness, sh, azimuth, az), and their corresponding measurement uncertainties (*deltim*, *delaz*, and *delslo*) are used to establish historical expectations and prediction uncertainties (ε_t, ε_{az}, and ε_{sh}) for events originating in seismically active areas. Modeling is used to establish expectations for aseismic areas as well as grid tolerances to ensure that events don't get missed between grid nodes.

Spatial Fitness using Pairs of Arrivals (Parallelizable Computation) on a uniform Earth grid, including depth in seismic areas

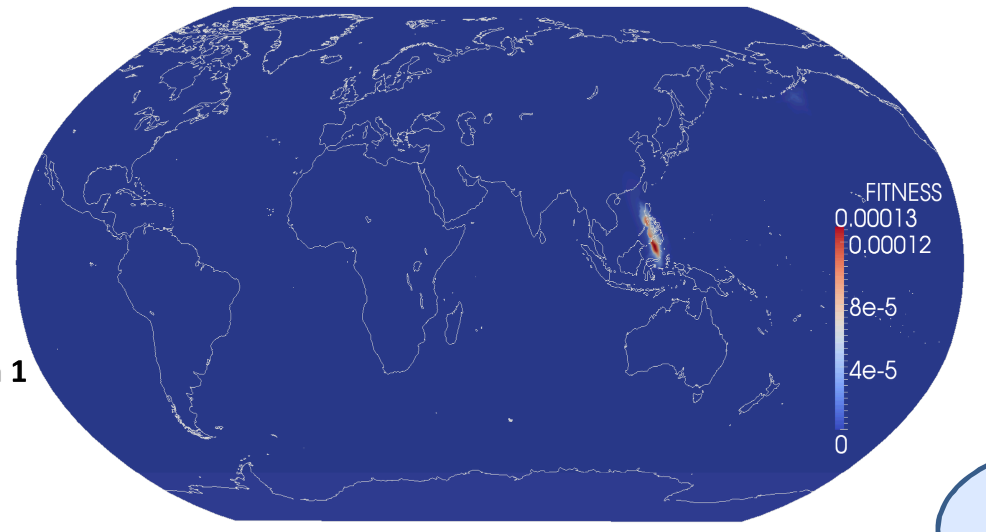
$$\mathrm{P}(\mathrm{O}_\omega)\sum_{i=1}^{NA-1}\sum_{j=2}^{NA}\mathrm{P}(\mathrm{d}_{s_i}\mid \mathrm{O}_\omega)\mathrm{P}(\mathrm{d}_{s_j}\mid \mathrm{O}_\omega)w_{ij}e^{-r_{ij}^2}$$

where N_A = number of arrivals, p = predicted value, ε = uncertainty of the predicted value, $\mathrm{P}(\mathrm{d}_{s_i}|\mathrm{O}_\omega)$ = probability of station s_i detecting a first-P phase, given an event at location ω, and

