Incorporating seismic phase correlations into a probabilistic model of global-scale seismology

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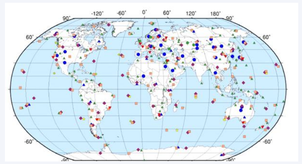
CTBTO PREPARATORY COMMISSION | preparatory commission for the comprehensive nuclear-test-ban treaty organization

NET-VISA

NET-VISA (NETwork processing Vertically Integrated Seismic Analysis) is a generative probabilistic model of global-scale seismology and an inference algorithm that deduces the seismic bulletin with the highest posterior probability given all the seismic detections (aka arrivals or triggers) and misdetections observed by a network of stations.



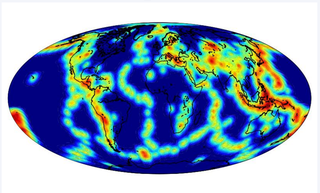
Blue dots and triangles are primary seismic stations.

Generative Model

A world (or hypothesis) is a complete sequence of seismic events, associated true arrivals, false arrivals and coda arrivals.

P(world) = P_θ(events) P_Φ(true | events) P_λ(false) P_γ(coda | true, false)

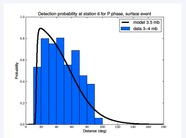
P_θ(events)



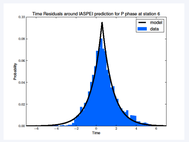
Event location density.

- Location prior
- Gutenberg Richter magnitude prior
- Uniform in depth, and time

P_Φ(true arrivals| events)



Detection probability vs distance.

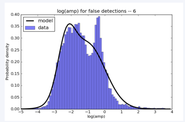


Arrival time vs IASPEI.

- Detection probability using Logistic model
- IASPEI + Laplace model for travel time
- SASC + Laplace model for azimuth and slowness
- Amplitude as a linear regression with Gaussian noise

Generative Model (continued)

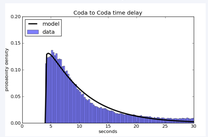
P_λ(false arrivals)



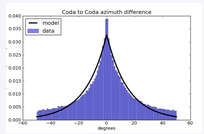
False arrival amplitude

- False amplitude as a mixture of Gaussians
- Uniform in time, slowness, and azimuth

P_γ(coda | true, false arrivals)



Coda time delay



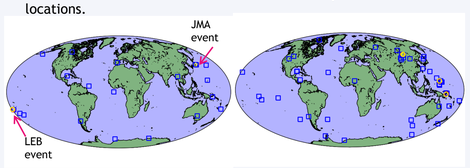
Coda azimuth difference

- Coda time delay as a Gamma distribution
- Azimuth, Slowness, and Amplitude differences as Laplacians

Heuristic Inference

- Start with a world with no events and all arrivals are noise or coda
- Series of moves change the world to improve its probability

❑ **Birth move**
- ○ Inverts detections to get seed locations.
- ○ Associates seed locations to detections to identify the best set of locations.



Example inverting detections of weak events

Example inverting detections of strong events

❑ **Improve Arrivals Move**
- ○ Associate each arrival with the best event-phase

❑ **Improve Event Move**
- ○ Find the best location for an event given the currently associated detections

❑ **Death Move**
- ○ Kill unsupported events.

Problem – Lack of Phase Correlations

Existing model assumed that all phases are generated independently.

This can lead to anomalous phase orders, for example an S phase before a P phase. Although this is quite rare, about 1 such occurrence in 30 days of data.

Also, an event could generate a P phase with a higher slowness than an S phase at the same station.

Some of the arrival time residuals could be quite high.

Often pP phases are freely associated whereas analysts prefer to be more conservative with such phases.

The following phase association rules have been added to the model to address the above shortcomings.

The following rules are not used during the birth move.

Phase Rules

- If phase X has an IASPEI time before phase Y then the measured arrival time of phase X should be before phase Y.
- If phase X has an IASPEI slowness less than that of phase Y then the measured slowness value of phase X should be less than that of phase Y.
- The absolute time residual for any phase should not exceed 20 seconds.
- Only associate pP phases if at least 3 such phases are associated to an event.