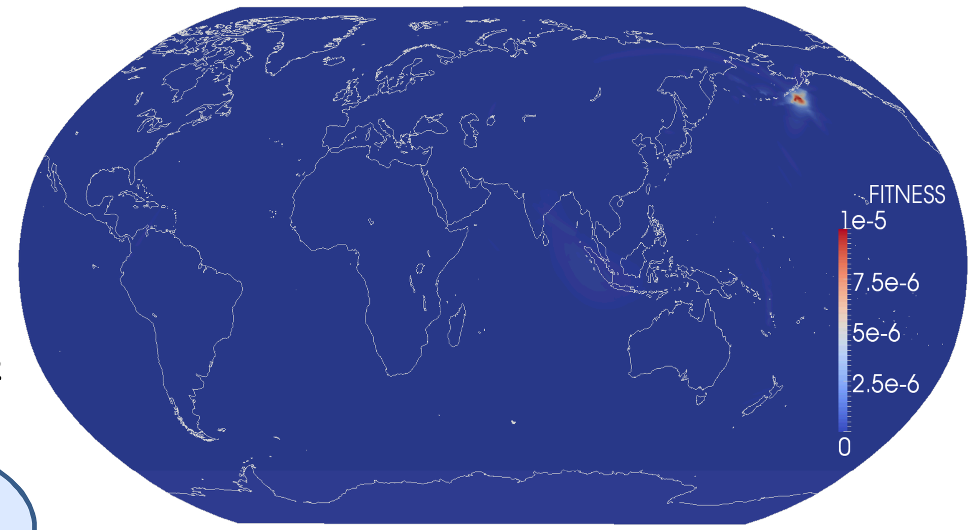
$$w_{i,j}=\frac{\sqrt{2}/_3\,N_t}{\left(\sigma_{tt,i}^2+\sigma_{tt,j}^2\right)^{1/2}}+\frac{1/_6\,N_{az}}{\sigma_{az,i}}+\frac{1/_6\,N_{az}}{\sigma_{az,j}}+\frac{1/_6\,N_{sh}}{\sigma_{sh,i}}+\frac{1/_6\,N_{sh}}{\sigma_{sh,j}},\quad r_{i,j}^2=\frac{([T_i-T_j]-[p_{tt,i}-p_{tt,j}])^2}{\sigma_{tt,i}^2+\sigma_{tt,j}^2}+\frac{(az_i-p_{az,i})^2}{\sigma_{az,i}^2}+\frac{(az_j-p_{az,j})^2}{\sigma_{az,j}^2}+\frac{(sh_i-p_{sh,i})^2}{\sigma_{sh,i}^2}+\frac{(sh_j-p_{sh,j})^2}{\sigma_{sh,j}^2}$$

Uncertainties: **Travel Time** $\sigma_{tt,i}^2=\varepsilon_{T,obs,i}^2+\varepsilon_{tt,pred,i}^2+\varepsilon_{tt,grid,i}^2$ **Azimuth** $\sigma_{az,i}^2=\varepsilon_{az,obs,i}^2+\varepsilon_{az,pred,i}^2+\varepsilon_{az,grid,i}^2$ **Slowness** $\sigma_{sh,i}^2=\varepsilon_{sh,obs,i}^2+\varepsilon_{sh,pred,i}^2+\varepsilon_{sh,grid,i}^2$

Spatial Fitness Map Iteration 1

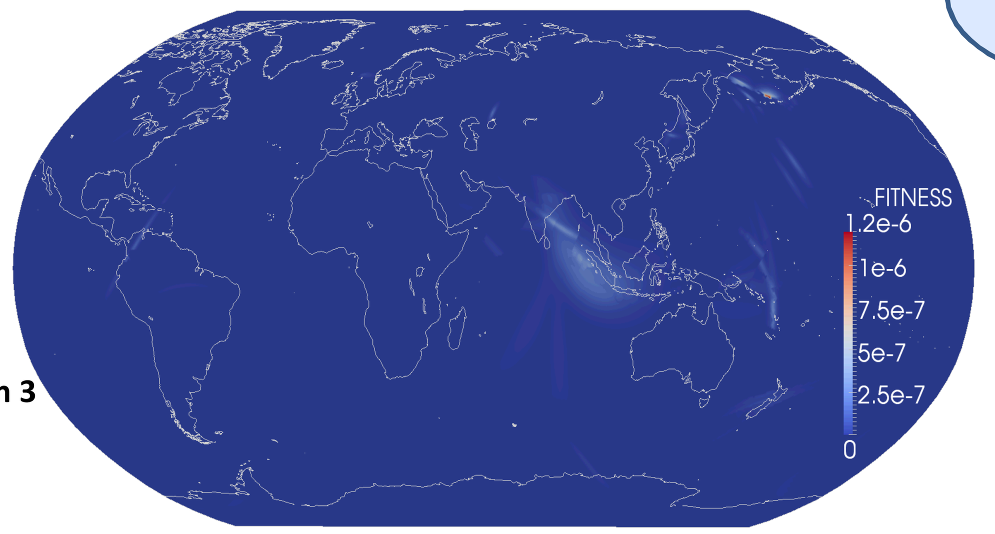


Spatial Fitness Map Iteration 2

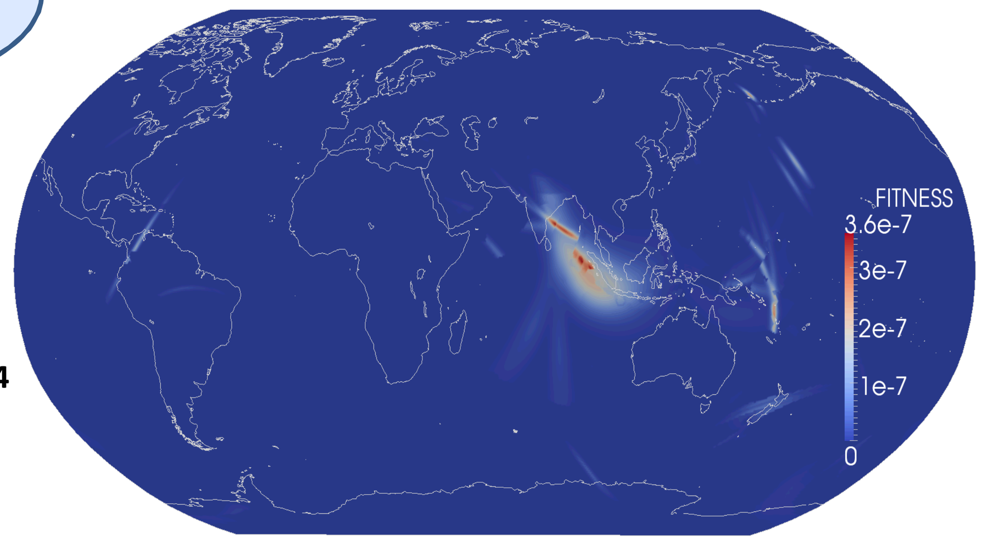


427,265 nodes for ½° Earth grid

Spatial Fitness Map Iteration 3



Spatial Fitness Map Iteration 4

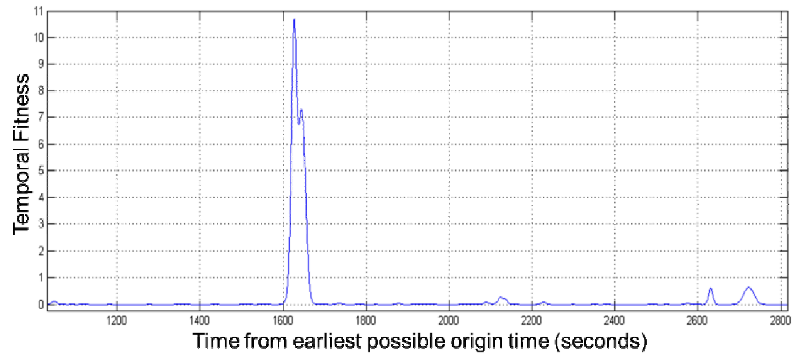


Origin Time Fitness

Once peak grid location ω has been found, the next step is to search the time axis for an origin time, T_o, with maximum temporal fitness.

$$\sum_{i=1}^{N_A}\mathrm{P}\left(\mathrm{d}_{s_i}\mid \mathrm{O}_\omega\right)w_i\exp\left[-\frac{\left((T_i-T_O)-p_{t,s_i,\omega}\right)^2}{\varepsilon_{t,s_i,\omega}^2+deltim_i^2}-\frac{\left(az_i-p_{az,s_i,\omega}\right)^2}{\varepsilon_{az,s_i,\omega}^2+delaz_i^2}-\frac{\left(sh_i-p_{sh,s_i,\omega}\right)^2}{\varepsilon_{sh,s_i,\omega}^2+delslo_i^2}\right]$$