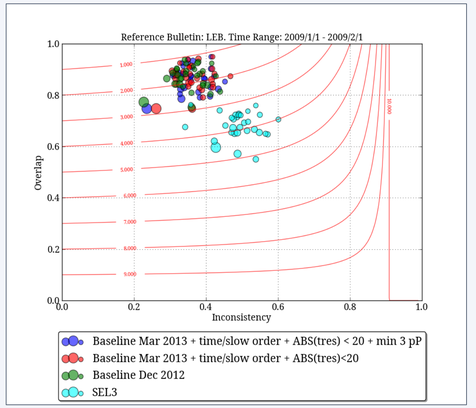
Performance Evaluation

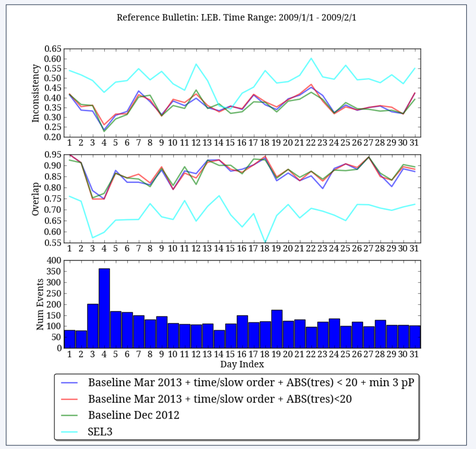
- Match events in a reference bulletin and the test bulletin which have two arrivals in common. We require that the arrivals be associated using a similar phase label for both events.
- Measure the overlap - the fraction of reference events that are matched.
- Measure the inconsistency - the fraction of the test events that are not matched.
- Compute the cost of the solution as a weighted average of the overlap and inconsistency normalized by the number of reference events. We assign a weight of 10 to the overlap and 1 to the inconsistency since it takes a lot more work by the analysts to add an event than to discard a false event.
- Cost = 10 * (1 - Overlap) + Overlap * Inconsistency / (1 – Inconsistency)
- For the comparison with ISC we require matching events to be within 5 degrees and 50 seconds. Further, we delete from the ISC bulletin all events which originate from IDC. In other words, we remove the REB events, and are interested in measuring the overlap of the LEB bulletin with the other ISC events.

DPRK 3 Event

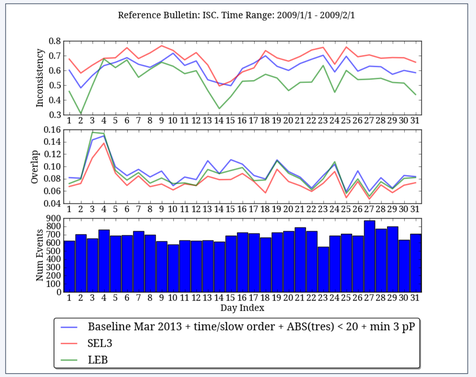
LEB :	41.3005	N	129.0652	E	NSTA=88	Gap=51
NET-VISA :	41.3058	N	129.0919	E	NSTA=84	Gap=51
SEL3:	41.3134	N	129.1012	E	NSTA=25	Gap=120

Results





Results (continued)



Conclusions

- NET-VISA has higher overlap with LEB than the current SEL3 bulletin and it also has lower inconsistency.
- The cost of generating a bulletin using NET-VISA would be half of the current cost.
- For the DPRK3 event, NET-VISA associated arrivals with more than thrice as many stations as SEL3. This led to a better solution with less than half the azimuthal gap.
- NET-VISA finds events which are not in LEB or SEL3, but can be corroborated by the ISC bulletin. Overall 0.5 % more overlap with ISC than LEB.
- The additional phase correlations added to NET-VISA make the resulting bulletin more seismologically sound without any loss in performance.

References

- NET-VISA: Network Processing Vertically Integrated Seismic Analysis. Nimar S. Arora, Stuart Russell, and Erik Sudderth. Bulletin of the Seismological Society of America, Vol. 103, No. 2a (to appear).
- Analyst Instructions for Seismic, Hydroacoustic, and Infrasonic Data. IDC Document 6.2.5.
- International Seismological Centre, *On-line Bulletin*, http://www.isc.ac.uk, Internatl. Seis. Cent., Thatcham, United Kingdom, 2011.

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Disclaimer

The views expressed in this paper are those of the authors and do not necessarily reflect the views of the CTBTO Preparatory Commission.