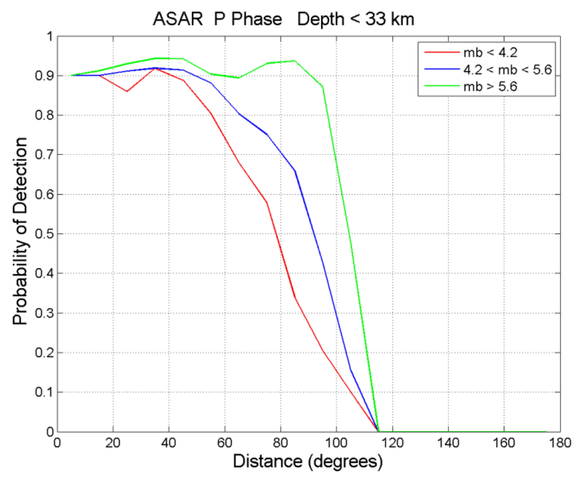
where $w_i=\frac{1/_3\,N_t}{\sigma_{tt,i}^2}+\frac{1/_3\,N_{az}}{\sigma_{az,i}}+\frac{1/_3\,N_{sh}}{\sigma_{sh,i}}$



Association Fitness

After an event is detected, located, and its origin time established, the arrivals that this event generated are identified and associated with the event. Given a detected event at location ω and origin time T_o, event magnitude is estimated from first-P associations and then we associate other arrivals i from station s_i using phase-specific predictions and tolerance values.

$$\mathrm{P}\left(ph\mid s_i,m_b,\Delta,depth\right)\exp\left[-\frac{\left((T_i-T_O)-p_{t,s_i,\omega,ph}\right)^2}{\varepsilon_{t,s_i,\omega,ph}^2+deltim_i^2}-\frac{\left(az_i-p_{az,s_i,\omega,ph}\right)^2}{\varepsilon_{az,s_i,\omega,ph}^2+delaz_i^2}-\frac{\left(sh_i-p_{sh,s_i,\omega,ph}\right)^2}{\varepsilon_{sh,s_i,\omega,ph}^2+delslo_i^2}\right]$$



PREDICTIONS

Predictions of travel time, azimuth, and slowness are made as follows.

- Travel time – iasp91 travel time model with SSSC corrections
- Azimuth – Estimated using a great circle path
- Slowness – Horizontal slowness derived from the iasp91 travel time model

These are the same predictions used by the Global Associator (GA) at the International Data Center (IDC), so the results below are a function of the different approaches to event detection and association, not a function of different predictions. PEDAL predictions for all stations are precomputed and stored for each grid node in the Earth model. We have experimented with Earth models of ¼, ½, 1, 2, and 3 degree spacing between grid nodes. Below, we show results using a 2-degree grid.

BULLETIN COMPARISON

Analyzing the output of PEDAL, an event bulletin, is challenging. We use an event commonality metric to compare the events in two different bulletins. The Event Commonality Score (ECS) between events E_1 and E_2 is a function of the location and association differences of the events. The higher the ECS, the better the match between the two events.

ECS = Location Difference Factor + False Association Factor + Missed Association Factor

Location Difference Factor = exp(–(d/A)²–(t/B)²), where d = distance in km between two events, t = origin time difference in seconds, A = distance scaling factor (e.g., 1500 km), and B = time difference scaling factor (e.g., 120 seconds)

False Association Factor = a_s / a_1
a_s = # shared associations
a_1 = # associations in E_1

Missed Association Factor = ta_s / ta_2
ta_s = # shared time-defining associations
ta_2 = # time-defining associations in E_2

Event Types

Each event in the Test Bulletin (B_T) is assigned a category based on its commonality with events in the Reference Bulletin (B_R).

- Valid: ECS > 0.3 with some event in B_R
- Split: Shares some associations with an event in B_R
- Merged: ECS > 0.3 with multiple events in B_R
- False: ECS < 0.3
- Events that share no associations with B_R have ECS = 0
- Missed: Events in B_R with no match in B_T

RESULTS AGAINST GROUND TRUTH BULLETINS (May 1-14, 2010)

PEDAL was evaluated on a 14-day window of IDCX arrivals from May 1-14, 2010. The LEB tables were augmented with additional valid events via expert analyst review to create a ground truth review bulletin. The maps show all PEDAL and GA events together with augmented LEB events.

A. **LEB** – International Data Center Analyst Reviewed Bulletin requiring three detecting stations.

1356 Ground Truth Events

Bulletin	# Origins	# Missed	# Valid	# False
PEDAL 2° Grid	2191	168	1181	887
GA	2062	236	1111	852

B. **Augmented LEB** – LEB bulletin augmented with additional events via rigorous analyst review. All of these events satisfy LEB criteria.

1541 Ground Truth Events

Bulletin	# Origins	# Missed	# Valid	# False
PEDAL 2° Grid	2191	261	1256	811
GA	2062	389	1137	680

C. **LEB Plus** – LEB bulletin augmented with additional events via rigorous analyst review without necessarily satisfying LEB criteria.

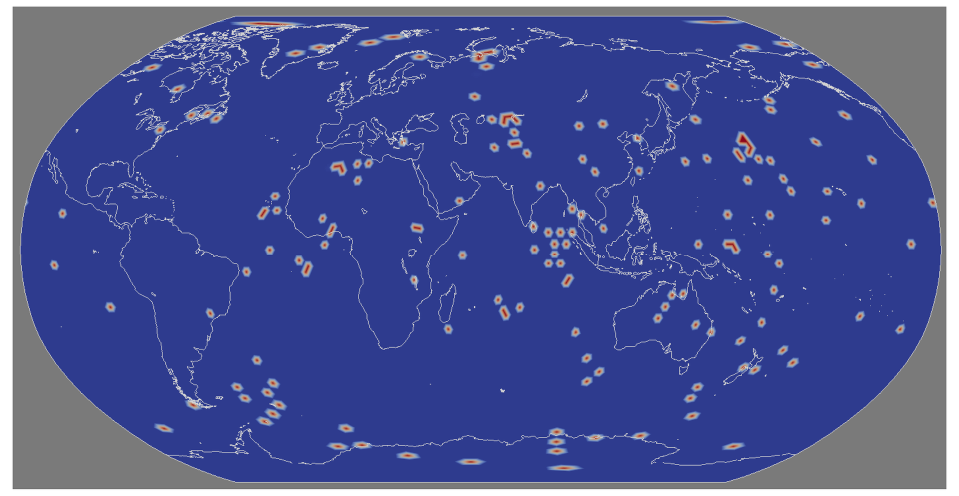
1846 Ground Truth Events

Bulletin	# Origins	# Missed	# Valid	# False
PEDAL 2° Grid	2191	332	1478	586
GA	2062	527	1299	662

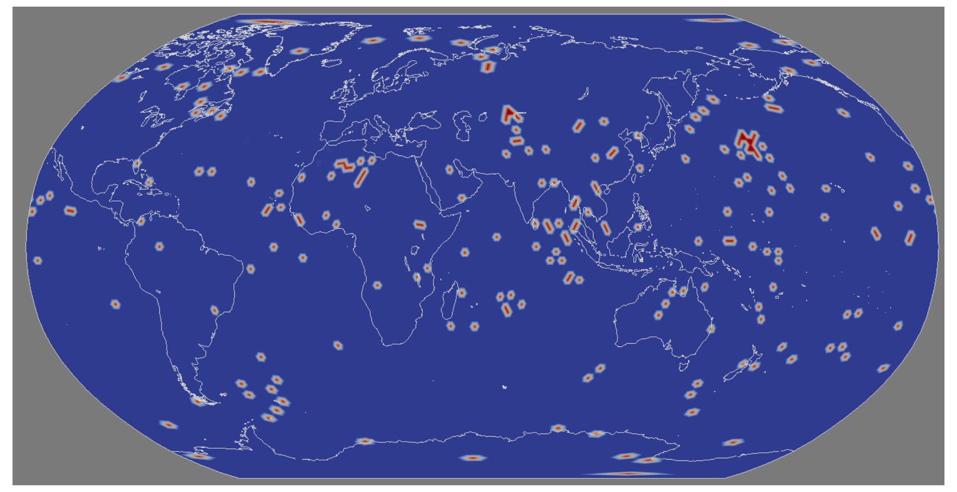
Results from testing PEDAL against the three ground truth bulletins described above indicate that PEDAL detects 887-498 = 389 events not identified by LEB analysts over a 14-day period.

RESULT MAPS and ECS HISTOGRAMS of PEDAL and GA BULLETINS COMPARED AGAINST 1846 EVENTS

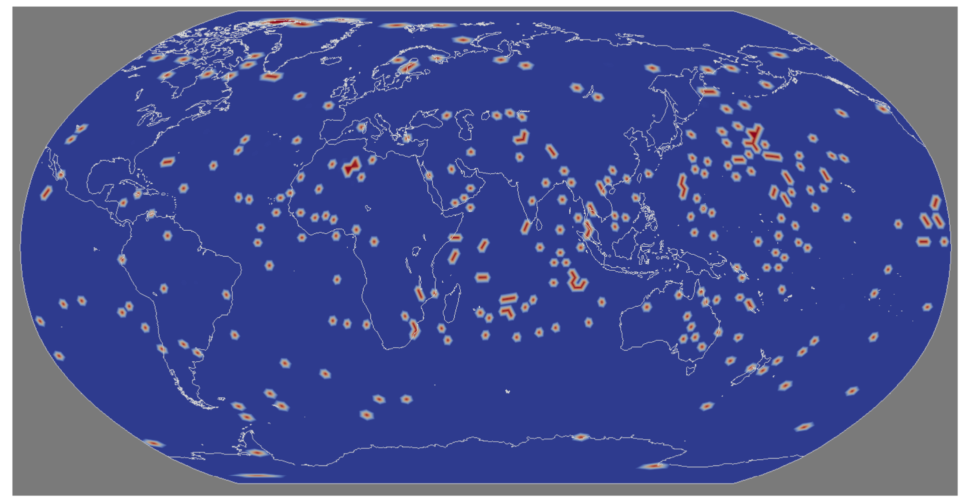
332 PEDAL Missed Events



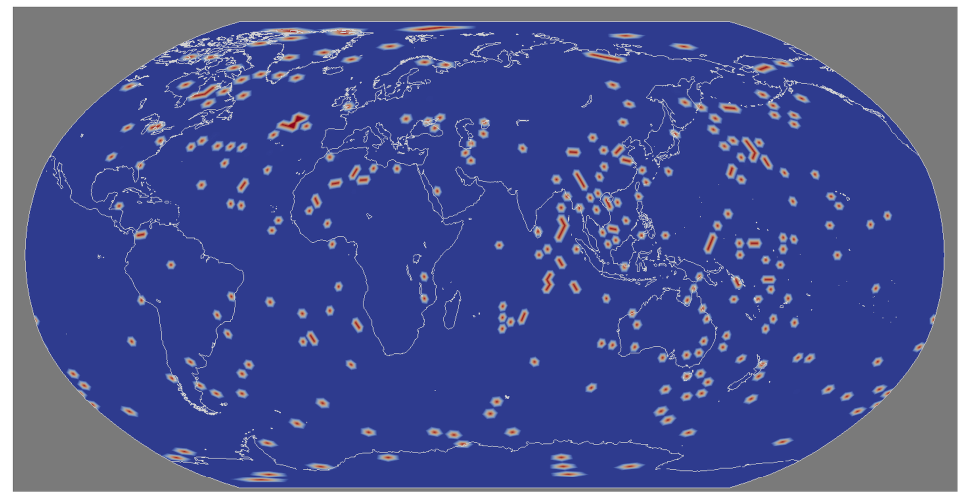
527 GA Missed Events

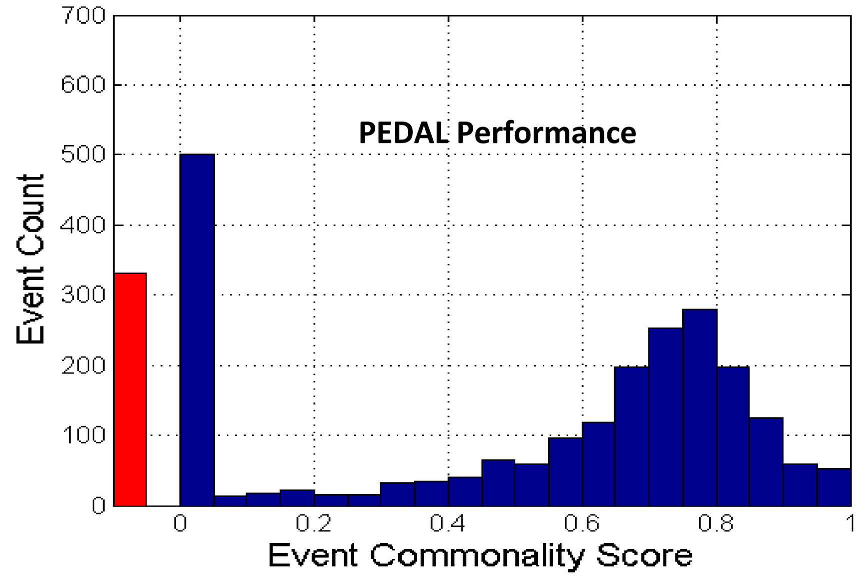


586 PEDAL False Events



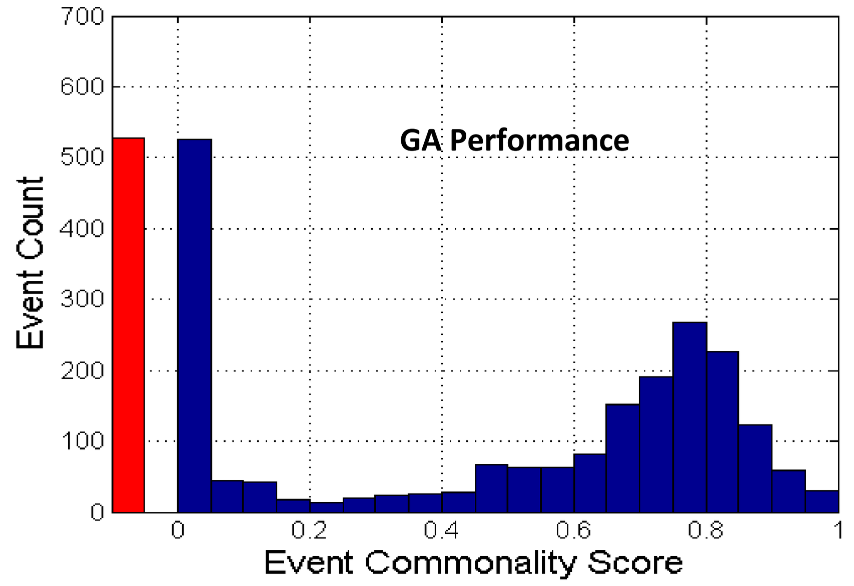
682 GA False Events





Histograms of ECS

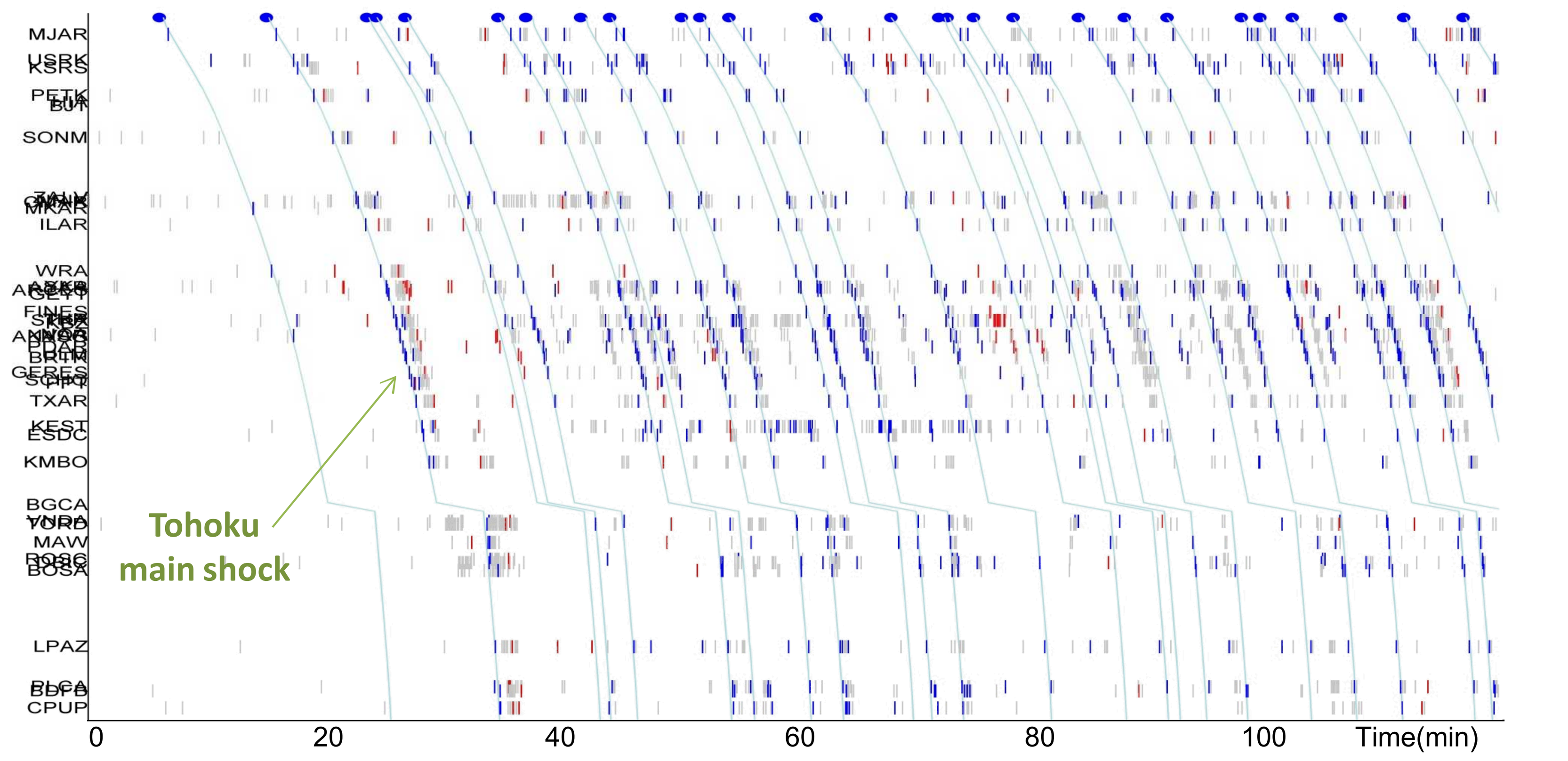
- Higher ECS values indicate a better match between an automated event and a reviewed event.
- Missed Events in Red



AFTERSHOCK PROCESSING

PEDAL processed a 10-day period of arrivals that included the 2011 Tohoku event. Using only array stations for spatial fitness when the number of arrivals in a 33-minute time window exceeds 350, PEDAL ran an order of magnitude faster than real time. PEDAL had 20% fewer missed events and slightly fewer false events than GA in this time period.

The graphic on the right shows arrivals detected at stations sorted by distance from the Tohoku event (vertical blue bars are PEDAL Tohoku associations, gray are unassociated, red are arrivals from non-Tohoku events). The blue circles at the top indicate PEDAL origins and the light blue lines are first P travel time curves. PEDAL detected most obvious events from this aftershock sequence.



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